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FARMERS' ADAPTIVE INVESTMENTS AND GROUNDWATER RESOURCE IMPACT IN A CHANGING CLIMATE.

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Abstract:

One of the many effects of Climate Change is increased drought making water availability scarcer in more regions of the world, and primarily affecting the agricultural sector. In this context, we study farmers' adaptation to Climate Change by developing a two-period discrete-time theoretical model of exploitation of a groundwater resource that studies the impact of adaptive investments as a response to climate change on farmers' profitability and the sustainability of the groundwater resource. In particular, we consider that the resource users, the farmers, may belong to different groups: adapters and non-adapters, and analytically solve the game under four scenarios: full cooperation, cooperation within groups, cooperation only within adapters and full non-cooperation between all farmers. Theoretical results show that under full cooperation, adaptation is not beneficial for the environment, meaning that lower final stock levels are obtained when farmers adapt compared to when they do not. Those results could also be observed numerically when there are strategic interactions among groups and/or among all farmers, i.e., when farmers do not cooperate. In contrast, numerical results suggest that the impact of adaptation could be positive for the resource and for the overall profits of the farmers when only the adapters are cooperating. Finally, defining the profitability (or scope) of cooperation as the difference between overall profits under full cooperation and non-cooperation, preliminary results suggest that the number of investing farmers would be a key element in estimating the scope of cooperation.

JEL Codes: C70, Q15, Q25, Q54
Keywords: Groundwater resource, Dynamic game, farmer’s adaptive investments, Climate change

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1 Introduction

One of the many effects of Climate Change is increased drought making water availability scarcer in more regions of the world. Droughts are occurring more often, last longer periods and affect wider areas due to higher temperatures, increased evapotranspiration and decreased precipitation, (IPCC (2023)). Drought threatens people's livelihoods, increases the risk of disease and death, impacts on human health and well-being and fuels mass migration. The agricultural sector is particularly affected by droughts, indeed, in 2017, the FAO stated that 83% of all damage and loss caused by drought worldwide was recorded by the agricultural sector (FAO (2023)).

Groundwater resources represent the world's vital store of freshwater and are increasingly important for irrigated agriculture in arid and semi-arid regions under climate change. One specific way in which climate change can impact groundwater availability and its management is by affecting the recharge rate of the groundwater aquifer. Meixner et al. (2016) found that six out of eight aquifers in Western United States will all experience a decrease of their recharge rate in the future as Climate Change intensifies. The extensive review by Atawneh et al. (2021) confirms that Climate Change may directly affect future groundwater recharge. Based on groundwater recharge projections, an overall negative impact on groundwater recharge emerges, regardless of emission scenarios or time horizons used.

Societies and individual farmers have been responding to reduction in water availability by implementing different adaptive measures. Some common adaptive measures at farmer's level to increase the resilience of the agriculture sector to climate change include the optimization of an irrigation schedule and farmers' production practices like for example, crop mix, adjustments in planting dates such as changes in harvest and sowing dates, changes in fertilizer application frequency and land use changes. Farmers have also been investing in water savings technologies like drip irrigation and micro irrigation. Other kinds of investments include the installation of early warning systems, increasing reservoir storage capacity and the creation of agricultural insurance systems, supportive financial schemes to protect against crop yield losses, to mention a few (see e.g., Iglesias and Garrote (2015) for a review).

Most of the works on farmer's adaptive measures and water management as a response to Climate Change effects have an empirical nature: in general, they focus on a specific geographical area and then they study the determinants of farmers' adaptation decisions and their impact. For example, Hornbeck and Keskin (2014) analyses the historical evolution of farmers' adaptation to groundwater and droughts in the Ogalalla Aquifer (EEUU) and conclude that while in the short run, farmers change irrigation practices to reduce the impact of droughts on crop yields, in the long run, farmers also shift land toward water intensive crops. However, the study does not include projections of technological change to deal with changes on water availability.

Indeed, few theoretical works deal with farmer's adaptation and groundwater resources in a changing climate by considering the dynamics of the resource.

De Frutos Cachorro et al. (2017) uses a dynamic optimization model at farm level and focuses on land-use and irrigation water choices to assess the impact of dry weather conditions and possible restriction policies on farmers' payoffs in the Beauce area in France. Koundouri and Christou (2006) analyse the optimal management of a groundwater resource with desalinisation as a backstop substitute to adapt to resource scarcity. Robert et al. (2018) addresses investment in irrigation adaptive measures to climate change by using a dynamic stochastic approach, with an application to groundwater irrigation in India. Quintana Ashwell et al. (2018) compares optimal and myopic solutions in a model of groundwater extraction and estimates that predicted gains from optimal management for a region in the Ogallala Aquifer are larger when accounting for climate change and technical progress.

In this paper we contribute to the literature on farmers' adaptation to Climate Change by developing a theoretical model of exploitation of a groundwater resource that studies the impact of adaptive investments as a response to climate change on farmers' profitability and the sustainability of the groundwater resource, and considers dynamic and strategic interactions between several farmers. In particular, we assume that Climate Change affects the dynamics of the groundwater, and this is modelled as an exogenous decrease in the recharge rate from one period to another, so that the impact of Climate Change is experienced equally by all water users. In contrast to Quintana Ashwell et al. (2018), which considers technical change as an exogenous variable, farmers' adaptive response to climate change is modelled as an endogenous and costly private investment that increases the efficiency of water used for irrigation by reducing the marginal extraction cost (e.g., one could think of an investment in a better irrigation system).

We develop a two-period discrete-time game of exploitation of a groundwater resource by a finite number of farmers, who may belong to two different groups (adapters and non-adapters). We consider that groups can have different sizes and identical farmers within each group. In the first period, farmers decide only their extraction rates and in the second period they simultaneously choose both their extraction rates and how much to invest in adaptation. We analytically solve the game under four scenarios: full cooperation, cooperation within groups while groups are not cooperating, cooperation only within adapters and full non-cooperation between all farmers.

Theoretical results show that under cooperation, adaptation is not beneficial for the environment. Specifically, higher extractions (equivalently, lower final stock levels) are obtained when farmers adapt compared to when they do not, and this result holds regardless of the number of adapters. Those results are also observed numerically when there are strategic interactions within groups and/or among farmers, i.e., when farmers do not cooperate within each group. However, these results are not always observed when assuming cooperation only among adapters, which can lead to a positive effect of adaptation on the final stock levels.

In contrast, numerical results show that adaptation could be beneficial for the profitability of the "adapters" and for the overall profitability of the farmers, under different levels of cooperation. Defining the profitability (or scope) of cooperation as the difference between overall profits under full cooperation and non-cooperation, preliminary results suggest that the number of investing farmers would be a key element in estimating the scope of cooperation.

The paper is organized as follows. In Section 2, we present the theoretical game, while in Sections 3-6 we analytically solve the model for different scenarios corresponding to different levels of cooperation. In Section 7 we describe the results from the numerical simulations, while Section 8 provides the conclusion.

2 Model

We consider $N \geqslant 2$ farmers whose production activity requires exploiting a common pool groundwater resource over two periods of time $t = 1, 2$. The number of total farmers, N, is fixed over the two periods. Denote by $g_{it} \geqslant 0$ the individual extraction rate of farmer i, $(i = 1 \ldots N)$ in period t, we assume that the benefits from water extraction in a given period are a quadratic function of the individual extraction rate g_{it}, as considered in previous literature (e.g., Rubio and Casino (2001), Pereau (2020) in continuous time and a recent study de Frutos Cachorro et al. (2024) in discrete time), that is

$$R_{it}\left(g_{it}\right) = a g_{it} - \frac{b}{2} g_{it}^2 \tag{1}$$

with $t = 1, 2$ and $a, b > 0$.

Farmers' extraction activity accumulate over time and the time evolution of the groundwater stock is assumed to be governed by the linear discrete-time equation

$$G_{t+1} = G_t + r - B_{t+1} - \alpha \sum_{i=1}^{N} g_{it+1} \text{ with } t = 0, 1 \tag{2}$$

where $G_t > 0$ is the previous period stock of groundwater, r is the natural recharge rate and $\alpha \in (0, 1]$ is the coefficient of water used for irrigation that percolates into the aquifer[1]. The parameter B_{t+1} is an exogenous parameter that represents the negative impact of climate change on the natural recharge rate[2] and we assume that $r > B_2 \geqslant B_1 \geqslant 0$.[3]

In each period, farmers bear an extraction cost that linearly depends both on the extraction rate and on the stock of the groundwater resource that is available at the beginning of each period, that is

$$C_{it}\left(g_{it}, G_{t-1}\right) = \left(z - c G_{t-1}\right) g_{it} \tag{3}$$

with $t = 1, 2$ and $z, c > 0$.

[1]Equivalently, $(1 - \alpha)$ represents the return flow coefficient of water extraction that comes back to the aquifer by percolation.

[2]Here we think of droughts as a consequences of climate change.

[3]This can be re-written as having two possibly different recharge rates for the two periods, i.e. $r_1 \geqslant r_2 > 0$.

This cost function shows the following properties. About the marginal extraction cost:

$$\frac{\partial C}{\partial g} = z - cG_{t-1} > 0$$

$$\frac{\partial^2 C}{\partial g \partial G} = -c < 0$$

from which we have that the marginal extraction cost is positive and it is decreasing with the level of the natural groundwater resource that is available.

Furthermore,

$$\frac{\partial C}{\partial G} = -cG_{t-1}g_{it} < 0$$

$$\frac{\partial^2 C}{\partial G \partial g} = -cG_{t-1} < 0$$

which means that larger groundwater stocks reduce the extraction cost but, as the extraction rate increases, the savings from the positive stock effect decrease.

As a response to the adverse effect of climate change which, in this case, hinders the availability of the natural resource, we assume that farmers, only in the second period, can invest in adaptive measures. In particular, we assume that farmers make investments that allow them to reduce the marginal extraction cost, like better irrigation practices. When a farmer i, in the second period, invests in an adaptive measure, the extraction cost function becomes

$$C_{i2} = (z - I_{i2} - cG_2)\, g_{i2} \tag{4}$$

where I_{i2} is the level of investment in adaptive measures. The cost of adaptive investments is increasing and convex in the level of adaptation and is given by

$$K_i(I_{i2}) = \frac{\gamma}{2} I_{i2}^2.$$

Next, to model the asymmetry among farmers regarding the investment option, we partition the set of farmers into two groups: a set of size n, called "adapters" (indexed by A) which includes all the farmers that decide to invest in adaptive measures in the second period and a group of size $N - n = m$ called "non-adapters/regulars" (indexed by NA) which includes all the farmers that decide not to invest in adaptive measures.

In the sequel, to simplify the exposition, we denote the extraction rate and investment adaptation decisions of an individual adapter (indexed by i) by the pair (x_{it}, I_{i2}) and the extraction rate a non-adapter (indexed by j) by y_{jt}.

Considering the previous assumptions about farmers' benefits and costs, the overall profit function of an individual non-adaptive farmer j is given by

$$\pi_j^{NA} = \pi_{j1}^{NA} + \beta \pi_{j2}^{NA} \quad \text{with } j = 1 \ldots m \tag{5}$$

with the (per period) profit, π_{jt}^{NA},

$$\pi_{j1}^{NA}(y_{j1}, G_0) = ay_{j1} - \frac{b}{2}y_{j1}^2 - (z - cG_0)\, y_{j1}, \tag{6}$$

$$\pi_{j2}^{NA}(y_{j2}, G_1, G_2) = ay_{j2} - \frac{b}{2}y_{j2}^2 - (z - cG_1)\, y_{j2} + AG_2, \tag{7}$$

and the overall profit function of an individual adaptive farmer i is given by

$$\pi_i^A = \pi_{i1}^A + \beta\pi_{i2}^A \quad \text{with } i = 1 \dots n \tag{8}$$

with the (per period) profit, π_{it}^x,

$$\pi_{i1}^A(x_{i1}, G_0) = ax_{i1} - \frac{b}{2}x_{i1}^2 - (z - cG_0)\, x_{i1}, \tag{9}$$

$$\pi_{i2}^A(x_{i2}, G_1, G_2) = ax_{i2} - \frac{b}{2}x_{i2}^2 - (z - I_{i2} - cG_1)\, x_{i2} - \frac{\gamma}{2}I_{i2}^2 + AG_2. \tag{10}$$

where β represents the discount factor and the product AG_2 adds the possibility that the farmers value the final resource stock at the end of the second period[4].

The objective of each type of farmer is to maximize her/his overall profit, (5) or (8) depending on the group to which the farmer belongs, subject to the resource constraint (2). This problem is solved by backward induction starting from the second period.

Denote the total extraction in period 1 by $T_1 = \sum_{i=1}^{n} x_{i1} + \sum_{j=1}^{m} y_{j1}$ and the total extraction in period 2 by $T_2 = \sum_{i=1}^{n} x_{i2} + \sum_{j=1}^{m} y_{j2}$. The second period profit of a farmer i that adapts, accounting for the resource constraint, can be rewritten as

$$\begin{aligned}\pi_{i2}^A = {} & ax_{i2} - \frac{b}{2}x_{i2}^2 - (z - I_{i2} - c\,(r - B_1 + G_0 - \alpha T_1))\, x_{i2} - \frac{\gamma}{2}I_{i2}^2 \\ & + A\,(2r - B_2 - B_1 + G_0 - \alpha T_1 - \alpha T_2)\end{aligned} \tag{11}$$

and for the farmer j that does not adapt, it is given by

$$\begin{aligned}\pi_{j2}^{NA} = {} & ay_{j2} - \frac{b}{2}y_{j2}^2 - (z - c\,(r - B_1 + G_0 - \alpha T_1))\, y_{j2} \\ & + A\,(2r - B_2 - B_1 + G_0 - \alpha T_1 - \alpha T_2)\,.\end{aligned} \tag{12}$$

After some further manipulations, those expressions can be rewritten as

$$\pi_{i2}^A = -\frac{1}{2}bx_{2i}^2 + (L + I_{i2} + c\,(r - B_1 - \alpha T_1))\, x_{2i} + \frac{\gamma}{2}I_{i2}^2 + (A\,(E - \alpha T_1 - \alpha T_2)) \tag{13}$$

$$\pi_{j2}^{NA} = -\frac{b}{2}y_{j2}^2 + (L + c\,(r - B_1 - \alpha T_1))\, y_{j2} + (A\,(E - \alpha T_1 - \alpha T_2)) \tag{14}$$

[4]For example they can sell their right to exploit the resource.

with

$$L = a - z + cG_0,$$
$$E = 2r - B_1 - B_2 + G_0.$$

Moving now to the first period problem, the overall profit of farmer i that adapts and accounts for the resource constraint can be rewritten as

$$\pi_i^A = -\frac{b}{2}x_{i1}^2 + Lx_{i1} + \beta\pi_{i2}^A \tag{15}$$

and the profit of a farmer j that does not adapt corresponds to

$$\pi_j^{NA} = -\frac{b}{2}y_{j1}^2 + Ly_{j1} + \beta\pi_{j2}^{NA}. \tag{16}$$

In what follows we address the key question about the impact of adaptation. We do this any size of the adapters' group and different scenarios related to the degree of cooperation, that is, the full cooperative case (FC), cooperation within groups case (CG), cooperation within adapters case (CA) and the full non-cooperative case (NC).

For each setting, we study the impact of adaptation by comparing the results obtained in the game without adaptation (benchmark) with the ones when any fraction of adapters is allowed.

3 Full cooperative case (FC)

In this section we assume a full cooperative setting, meaning that farmers choose their control variables to maximize the aggregate profit of all farmers and we allow for any degree of asymmetry in the number of adaptive farmers, i.e., the number of farmers who choose to invest in adaptation, $n \in [0, N]$.

The problem to solve is then:

$$\begin{aligned} \max_{\substack{\{x_{i1}, x_{i2}, I_{i2} \geq 0\}_{i=1}^n, \\ \{y_{j1}, y_{j2} \geq 0\}_{j=1}^m}} \quad & \sum_{i=1}^n \pi_i^A + \sum_{j=1}^m \pi_j^{NA}, \\ & s.t. \ (2), \\ & G_1, G_2 \geq 0 \end{aligned} \tag{17}$$

We solve the problem in two steps by backward induction starting from the second period. As farmers are symmetric within each group, we denote in what follows $x_t = x_{it}, y_t = y_{jt}, \pi_t^A = \pi_{it}^A, \pi_t^{NA} = \pi_{jt}^{NA},\ t = 1, 2$ and $I_2 = I_{i2}$, the second period profits of an adaptive (13) and a non-adaptive (14) farmer, accounting for the resource constraint become

$$\pi_2^A(x_2, y_2, T_1) = -\frac{1}{2}bx_2^2 + (L - D_1 + I_2 - c\alpha T_1)x_2 - \frac{1}{2}\gamma I_2^2 + A(E - \alpha T_1 - m\alpha y_2)$$
$$\pi_2^{NA}(x_2, y_2, T_1) = -\frac{1}{2}by_2^2 + (L - D_2 - c\alpha T_1)y_2 + A(E - \alpha T_1 - n\alpha x_2)$$

with

$$D_1 = An\alpha + cB_1 - cr$$
$$D_2 = Am\alpha + cB_1 - cr.$$

The second period problem then reads as

$$\max_{x_2, y_2, I_2 \geq 0} \Pi_2 = n\pi_2^A + m\pi_2^{NA}$$

and from the first order conditions we obtain the reaction functions of the decisions in the second period as a function of first-period extraction decisions

$$x_2(I_2, T_1) = \frac{L - D_1 - Am\alpha + I_2 - c\alpha T_1}{b}$$

and

$$I_2(x_2) = \frac{x_2}{\gamma}$$

which together give

$$x_2(T_1) = \gamma \frac{L - D_1 - Am\alpha - c\alpha T_1}{b\gamma - 1}. \tag{18}$$

Finally, we have

$$y_2(T_1) = \frac{L - D_1 - Am\alpha - c\alpha T_1}{b}. \tag{19}$$

It is immediate to note that

$$x_2(T_1) = \frac{b\gamma}{b\gamma - 1} y_2(T_1).$$

Sufficient conditions for optimization in the second period are satisfied when

$$SOC_{2FC}\colon\ b\gamma - 1 > 0.$$

We can now compute the second period profit of a farmer i that adapts as a function of T_1, the total extractions in period 1,

$$\pi_2^A(T_1) = \frac{b\gamma(L - D_1 - Am\alpha - c\alpha T_1)^2 + 2Am\alpha(L - D_1 - Am\alpha - c\alpha T_1) - 2Ab(b\gamma - 1)(-E + \alpha T_1)}{2b(b\gamma - 1)}. \tag{20}$$

Similarly, for a farmer j that does not adapt, the second period profit as a function of T_1 is given by

$$\pi_2^{NA}(T_1) = \frac{(b\gamma+1)(L-D_1-Am\alpha-c\alpha T_1)^2 - 2(L-D_2-c\alpha T_1)(L-D_1-Am\alpha-c\alpha T_1)}{2b(b\gamma-1)} - \frac{2Ab(b\gamma-1)(-E+\alpha T_1)}{2b(b\gamma-1)}. \tag{21}$$

Finally, the aggregate profit in period 2 as a function of T_1 is given by

$$\Pi_2(T_1) = \frac{(b\gamma N-m)(L-D_1-Am\alpha-c\alpha T_1)^2 - 2AbN(b\gamma-1)(\alpha T_1-E)}{2b(b\gamma-1)}.$$

Moving to the first period problem, the overall period profits of an adaptive (15) and a non-adaptive farmer (16) accounting for the resource constraint become

$$\pi^A(T_1) = -\frac{b}{2}x_1^2 + Lx_1 + \beta\pi_2^A(T_1)$$
$$\pi^{NA}(T_1) = -\frac{b}{2}y_1^2 + Ly_1 + \beta\pi_2^{NA}(T_1).$$

with $T_1 = my_1 + nx_1$. In the first period, the problem to solve is

$$\max_{x_1, y_1 \geq 0} \Pi_1 = n\pi^A(T_1) + m\pi^{NA}(T_1)$$

and from the first order conditions we obtain

$$x_1(y_1) = \frac{b(b\gamma-1)(L-AN\alpha\beta) + c\alpha\beta(Nb\gamma-m)(-L+D_1+Am\alpha) + c^2m\alpha^2\beta(Nb\gamma-m)y_1}{b^2(b\gamma-1) - nc^2\alpha^2\beta(Nb\gamma-m)} \tag{22}$$

and

$$y_1(x_1) = \frac{b(b\gamma-1)(L-AN\alpha\beta) + c\alpha\beta(Nb\gamma-m)(-L+D_1+Am\alpha) + c^2n\alpha^2\beta(Nb\gamma-m)x_1}{b^2(b\gamma-1) - mc^2\alpha^2\beta(+Nb\gamma-m)}. \tag{23}$$

The sufficient condition for optimization in the first-period problem requires

$$SOC_{1FC}\colon\ b^2(b\gamma-1) - c^2N\alpha^2\beta(Nb\gamma-m) > 0.$$

To find the first period equilibrium extraction levels we solve the system given by equations (22) and (23), so that we have

$$x_{1FC}^*(n,m) = y_{1FC}^*(n,m) = \frac{b(b\gamma-1)(L-AN\alpha\beta) - (L-D_1-Am\alpha)c\alpha\beta(Nb\gamma-m)}{b^2(b\gamma-1) - c^2\alpha^2\beta N(Nb\gamma-m)}. \tag{24}$$

Substituting the results obtained in the reaction functions in period 2, we obtain

$$x_{2FC}^*(n,m) = \gamma b\frac{b(L-D_1-Am\alpha) - Nc\alpha(L-AN\alpha\beta)}{b^2(b\gamma-1) - Nc^2\alpha^2\beta(Nb\gamma-m)}, \tag{25}$$

$$y_{2FC}^*(n,m) = \frac{b\gamma-1}{b\gamma}x_{2FC}^*(n,m), \tag{26}$$

$$I_{2FC}^*(n,m) = \frac{x_{2FC}^*(n,m)}{\gamma}.$$

Proposition 1 *Sufficient conditions for the second period extraction levels to be positive are that $b - Nc\alpha > 0$ and*

$$A_{x^*_{2+}} = \frac{b\left(L\left(b - Nc\alpha\right) + bc\left(r - B_1\right)\right)}{b\alpha N\left(b - Nc\alpha\beta\right)} > A > 0$$

Proof in Appendix 9.1.

Proposition 1 states that in the second period, farmers extract water if farmers valuation of the final stock level at the end of the second period, A, is not too large.

3.1 Benchmark case (no adaptation) and special case (full adaptation)

From the above results we can easily retrieve the benchmark case where *no farmer* invests in adaptation, that is $n = 0$ and $m = N$.

In this case the extraction rate in the first period (being nil the extractions rates of the adaptive farmers) is given by

$$y^B_{1FC} = \frac{b\left(L - AN\alpha\beta\right) - Nc\alpha\beta\left(L - AN\alpha + c\left(r - B_1\right)\right)}{b^2 - N^2c^2\alpha^2\beta},$$

and the extraction rate in the second period is

$$y^B_{2FC} = \frac{b\left(L - AN\alpha + c\left(r - B_1\right)\right) - Nc\alpha\left(L - AN\alpha\beta\right)}{b^2 - N^2c^2\alpha^2\beta},$$

Second order conditions for the first and second extraction periods become respectively

$$SOC^B_{2FC}\colon b\gamma - 1 > 0$$
$$SOC^B_{1FC}\colon b^2 - Nc^2\alpha^2\beta > 0.$$

We can also compute the special case given by the situation when *every farmer* invests in adaptation (S), that is $n = N$ and $m = 0$. The extraction rates in the first and second period (being nil the extractions of the non-adaptive farmers) are given by

$$x^S_{1FC} = \frac{\left(b\gamma - 1\right)\left(L - AN\alpha\beta\right) - Nc\alpha\beta\gamma\left(L - AN\alpha + c\left(r - B_1\right)\right)}{b\left(b\gamma - 1\right) - \beta\gamma N^2c^2\alpha^2}$$

and

$$x^S_{2FC} = \gamma\frac{b\left(L - AN\alpha\right) + c\left(b\left(r - B_1\right) - N\alpha\left(L - AN\alpha\beta\right)\right)}{b\left(b\gamma - 1\right) - \beta\gamma N^2c^2\alpha^2}.$$

The second order conditions for the first and second extraction periods are

$$SOC^S_{1FC}\colon b\gamma - 1 > 0$$
$$SOC^S_{2FC}\colon b\left(b\gamma - 1\right) - N^2\beta\gamma c^2\alpha^2 > 0.$$

3.2 Theoretical results: Impact of adaptation on the final stock levels

We can now study analytically in the full cooperative setting the impact of adaptation on the extraction rates of farmers and on the stock of groundwater left at the end of the program (i.e., at the end of the second period). For the impact of adaptation on farmers profits, we rely on numerical simulations in section 7. In order to do this we compare how the equilibrium values of the above variables change when we move from a situation when there is no adaptation, (i.e., the benchmark case, where $n = 0$ and $m = M$), to a situation with adaptation, i.e., for any $n \in [0 \ldots N]$. With regard to the extraction levels and the final stock levels, results are reported in Proposition 2.[5].

Proposition 2 *Assuming positive extraction levels in the second period, for any number of farmers investing in adaptation measures,*

- *in the first period, the water extracted by any farmer under adaptation is less than what is extracted in the case when nobody adapts ($x^*_{1FC}(n) = y^*_{1FC}(n) < y^B_{1FC}$);*
- *in the second period, individual extraction levels of adapters and non-adapters in presence of adaptation are greater than what is extracted in the case when nobody adapts ($x^*_{2FC}(n) > y^B_{2FC}$ and $y^*_{2FC}(n) > y^B_{2FC}$);*
- *over the two periods, the overall extraction in the presence of adaptation is greater than the overall extractions when nobody adapts, making the final stock levels in the presence of adaptation smaller than when there is no adaptation at all ($G^*_{2FC}(n) < G^B_{2FC}$).*

See Proof in the Appendix 9.2.

Indeed, as in the first period, adapters and non-adapters extract the same amount of groundwater under adaptation, Proposition 2 states that for both kinds of farmers, the extraction level in the first period is lower when there is someone, even just one farmer, doing adaptation in the second period than when nobody does. The extraction of groundwater is then concentrated in the second period when it is cheaper, regardless of the number of adapters. This means that no matter the number of farmers investing in adaptation, just one farmer making an investment shifts everybody effort in the second period and the overall extraction is greater with adaptation. In order words, stock level at the end of the second period is always lower when some farmers invest that when they not. In the full cooperative case, we can conclude that any degree of adaptation is negative from a strict environmental point of view.

In what follows, we solve the problem for three different non-cooperative settings: cooperation within groups, cooperation only within adapters and the fully non-cooperative case where no farmers cooperate with each other.

[5]These results hold also in the extreme case $n = N$.

4 Cooperation within groups (CG)

In this case, we assume that the two groups of farmers (adapters and non-adapters) compete against each other, and farmers within the same group cooperate with each other. The objective of the farmers is to choose their control variables that maximize the aggregate profit of the group of farmers to which she/he belong subject to the dynamic constraint (2).

As farmers are symmetric within each group, the problems to solve for a farmer who belongs to the group of adapters and non-adapters are now respectively:

$$\begin{aligned} \max_{\{x_1,x_2,I_2\geq 0\}} \quad & n\pi^A, \\ s.t. \quad & (2), \\ & G_1, G_2 \geq 0 \end{aligned} \tag{27}$$

$$\begin{aligned} \max_{\{y_1,y_2\geq 0\}} \quad & m\pi^{NA} \\ s.t. \quad & (2), \\ & G_1, G_2 \geq 0 \end{aligned} \tag{28}$$

We again solve the problem in two steps by backward induction. Starting from the second period, the second period aggregate profits of an adapter and a non-adapter (equations (13) and (14)) accounting for the resource constraint are the same ones as in section 3 and given by

$$\pi_2^A(x_2, y_2, T_1) = -\frac{1}{2}bx_2^2 + (L - D_1 + I_2 - c\alpha T_1)\,x_2 - \frac{1}{2}\gamma I_2^2 + A\,(E - \alpha T_1 - m\alpha y_2)$$
$$\pi_2^{NA}(x_2, y_2, T_1) = -\frac{1}{2}by_2^2 + (L - D_2 - c\alpha T_1)\,y_2 + A\,(E - \alpha T_1 - n\alpha x_2)\,.$$

The second period problem of an adapter corresponds to

$$\max_{x_2,I_2\geq 0} n\pi_2^A$$

and from the first order conditions we obtain again the reaction function of second-period decisions of an adapter as a function of first-period extractions

$$x_2(I_2, T_1) = \frac{L - D_1 + I_2 - c\alpha T_1}{b}$$

and

$$I_2(x_2) = \frac{x_2}{\gamma} \tag{29}$$

which give

$$x_2(T_1) = \gamma\frac{L - D_1 - c\alpha T_1}{b\gamma - 1}. \tag{30}$$

The second order condition for this problem is

$$SOC_{2CG} : b\gamma - 1 > 0$$

The second period problem of a non-adapter or regular farmer corresponds to

$$\max_{y_2 \geq 0} m\pi_2^{NA}$$

and from the first order condition we derive the second-period reaction function of the non-adapter

$$y_2\left(T_1\right) = \frac{L - D_2 - c\alpha T_1}{b} \tag{31}$$

We can now compute the second period profit of an adapter and respectively, of a non-adapter as a funcion of T_1

$$\pi_2^A\left(T_1\right) = \frac{b\gamma\left(L - D_1 - c\alpha T_1\right)^2 - 2A\left(b\gamma - 1\right)\left(b\left(T_1\alpha - E\right) + m\alpha\left(L - D_2 - c\alpha T_1\right)\right)}{2b\left(b\gamma - 1\right)}$$

$$\pi_2^{NA}\left(T_1\right) = \frac{\left(b\gamma - 1\right)\left(L - D_2 - c\alpha T_1\right)^2 - 2Ab\left(\left(b\gamma - 1\right)\left(T_1\alpha - E\right) + n\alpha\gamma\left(L - D_1 - c\alpha T_1\right)\right)}{2b\left(b\gamma - 1\right)}$$

Next, moving to the first period problem, the overall profits of the different types of farmers (15) and (16) accounting for the resource constraint become respectively

$$\pi^A\left(T_1\right) = -\frac{b}{2}x_1^2 + Lx_1 + \beta\pi_2^A\left(T_1\right)$$
$$\pi^{NA}\left(T_1\right) = -\frac{b}{2}y_1^2 + Ly_1 + \beta\pi_2^{NA}\left(T_1\right)$$

with $T_1 = nx_1 + my_1$, the total extractions in period 1. The first period problem of an adaptive farmer then reads

$$\max_{x_1 \geq 0} n\pi_1^A = n\left(-\frac{b}{2}x_1^2 + Lx_1 + \beta\pi_2^A\right)$$

and from the first order condition we derive

$$x_1\left(y_1\right) = \frac{b\left(b\gamma - 1\right)\left(L - An\alpha\beta\right) - cn\alpha\beta\left(Am\alpha - b\gamma\left(-L + D_2 + An\alpha\right)\right) + bc^2mn\alpha^2\beta\gamma y_1}{b\left(b\left(b\gamma - 1\right) - c^2n^2\alpha^2\beta\gamma\right)} \tag{32}$$

and the second order condition for this problem corresponds to

$$SOC_{1CG}^A\text{:}\ b\left(b\gamma - 1\right) - c^2n^2\alpha^2\beta\gamma > 0.$$

Turning now to the first period problem of a non-adaptive farmer, this reads

$$\max_{y_1 \geq 0} m\pi_1^{NA} = m\left(-\frac{b}{2}y_1^2 + Ly_1 + \beta\pi_2^{NA}\right)$$

Again, from the first order condition we obtain

$$y_1(x_1) = \frac{b(b\gamma-1)(L-Am\alpha\beta)+cm\alpha\beta(L-D_2-b\gamma(L-D_1-Am\alpha))+c^2mn\alpha^2\beta(b\gamma-1)x_1}{(b\gamma-1)(b^2-c^2m^2\alpha^2\beta)} \tag{33}$$

and the sufficient condition for optimization

$$SOC_{1CG}^{NA}\colon\ b^2-c^2m^2\alpha^2\beta>0.$$

Both reaction functions (32) and (33) show that the first-period extraction levels of both types of farmers are strategic complements. This means that the more one type of farmer extracts in the first period, the more the other type of farmer will react. We can now compute the Nash equilibrium in the first period as the solution of the system given by the reaction functions (32) and (33) as

$$\begin{cases} x_1 = \frac{Q_1+Q_2y_1}{Q_3} \\ y_1 = \frac{W_1+W_2x_1}{W_3} \end{cases}$$

with

$$\begin{aligned}
Q_1 &= b(b\gamma-1)(L-An\alpha\beta)-cn\alpha\beta(Am\alpha-b\gamma(-L+D_1+Am\alpha)) \\
Q_2 &= bc^2mn\alpha^2\beta\gamma \\
Q_3 &= b\left(b(b\gamma-1)-c^2n^2\alpha^2\beta\gamma\right) \\
W_1 &= b(b\gamma-1)(L-Am\alpha\beta)+cm\alpha\beta(L-D_2-b\gamma(L-D_1-Am\alpha)) \\
W_2 &= c^2mn\alpha^2\beta(b\gamma-1) \\
W_3 &= (b\gamma-1)\left(b^2-c^2m^2\alpha^2\beta\right)
\end{aligned}$$

The equilibrium extraction levels in period 1 are then given by

$$x_{1CG}^*(n,m) = \frac{W_1Q_2+W_3Q_1}{W_3Q_3-W_2Q_2} \tag{34}$$

$$y_{1CG}^*(n,m) = \frac{W_2Q_1+W_1Q_3}{W_3Q_3-W_2Q_2} \tag{35}$$

From (29), (30) and (31), by using (34) and (35), we can compute the equilibrium extractions for both adapters and non-adapters in the second period, as well as optimal investments of the adapters.

In this case, both the benchmark case (B) where nobody adapts and the special case (S) where everybody adapts correspond to the same solutions found in the section of full cooperation (see section 3).

5 Cooperation within adapters case (CA)

In this section, we assume that only the farmers who take adaptive measures coordinate their decisions with each other while competing against the non-adapters. Moreover, the non-adapters compete against each other and against the group of adapters. Again, we solve the problem in two steps by backward induction.

In this specific setting, as farmers who invest in adaptive measures choose their control variables to maximize the aggregate profit of all adapters, and as they are symmetric within their group, the problem to solve for an adapter is the same than in the previous section (problem (27)). We can now write $T_2 = nx_2 + Y_2$ with $Y_2 = \sum_{j=1}^{m} y_{j2}$, the total extractions of the non-adapters, and the second period profit of an adapter (see equation (13)) accounting for the resource constraint can be rewritten as

$$\pi_2^A = -\frac{1}{2}bx_2^2 + \left(L - D_1 + I_2 - c\alpha T_1\right)x_2 - \frac{1}{2}\gamma I_2^2 + A\left(E - \alpha T_1 - \alpha Y_2\right)$$

with

$$D_1 = An\alpha + cB_1 - cr.$$

The second period problem for a farmer who takes adaptive measures is given by

$$\max_{x_2, I_2 \geq 0} n\pi_2^A.$$

From the first order conditions we derive

$$x_2\left(I_2, T_1\right) = \frac{L - D_1 + I_2 - c\alpha T_1}{b}$$

and

$$I_2\left(x_2\right) = \frac{x_2}{\gamma} \tag{36}$$

which give

$$x_2\left(T_1\right) = \gamma\frac{L - D_1 - c\alpha T_1}{b\gamma - 1} \tag{37}$$

which is the same as the one in Section 4. The second order condition requires

$$SOC_{2CA}^A\colon\ b\gamma - 1 > 0$$

As non-adapters (also named regular farmers) compete against each other and against the group of adapters, the objective of the individual non-adapter is to choose his/her control variables y_{j1}, y_{j2} that maximize the individual total profits over the two periods. Starting by the second-period, we now write $T_2 = O_2 + y_{j2} + nx_2$ where O_2 represents the extractions in the second period of all the other regular farmers, so that second-period profits (14) accounting for the resource constraint can be rewritten as

$$\pi_{j2}^{NA} = -\frac{b}{2}y_{2j}^2 + \left(L - D - c\alpha T_1\right)y_{2j} + A\left(E - \alpha T_1 - \alpha\left(O_2 + nx_2\right)\right)$$

with

$$D = A\alpha + cB_1 - cr.$$

The second period problem of a regular non-adapter, j, is given by

$$\max_{y_{j2}\geq 0} \pi_{j2}^{NA}$$

and from the first order condition we derive

$$y_{j2}\left(T_1\right) = y_2\left(T_1\right) = \frac{L - D - c\alpha T_1}{b}. \tag{38}$$

We can now compute the second period profit of an adapter and a non-adapter as functions of T_1, the total extractions in the first period, as follows

$$\pi_2^A\left(T_1\right) = \frac{\gamma b\left(L - D_1 - c\alpha T_1\right)^2 + 2A\left(b\gamma - 1\right)\left(b\left(E - \alpha T_1\right) - \alpha m\left(L - D - c\alpha T_1\right)\right)}{2b\left(b\gamma - 1\right)}$$

$$\begin{aligned}\pi_{j2}^{NA}\left(T_1\right) = & \frac{\left(b\gamma - 1\right)\left(L - D - c\alpha T_1\right)^2 - 2A\alpha\left(m - 1\right)\left(b\gamma - 1\right)\left(L - D - c\alpha T_1\right)}{2b\left(b\gamma - 1\right)} \\ & - \frac{2Ab\left(\left(b\gamma - 1\right)\left(\alpha T_1 - E\right) + n\alpha\gamma\left(L - D_1 - c\alpha T_1\right)\right)}{2b\left(b\gamma - 1\right)}\end{aligned}$$

Moving to the first period problem, considering the reaction functions of second-period decisions, total profit of an adapter reads

$$\pi^A\left(T_1\right) = -\frac{b}{2}x_1^2 + Lx_1 + \beta\pi_2^A\left(T_1\right)$$

with $T_1 = nx_1 + Y_1$ and $Y_1 = \sum_{j=1}^{m} y_{j1}$. The first period problem to solve corresponds to

$$\max_{x_1\geq 0} n\pi_1^A$$

and from the first order condition we obtain

$$x_1(Y_1) = \frac{b\left(b\gamma - 1\right)\left(L - An\alpha\beta\right) - cn\alpha\beta\left(Am\alpha + b\gamma\left(L - D_1 - Am\alpha\right)\right) + bc^2n\alpha^2\beta\gamma Y_1}{b\left(b\left(b\gamma - 1\right) - c^2n^2\alpha^2\beta\gamma\right)} \tag{39}$$

and a second order condition

$$SOC_{1CA}^{CA}\text{: } b\left(b\gamma - 1\right) - c^2n^2\alpha^2.\beta\gamma > 0$$

Turning to the non-adapters, the total profit of an individual regular farmer, j, is given by

$$\pi_j^{NA}\left(T_1\right) = -\frac{b}{2}y_{j1}^2 + Ly_{j1} + \beta\pi_{j2}^{NA}\left(T_1\right)$$

with $T_1 = nx_1 + O_1 + y_{j1}$ and O_1 representing the extractions in the first period of all other regular farmers.

The first period problem of a regular farmer j corresponds to

$$\max_{y_{j1}\geq 0} \pi_{j1}^{NA}$$

and from the first order condition we get

$$\begin{aligned} y_{j1}(x_1) &= y_1(x_1) \qquad (40)\\ &= \frac{b\,(b\gamma-1)\,(L-A\alpha\beta)-c\alpha\beta\,((b\gamma-1)\,(L-D)+A\alpha\,(m-1-b\gamma\,(N-1)))}{(b\gamma-1)\,(b^2-c^2m\alpha^2\beta)}\\ &+\frac{c^2\alpha^2\beta\,(b\gamma-1)\,nx_1}{(b\gamma-1)\,(b^2-c^2m\alpha^2\beta)} \end{aligned}$$

with second order condition

$$SOC_{2CA}^{NA}\colon\ b^2-c^2\alpha^2\beta>0.$$

As found in the previous section, the first period extraction levels of the different kinds of farmers, adapters and non-adapters, are strategic complements. We can now compute in the first period the Nash equilibrium as the solutions of the system given by the reaction functions (39) and (40)

$$\begin{cases} x_1 = \frac{Q_1+Q_2y_1}{Q_3} \\ y_1 = \frac{W_1+W_2x_1}{W_3} \end{cases}$$

with

$$\begin{aligned} Q_1 &= b\,(b\gamma-1)\,(L-An\alpha\beta)-cn\alpha\beta\,(Am\alpha+b\gamma\,(L-D_1-Am\alpha))\\ Q_2 &= bc^2\alpha^2\beta\gamma nm\\ Q_3 &= b\left(b\,(b\gamma-1)-c^2n^2\alpha^2\beta\gamma\right)\\ W_1 &= b\,(b\gamma-1)\,(L-A\alpha\beta)-c\alpha\beta\,((b\gamma-1)\,(L-D)+A\alpha\,(m-1-b\gamma\,(N-1)))\\ W_2 &= c^2n\alpha^2\beta\,(b\gamma-1)\\ W_3 &= (b\gamma-1)\left(b^2-c^2m\alpha^2\beta\right) \end{aligned}$$

The solution is then

$$x_{1CA}^*(n,m) = \frac{W_1Q_2+W_3Q_1}{W_3Q_3-W_2Q_2} \qquad (41)$$

$$y_{1CA}^*(n,m) = \frac{W_2Q_1+W_1Q_3}{W_3Q_3-W_2Q_2} \qquad (42)$$

From (36), (37) and (38), by using (41) and (42), we can compute the equilibrium investment and extractions for both adapters and non-adapters in the second period.

5.1 Benchmark case: no adaptation

We now compute the benchmark case when no farmer adapts and they all compete against each other. This case can be retrieved by setting $n = 0$ and $m = N$ in the previous problem so that we obtain

$$y_{1CA}^{B} = \frac{b\left(L - A\alpha\beta\right) - c\alpha\beta\left(L - D - A\alpha\left(N-1\right)\right)}{b^2 - Nc^2\alpha^2\beta}$$
$$y_{2CA}^{B} = \frac{b^2\left(L - D\right) - Nc\alpha\left(b\left(L - A\alpha\beta\right) + Ac\alpha^2\beta\left(N-1\right)\right)}{b\left(b^2 - Nc^2\alpha^2\beta\right)}$$

being nil the decisions of the adapters, and the second order conditions for the two periods are

$$SOC_{2CA}^{B}\colon b > 0$$
$$SOC_{1CA}^{B}\colon b^2 - c^2\alpha^2\beta > 0.$$

The special case where all farmers adapt still corresponds to the solution found in Section 3 .

6 Non-cooperative setting

We now address the full non-cooperative case in which each farmer, adapter or non-adapter, competes against all the other non-adapters and all the other farmers who takes adaptive measures, i.e., there is no cooperation among any of the farmers. As a consequence, each farmer, regardless of the type, maximizes her/his individual profits over the two periods subject to the resource constraint (2). The problem is solved in two steps by backward induction.

As adapters compete against each other and against the group of non-adapters, we can write $T_2 = Y_2 + O_2 + x_{i2}$ where O_2 represents the extractions in the second period of all the other adapters and $Y_2 = \sum_{j=1}^{m} y_{j2}$ corresponds to the total extractions of the non-adapters, so that second-period profit of an adapter in (13), considering the resource constraint, can be rewritten as

$$\pi_{i2}^{A} = -\frac{1}{2}bx_{i2}^2 + \left(L - D + I_{i2} - c\alpha T_1\right)x_{i2} - \frac{1}{2}\gamma I_{i2}^2 + A\left(E - \alpha T_1 - \alpha\left(O_2 + Y_2\right)\right)$$

with

$$D = A\alpha + cB_1 - cr.$$

Thus, a representative adapter i faces the second- period problem

$$\max_{x_{i2}, I_{i2} \geq 0} \pi_{i2}^{A}.$$

From the first order conditions we derive

$$x_{i2} = \frac{L - D + I_{i2} - c\alpha T_1}{b}$$

and

$$I_{i2} = \frac{x_{i2}}{\gamma}. \tag{43}$$

Putting these expressions together, we have the reaction function of second-period extraction as a function of T_1

$$x_{i2}(T_1) = x_2(T_1) = \gamma \frac{L - D - c\alpha T_1}{b\gamma - 1} \tag{44}$$

and the second order condition (or sufficient condition for optimization) is

$$SOC^A_{2NC}\colon \; b\gamma - 1 > 0.$$

Similarly, as farmers that do not adapt compete against each other and against the group of adapters, we can write $T_2 = X_2 + O_2 + y_{j2}$ where O_2 represents the second-period extractions of all the other non-adapters and $X_2 = \sum_{i=1}^{n} x_{i2}$, the second-period total extractions of the adapters, so that second-period profits of an adapter in (14), considering the resource constraint, can be written as

$$\pi^{NA}_{j2} = -\frac{1}{2} b y^2_{j2} + (L - D - c\alpha T_1)\, y_{j2} + A\left(E - \alpha T_1 - \alpha (X_2 + O_2)\right)$$

with

$$D = A\alpha + cB_1 - cr.$$

The second period problem of a representative non-adapter j is then given by

$$\max_{y_{j2} \geq 0} \pi^{NA}_{j2}.$$

From the first order condition is immediate to get the reaction function

$$y_{j2}(T_1) = y_2(T_1) = \frac{L - D - c\alpha T_1}{b} \tag{45}$$

which is the same as found in Section 5. Note that

$$x_2(T_1) = \frac{b\gamma}{b\gamma - 1} y_2(T_1)$$

with $\frac{b\gamma}{b\gamma-1} > 1$.

We can now compute the second period profit of a representative adapter and a non-adapter as functions of T_1

$$\pi^A_2(T_1) = \frac{b\gamma (L - D - c\alpha T_1)^2 - 2A\alpha \left(b\gamma (N-1) - m\right)(L - D - c\alpha T_1)}{2b(b\gamma - 1)} \tag{46}$$
$$\frac{-2Ab(b\gamma - 1)(\alpha T_1 - E)}{2b(b\gamma - 1)}$$

$$\pi_2^{NA}(T_1) = \frac{(b\gamma-1)(L-D-c\alpha T_1)^2 - 2A\alpha(b\gamma(N-1)+1-m)(L-D-c\alpha T_1)}{2b(b\gamma-1)} - \frac{2Ab(b\gamma-1)(\alpha T_1 - E)}{2b(b\gamma-1)} \tag{47}$$

Next, moving to the first period problem, total profits of an adapter i reads

$$\pi_i^A = -\frac{b}{2}x_{i1}^2 + Lx_{i1} + \beta\pi_{i2}^A(T_1)$$

with $T_1 = O_1 + x_{i1} + Y_1$ and where O_1 represents the first period total extractions of all the other adapters. The problem to solve for an adapter is then

$$\max_{x_{i1}\geq 0} \pi_i^A$$

which, from the first order condition, gives

$$x_1(Y_1) = \frac{b(b\gamma-1)(L-A\alpha\beta) + c\alpha\beta(b\gamma(-L+D+A\alpha(N-1)) - Am\alpha) + bc^2\alpha^2\beta\gamma Y_1}{b(b(b\gamma-1) - c^2n\alpha^2\beta\gamma)} \tag{48}$$

Second order condition of this problem requires

$$SOC_{1NC}^A\colon\ b(b\gamma-1) - c^2\alpha^2\beta\gamma > 0$$

For the representative non-adapter j, total profits read

$$\pi_j^{NA} = -\frac{b}{2}y_{j1}^2 + Ly_{j1} + \beta\pi_{j2}^{NA}(T_1)$$

with $T_1 = X_1 + O_1 + y_{j1}$ and O_1 representing the first-period extractions of all other non-adapters (or regular farmers), so that her/his first-period problem corresponds to

$$\max_{y_{j1}\geq 0} \pi_j^{NA}.$$

From the first order condition we derive the reaction function

$$y_1(X_1) = \frac{b(b\gamma-1)(L-A\alpha\beta) - c\alpha\beta((b\gamma-1)(L-D+A\alpha) - A\alpha(Nb\gamma-m))}{(b\gamma-1)(b^2-c^2m\alpha^2\beta)} + \frac{c^2\alpha^2\beta(b\gamma-1)X_1}{(b\gamma-1)(b^2-c^2m\alpha^2\beta)} \tag{49}$$

and the second order condition corresponds to

$$SOC_{1NC}^{NA}\colon\ b^2 - c^2\alpha^2\beta > 0.$$

We can now compute the first-period Nash equilibrium as the solutions of the system given by the reaction functions (48) and (49). This can be written as

$$\begin{cases} x_1 = \frac{Q_1+Q_2y_1}{Q_3} \\ y_1 = \frac{W_1+W_2x_1}{W_3} \end{cases}$$

with

$$\begin{aligned}
Q_1 &= b\left(b\gamma-1\right)\left(L-A\alpha\beta\right)+c\alpha\beta\left(b\gamma\left(-L+D+A\alpha\left(N-1\right)\right)-Am\alpha\right)\\
Q_2 &= bc^2\alpha^2\beta\gamma m\\
Q_3 &= b\left(b\left(b\gamma-1\right)-c^2n\alpha^2\beta\gamma\right)\\
W_1 &= b\left(b\gamma-1\right)\left(L-A\alpha\beta\right)+c\alpha\beta\left(\left(b\gamma-1\right)\left(-L+D-A\alpha\right)+A\alpha\left(Nb\gamma-m\right)\right)\\
W_2 &= c^2\alpha^2\beta\left(b\gamma-1\right)n\\
W_3 &= \left(b\gamma-1\right)\left(b^2-c^2m\alpha^2\beta\right)
\end{aligned}$$

which gives

$$x^*_{1NC}\left(n,m\right)=\frac{W_1Q_2+W_3Q_1}{W_3Q_3-W_2Q_2} \tag{50}$$

$$y^*_{1NC}\left(n,m\right)=\frac{W_2Q_1+W_1Q_3}{W_3Q_3-W_2Q_2} \tag{51}$$

From (43), (44) and (45), by using (50) and (51), we can compute the equilibrium investment for adapters and extraction levels for both adapters and non-adapters in the second period.

In this case, the benchmark case where nobody adapts corresponds to the same solution found in the case "Cooperation within Adapters" in section 5.

The special case where everybody adapts can be easily obtained by setting $n=N$ and $m=0$ in (48), which gives

$$\begin{aligned}
x^S_{1NC} &= \frac{b\left(b\gamma-1\right)\left(L-A\alpha\beta\right)-c\alpha\beta\left(b\gamma\left(L-D-A\alpha\left(N-1\right)\right)\right)}{b\left(b\left(b\gamma-1\right)-c^2N\alpha^2\beta\gamma\right)}\\
x^S_{2NC} &= \gamma\frac{b\left(b\gamma-1\right)\left(L-D\right)-Nc\alpha\left(\left(b\gamma-1\right)\left(L-A\alpha\beta\right)+Ac\alpha^2\beta\gamma\left(N-1\right)\right)}{\left(b\gamma-1\right)\left(b\left(b\gamma-1\right)-Nc^2\alpha^2\beta\gamma\right)}.
\end{aligned}$$

7 Numerical simulations

Parameter	**Description**	**Value**
a	Coefficient of revenue agricultural use (linear term)	1
b	Coefficient of revenue agricultural use (nonlinear term)	1
z	Marginal pumping cost intercept	0.8
c	Marginal pumping cost slope	0.01
G_0	Initial stock level	10
r	Natural recharge rate	0.45
B_1	Climate change (period 1)	0.05
B_2	Climate change (period 2)	0.05
α	Return flow coefficient	1
γ	Coefficient of the investment cost	1.5
A	Coefficient of the valuation of the final stock	0.02
β	Discount factor	0.9
N	Total number of farmers	$N = \{2, 5, 10\}$
n	Number of adaptive farmers	$n \in [0 \dots N]$
m	Number of non adaptive farmers	$m \in [0, N - n]$

Table 1: Parameter values of the model.

To perform the numerical simulations, we use parameter values in Table 1 that satisfy sufficient conditions of optimization for all the different settings. First, we fix $N = 10$ farmers with $n \in [0, 10]$, the number of adaptive farmers and $m = N - n$, the number of non-adaptive farmers. In what follows, we study if adaptation is beneficial for the resource (i.e., for final stock levels, G_2) and for the profitability of the farmers (i.e., total profits of the farmers defined by $\Pi = \sum_{i=1}^{n} \pi_i^A + \sum_{j=1}^{m} \pi_j^{NA}$) depending on the number of adaptive farmers and for different scenarios: full cooperation (FC), cooperation within groups (CG), cooperation within adapters (CA) and non-cooperation between all farmers (NC). Results are summarized in Figures 1-4. Next, we perform a sensitivity analysis with respect to all the parameters of the model to test the robustness of previous results. Finally, we will analyze the scope of cooperation, defined as the difference between the cooperative and non-cooperative solutions, when the total number of farmers varies, i.e., for $N = 2$ and $N = 5$.

7.1 Impact of adaption on final stock levels

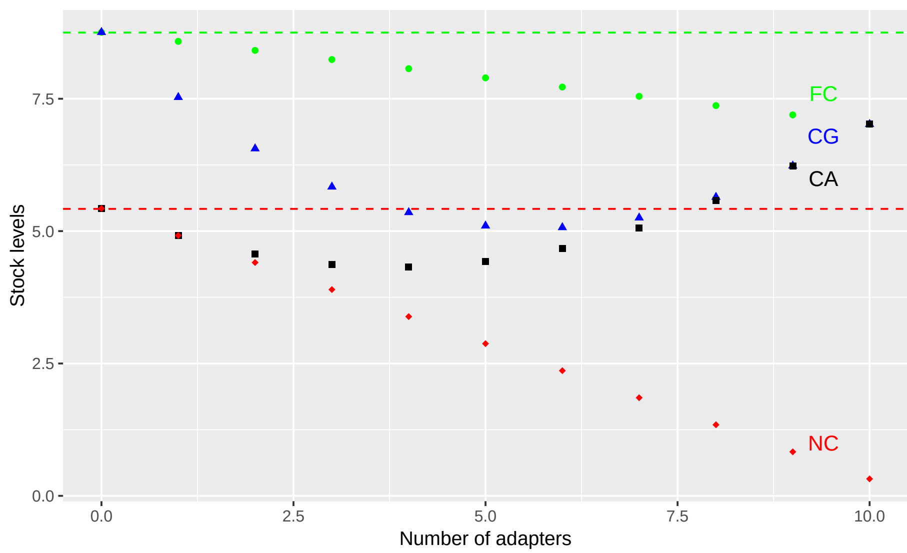

Figure 1: Final stock levels in function of the number of adapting farmers, for the different scenarios and $N = 10$.

Firstly, we focus on the impact of adaptation on final stock levels of the resource (see Figure 1). We confirm theoretical results for the full cooperative setting (FC). Adaptation is not beneficial for the stock level of the resource despite the number of adaptive farmers. In order words, stock level at the end of the second period is always lower when some farmers invest $n > 0$, that when they not, $n = 0$, (i.e., the benchmark scenario, green dashed horizontal line). Moreover, numerical simulations suggest that final stock levels decreases the greater the number of adapters when all farmers cooperate.

Next, we study if previous result is maintained under different levels of cooperation. In Figure 1, considering the same benchmark situation, we observe that under cooperation within groups (CG), adaptation is also negative for the environment. Same result hold under full non-cooperation between farmers (NC), being now the benchmark case of no adaptation ($n = 0$) represented by the horizontal red dashed line.

However, when farmers cooperate only within adapters (CA), lower final stock levels are obtained for a low number of adapters and higher stock levels results for a large number of adapters with respect to the benchmark case (red horizontal dashed line). In fact, in the case of cooperation within adapters, numerical results suggest that adaptation could be beneficial for the stock level of the resource for a high number of adapters.

7.2 Impact of adaption on farmers' profits

We next analyze the impact of adaptation on total farmers' profits over the two periods (see Figure 2). First, the figure illustrates that adaptation is now beneficial for the profitability of the farmers for any number of adaptive farmers in the cooperative setting (FC). In addition, total farmers' profits increases when the number of adapters increases. In fact, as observed in the previous section, total extraction increases (and equivalently, stock level decreases) the greater the number of adapters, leading to higher profits.

However, results may change for the different scenarios of cooperation. When considering cooperation within groups (CG) or cooperation only within adapters (CA), the impact of adaptation on the profitability of the farmers seems to be negative for a low number of adapters and positive for a high number of adapters. In the full non-cooperative setting, in contrast with the full cooperative case, total profits decrease when the number of adapters increase. To understand this result, in Figure 3 (and Table 2 for detailed numbers), profits (per group) and total profits are shown for the different scenarios. While in the cooperative case, the adapters' profits increase is more important than the non-adapters' profits decrease, in the full non-cooperative case, the non-adapters profits drive results concerning total profits. The intuition behind this result could be that under full cooperation, the adapters push the non-adapters to extract more than what they would desire under competition.

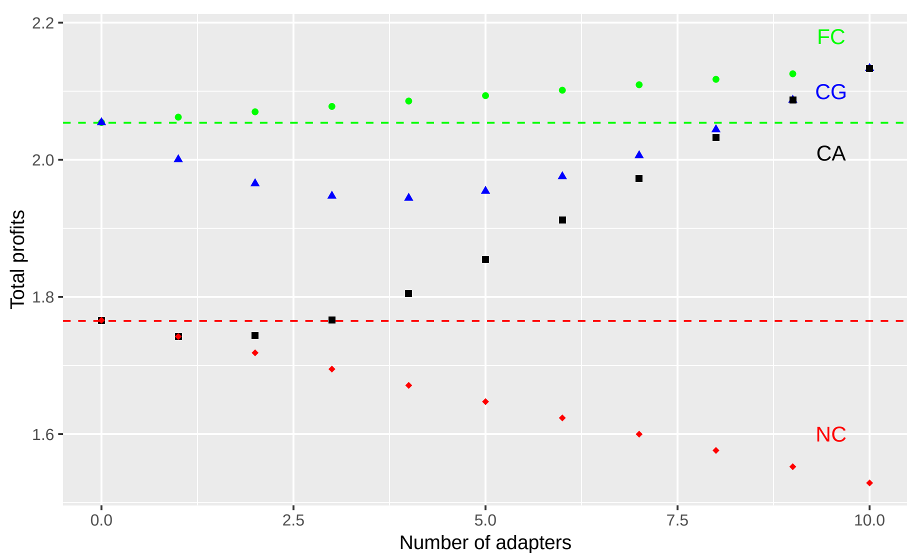

Figure 2: Total farmers' profits over the two periods in function of the number of adapting farmers, for the different scenarios and $N = 10$.

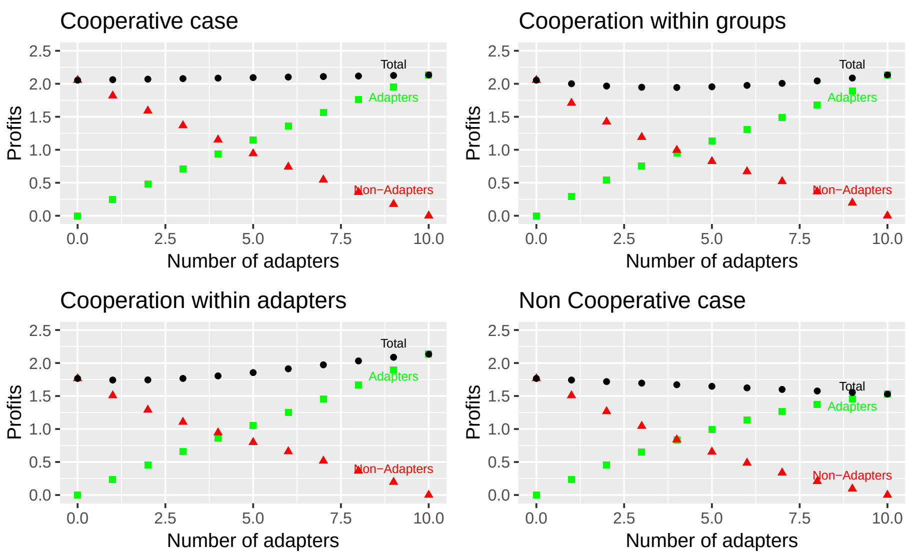

Figure 3: Profits per group (adapters and non-adapters) and total farmers' profits in function of the number of adapting farmers for the different scenarios and $N = 10$.

	Adapters'Profit		**Non-Adapters'Profit**		**Total profit**		
n	**FC**	**NC**	**FC**	**NC**	**FC**	**NC**	**FC-NC**
0	0	0	2.05	1.77	2.05	1.77	0.29
1	0.24	0.24	1.82	1.51	2.06	1.74	0.32
2	0.48	0.45	1.59	1.27	2.07	1.72	0.35
3	0.71	0.65	1.37	1.04	2.08	1.69	0.38
4	0.93	0.83	1.15	0.84	2.09	1.67	0.41
5	1.15	0.99	0.94	0.65	2.09	1.65	0.45
6	1.36	1.14	0.74	0.49	2.10	1.62	0.48
7	1.56	1.26	0.55	0.34	2.11	1.60	0.51
8	1.76	1.37	0.36	0.21	2.12	1.58	0.54
9	1.95	1.46	0.17	0.09	2.13	1.55	0.57
10	2.13	1.53	0	0	2.13	1.53	0.60

Table 2: Profits per group (adapters and non-adapters) , total farmers' profits and differences in profits in function of the number of adapting farmers for the cooperative (FC) and full non-cooperative (NC) scenarios and, $N = 10$.

7.3 Sensitivity analysis

In this section, we perform an extensive numerical exploration of the set of feasible model parameter values to test how previous results change with respect to model parameters for the different scenarios of cooperation. Main results concerning the impact of adaptation on the resource G_2^* and the total profits of the farmers Π^* are summarized in Tables 3-6.

Impact of adaptation (FC)	
G_{2FC}^*	Π_{FC}^*
Negative for any n	Positive for any n

Table 3: Impact of adaptation G_{2FC}^* and Π_{FC}^* in the full cooperative case.

First of all, concerning the full cooperative case in Table 3, we can conclude that any degree of adaptation, or equivalently, any number of adapters, is positive from an economic perspective but negative from a strict environmental point of view, regardless of the other model parameters.

Key parameter	Impact of adaptation	
A	G_{2CG}^*	Π_{CG}^*
Large	Negative for any n	Varies with n $(-,+)^*$
$\downarrow$	Negative for any n	Positive for any n

Table 4: Impact of adaptation G_{2CG}^* and Π_{CG}^* in the cooperation within groups case.

For the cooperation within groups case (CG) in Table 4 , for any $n \in [0 \ldots N]$, we can conclude that adaptation is negative from a strict environmental point of view, and it can also be negative from an economic point of view. The latter result is only observed when the number of adapters (n) is small and the final value of the final stock levels (A) is large. In all the other cases the two criteria, the exclusive environmental one and the economic one, reach opposite conclusions.

Key parameter	Impact of adaptation	
A	G_{2CA}^*	Π_{CA}^*
Large	Varies with n $(-,+)$	Varies with n $(-,+)$
$\downarrow$	Varies with n $(-,+)$	Positive for any n
$\downarrow\downarrow$	Negative for any n	Positive for any n

Table 5: Impact of adaptation G_{2CA}^* and Π_{CA}^* in the cooperation within adapters case.

Turning to the results concerning the case of cooperation with adapters (see Table 5, the key parameter that determines the impact of adaptation on the resource and the total profit is the value given to the final stock levels A. We can conclude that when A is large, the impact of adaptation from both a strict environmental and economic perspective is positive if the number of adapters is large. For smaller values of A, we can still have that the two criteria point in the same direction if n is large. The two perspectives reach different conclusions when A is very small despite the number of adapters.

Key parameter	Impact of adaptation	
A	G^*_{2NC}	Π^*_{NC}
Large	Negative for any n	Negative for any n
$\downarrow$	Negative for any n	Positive for any n

Table 6: Impact of adaptation G^*_{2CG} and Π^*_{CG} in the non cooperative case.

For the non-cooperative case in Table 6, adaptation is again negative for the resource, regardless of the model parameter values. However, the value assigned to the final stock, A, is also a key parameter that changes the sign of the impact of adaptation on the overall profit. For a given set of parameters for which the impact is always positive regardless of the number of adapters, a reduction of the final stock values A can change the impact into negative.

7.4 Discussion on the scope of cooperation: Cooperative vs. Non-cooperative case

We now compare the full cooperative and non-cooperative scenarios by computing differences in terms of final stock and total profits between scenarios. In Figures 1 and 2, we can observe that final stock levels and total profits are always greater under full cooperation than under non-cooperation for any number of adapters, that is, cooperation is always beneficial for the sustainability and profitability of the resource. This is consistent with the existing literature on Nash equilibria in resource management (e.g., Rubio and Casino (2001) and de Frutos Cachorro et al. (2019)).

Moreover, Figures 4 shows how these differences vary depending on the number of adapters. We can see that stock and profit differences between the cooperative and non-cooperative solution increases with the number of adapting farmers. In order words, defining the profitability or the scope of cooperation as the difference in total profits under cooperation and non-cooperation, this reaches the maximum for the case in which all farmers adapt ($N = n = 10$), (see detailed numbers in the last column, Table 2).

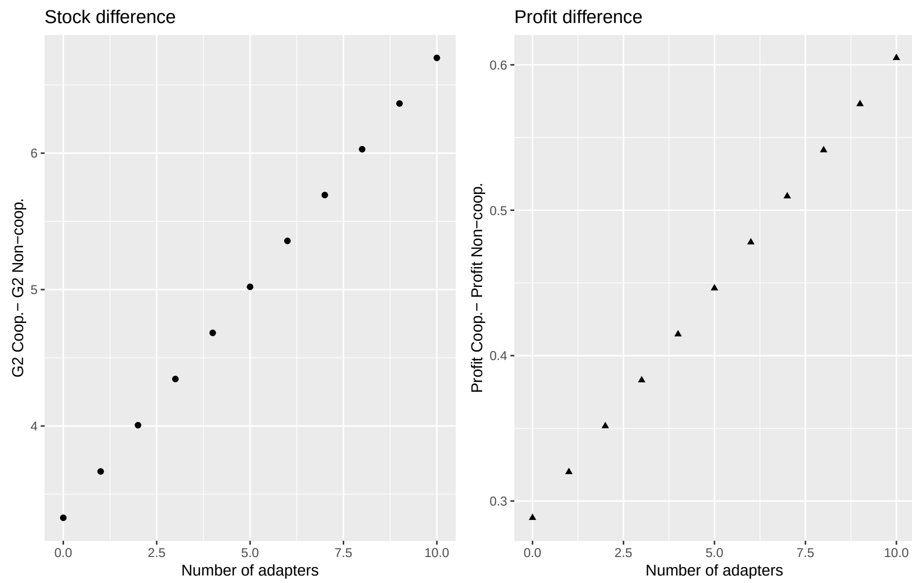

Figure 4: Final stock and profit differences between the cooperative and non-cooperative scenarios, in function of the number of adapting farmers, for the case $N = 10$.

Finally, we conduct additional simulations to demonstrate the robustness of our results concerning the total number of farmers N. Focusing on the full cooperative and non-cooperative cases, in contrast with the case $N = 10$, total profits under non-cooperation now increase with the number of adapters for $N = 2$ and $N = 5$ (see Figures 5 and 7 in Appendix 9.3). Anyway, main result is maintained regarding differences in final stock levels and the profitability of cooperation with increasing differences as the number of adaptive farmers increase (see Figures 6 and 8 in Appendix 9.3)

8 Conclusion

In this study, we develop a two-period discrete game to examine groundwater exploitation by multiple farmers, focusing on the impact of investment adaptation measures to climate change on the sustainability and profitability of the resource. Specifically, farmers' adaptive responses to climate change are modeled as costly private investments that enhance irrigation efficiency by lowering marginal extraction costs (e.g., investing in improved irrigation systems). We consider farmers as either adapters or non-adapters, assuming symmetric farmers within each group, and solve the problem under cooperation, cooperation within groups, cooperation within adapters and full non-cooperation among all farmers.

Theoretical results indicate that under cooperation, adaptation is not environmentally beneficial, meaning that, higher total extractions (or lower final stock levels) are observed when farmers adapt, compared to when they do not, regardless of the number of adapters. This is mainly due to an increase in extractions during the second period when some adapters are present. In fact, since investments in adaptations reduce the cost of extraction in the second period, farmers prioritize extraction in the second period over the first period. In addition, numerical simulations indicate that final stock levels decrease as the number of adapters increases. These outcomes are also numerically observed when there are strategic interactions among groups and/or among farmers. However, interestingly, the impact of adaptation could be positive for the environment when considering only cooperation among adapters, and a high number of adapters.

In contrast, numerical results indicate that adaptation could enhance the profitability of the "adapters" and the overall profitability of farmers for different levels of cooperation. Preliminary results of the sensitivity analysis suggest that these outcomes will mainly depend on the value assigned to the final stock levels and the number of adapters.

To conclude, numerical results suggest that the impact of adaptation could be positive from an economic and an environmental point of view when only the farmers who decide to make investment adaptive measures cooperate between them. Moreover, the number of farmers investing in adaptive measures is crucial in ensuring a positive impact of adaptation from an economic and an environmental point of view and in determining the profitability (or scope) of cooperation, which is defined as the difference between overall profits under full cooperation and non-cooperation. In fact, the impact of adaptation becomes positive and the scope of cooperation increases, as the number of adapters rises. The main policy implication derived from this study is that cooperation becomes increasingly necessary as investment measures are implemented to adapt to a changing climate.

Finally, as this is a preliminary work, there is still work to be done regarding the sensitivity analysis concerning other important parameters of the model, as well as other possible extensions. In fact, it will be interesting to analyze how results could differ when implementing other types of adaptation measures related to the revenue function.

9 Appendix

9.1 Proof of Proposition 1

In this section, we check for the positivity of the extraction rates in the second period in the cooperative setting for any number of farmers investing in adaption measures.

1. We have obtained that

   $x_2^* = \gamma \frac{-b^2(-L+D_1+Am\alpha)+c\alpha N(b(-L+AN\alpha\beta)+cm\alpha\beta(D_1-D_2+A\alpha(m-n)))}{b^2(b\gamma-1)+c^2\alpha^2\beta N(m-b\gamma N)}$

   The denominator is always positive because of the sufficient conditions for optimization. With respect to the numerator,

$$
\begin{aligned}
& -b^2\left(-L+D_1+Am\alpha\right)+c\alpha N\left(b\left(-L+AN\alpha\beta\right)+cm\alpha\beta\left(D_1-D_2+A\alpha\left(m-n\right)\right)\right)>0 \\
& \iff -b^2\left(-L+\left(An\alpha+cB_1-cr\right)+Am\alpha\right) \\
& +c\alpha N\left(b\left(-L+AN\alpha\beta\right)+cm\alpha\beta\left(\left(An\alpha+cB_1-cr\right)-\left(Am\alpha+cB_1-cr\right)+A\alpha\left(m-n\right)\right)\right)>0 \\
& \iff Ab\alpha\left(-b\left(m+n\right)+N^2c\alpha\beta\right)+b\left(L\left(b-Nc\alpha\right)+bc\left(r-B_1\right)\right)>0 \\
& \iff Ab\alpha\left(-bN+N^2c\alpha\beta\right)+b\left(L\left(b-Nc\alpha\right)+bc\left(r-B_1\right)\right)>0 \\
& \iff Ab\alpha N\left(-b+Nc\alpha\beta\right)+b\left(L\left(b-Nc\alpha\right)+bc\left(r-B_1\right)\right)>0
\end{aligned}
$$

   If $(b-Nc\alpha)>0$ then $(-b+Nc\alpha\beta)<0$ and the numerator is positive if $A<\frac{b(L(b-Nc\alpha)+bc(r-B_1))}{b\alpha N(b-Nc\alpha\beta)}=\frac{L(b-Nc\alpha)+bc(r-B_1)}{\alpha N(b-Nc\alpha\beta).}$

2. $y_2^* = \frac{-b(b\gamma-1)(-L+D_2+An\alpha)+c\alpha N((b\gamma-1)(-L+AN\alpha\beta)-cn\alpha\beta\gamma(D_1-D_2+A\alpha(m-n)))}{b^2(b\gamma-1)+c^2\alpha^2\beta N(m-b\gamma N)}$

   The denominator is always positive because of the sufficient conditions for optimization. With respect to the numerator,

$$
\begin{aligned}
& -b\left(b\gamma-1\right)\left(-L+D_2+An\alpha\right)+c\alpha N\left(\left(b\gamma-1\right)\left(-L+AN\alpha\beta\right)-cn\alpha\beta\gamma\left(D_1-D_2+A\alpha\left(m-n\right)\right)\right)>0 \\
& \iff -b\left(b\gamma-1\right)\left(-L+\left(Am\alpha+cB_1-cr\right)+An\alpha\right) \\
& +c\alpha N\left(\left(b\gamma-1\right)\left(-L+AN\alpha\beta\right)-cn\alpha\beta\gamma\left(\left(An\alpha+cB_1-cr\right)-\left(Am\alpha+cB_1-cr\right)+A\alpha\left(m-n\right)\right)\right)>0 \\
& \iff \left(b\gamma-1\right)\left(L\left(b-Nc\alpha\right)+bc\left(r-B_1\right)+A\alpha\left(-b\left(m+n\right)+N^2c\alpha\beta\right)\right)>0 \\
& \iff \left(L\left(b-Nc\alpha\right)+bc\left(r-B_1\right)+A\alpha\left(-bN+N^2c\alpha\beta\right)\right)>0 \\
& \iff \left(L\left(b-Nc\alpha\right)+bc\left(r-B_1\right)+A\alpha N\left(-b+Nc\alpha\beta\right)\right)>0
\end{aligned}
$$

   If $(b-Nc\alpha)>0$ then $(-b+Nc\alpha\beta)<0$ and the numerator is positive if $A<\frac{L(b-Nc\alpha)+bc(r-B_1)}{\alpha N(b-Nc\alpha\beta).}$, which is the same condition obtained for the positivity of x_2^*.

Therefore, if

$$
\begin{aligned}
b - Nc\alpha &> 0 \text{and} \\
A_{x_2^*+} &= \frac{b\left(L\left(b - Nc\alpha\right) + bc\left(r - B_1\right)\right)}{b\alpha N\left(b - Nc\alpha\beta\right)} > A > 0 \text{ then} \\
x_2^* &> 0 \\
y_2^* &> 0
\end{aligned}
$$

9.2 Proof of Proposition 2

First, concerning the sign of $y_{1NA}^* - y_1^*$,

$$
\begin{aligned}
& y_{1NA}^* - y_1^* \\
&= \frac{(b\gamma - 1)\left(b\left(L - AN\alpha\beta\right) - cN\alpha\beta\left(L - D_2\right)\right)}{(b\gamma - 1)\left(b^2 - N^2c^2\alpha^2\beta\right)} \\
&- \frac{(b\gamma - 1)\left(b\left(-L + AN\alpha\beta\right) - cm\alpha\beta\left(-L + D_2 + An\alpha\right)\right) - bcn\alpha\beta\gamma\left(-L + D_1 + Am\alpha\right)}{-b^2\left(b\gamma - 1\right) + c^2\alpha^2\beta N\left(-m + b\gamma N\right)} \\
&= \frac{(b\gamma - 1)\left(b\left(L - AN\alpha\beta\right) - cN\alpha\beta\left(L - \left(AN\alpha + cB_1 - cr\right)\right)\right)}{(b\gamma - 1)\left(b^2 - N^2c^2\alpha^2\beta\right)} \\
&- \frac{(b\gamma - 1)\left(b\left(-L + AN\alpha\beta\right) - cm\alpha\beta\left(-L + \left(Am\alpha + cB_1 - cr\right) + An\alpha\right)\right) - bcn\alpha\beta\gamma\left(-L + \left(An\alpha + cB_1 - cr\right) + Am\alpha\right)}{-b^2\left(b\gamma - 1\right) + c^2\alpha^2\beta N\left(-m + b\gamma N\right)} \\
&= \frac{(b\gamma - 1)\left(b\left(L - AN\alpha\beta\right) - cN\alpha\beta\left(L - \left(AN\alpha + cB_1 - cr\right)\right)\right)}{(b\gamma - 1)\left(b^2 - N^2c^2\alpha^2\beta\right)} \\
&- \frac{(b\gamma - 1)\left(b\left(-L + AN\alpha\beta\right) - cm\alpha\beta\left(-L + cB_1 - cr + A\alpha\left(m + n\right)\right)\right) - bcn\alpha\beta\gamma\left(-L + cB_1 - cr + A\alpha\left(m + n\right)\right)}{-b^2\left(b\gamma - 1\right) + c^2\alpha^2\beta N\left(-m + b\gamma N\right)} \\
&= \frac{(b\gamma - 1)\left(b\left(L - AN\alpha\beta\right) - cN\alpha\beta\left(L - \left(AN\alpha + cB_1 - cr\right)\right)\right)}{(b\gamma - 1)\left(b^2 - N^2c^2\alpha^2\beta\right)} \\
&- \frac{(b\gamma - 1)\left(b\left(-L + AN\alpha\beta\right) - cm\alpha\beta\left(-L + cB_1 - cr + A\alpha N\right)\right) - bcn\alpha\beta\gamma\left(-L + cB_1 - cr + A\alpha N\right)}{-b^2\left(b\gamma - 1\right) + c^2\alpha^2\beta N\left(-m + b\gamma N\right)} \\
&= \frac{bc\alpha\beta}{\left(-b^2 + N^2c^2\alpha^2\beta\right)\left(-b^3\gamma + b^2 - Nc^2m\alpha^2\beta + N^2bc^2\alpha^2\beta\gamma\right)} \Big(LNb - Lbm - NbcB_1 + bcmB_1 \\
&- AN^2b\alpha - LNb^2\gamma - LN^2c\alpha + Lb^2m\gamma + Lb^2n\gamma + Nbcr - bcmr + ANbm\alpha + LNcm\alpha \\
&+ AN^2b^2\alpha\gamma + AN^3c\alpha^2\beta - Nb^2cr\gamma + b^2cmr\gamma + b^2cnr\gamma + Nb^2c\gamma B_1 - b^2cm\gamma B_1 - b^2cn\gamma B_1 \\
&- N^3c^3\alpha^2\beta\gamma B_1 - AN^2cm\alpha^2\beta - ANb^2m\alpha\gamma - ANb^2n\alpha\gamma - AN^4c^2\alpha^3\beta\gamma + LN^3c^2\alpha^2\beta\gamma \\
&+ N^3c^3r\alpha^2\beta\gamma + N^2c^3m\alpha^2\beta\gamma B_1 + N^2c^3n\alpha^2\beta\gamma B_1 + AN^3c^2m\alpha^3\beta\gamma + AN^3c^2n\alpha^3\beta\gamma - LN^2c^2m\alpha^2\beta\gamma \\
&- LN^2c^2n\alpha^2\beta\gamma - N^2c^3mr\alpha^2\beta\gamma - N^2c^3nr\alpha^2\beta\gamma \Big)
\end{aligned}
$$

Symplifying the expression, we obtain that

$$
y_{1NA}^* - y_1^* = bc\alpha\beta n \frac{AN\alpha\left(-b + Nc\alpha\beta\right) + L\left(b - Nc\alpha\right) + c\left(r - B_1\right)b}{\left(-b^2 + N^2c^2\alpha^2\beta\right)\left(-b^3\gamma + b^2 - Nc^2m\alpha^2\beta + N^2bc^2\alpha^2\beta\gamma\right)}
$$

The denominator is always positive as $-b^2 + N^2c^2\alpha^2\beta < 0$ and $-b^2\left(b\gamma - 1\right) + Nc^2\alpha^2\beta\left(-m + Nb\gamma\right) < 0$ because of concavity conditions.

The numerator is always positive, i.e., $AN\alpha\left(-b+Nc\alpha\beta\right)+L\left(b-Nc\alpha\right)+bc\left(r-B_1\right)>0$ because of the positivity condition of the second period extraction rate. Therefore,

$$y_{1NA}^{*}>y_{1}^{*}.$$

Next, concerning the sign of $y_{2NA}^{*}-x_{2}^{*}$,

$$\begin{aligned}\frac{y_{2NA}^{*}}{x_{2}^{*}} &= \frac{\frac{b(L-D_2)-Nc\alpha(L-AN\alpha\beta)}{b^2-N^2c^2\alpha^2\beta}}{\gamma\frac{-b^2(-L+D_1+Am\alpha)+c\alpha N(b(-L+AN\alpha\beta)+cm\alpha\beta(D_1-D_2+A\alpha(m-n)))}{b^2(b\gamma-1)+c^2\alpha^2\beta N(m-b\gamma N)}}\\ &= \frac{\frac{b(L-(AN\alpha+cB_1-cr))-Nc\alpha(L-AN\alpha\beta)}{b^2-N^2c^2\alpha^2\beta}}{\gamma\frac{-b^2(-L+(An\alpha+cB_1-cr)+Am\alpha)+c\alpha N(b(-L+AN\alpha\beta)+cm\alpha\beta((An\alpha+cB_1-cr)-(Am\alpha+cB_1-cr)+A\alpha(m-n)))}{b^2(b\gamma-1)+c^2\alpha^2\beta N(m-b\gamma N)}}\end{aligned}$$

Simplifying we obtain that,

$$\begin{aligned}\frac{y_{2NA}^{*}}{x_{2}^{*}} &= \Big(Lb-bcB_1+bcr-LNc\alpha-ANb\alpha+AN^2c\alpha^2\beta\Big)\\ &* \frac{-b^3\gamma+b^2-Nc^2m\alpha^2\beta+N^2bc^2\alpha^2\beta\gamma}{\gamma b\left(Lb-bcB_1+bcr-LNc\alpha-Ab\alpha\left(m+n\right)+AN^2c\alpha^2\beta\right)\left(-b^2+N^2c^2\alpha^2\beta\right)}\\ &= \Big(Lb-bcB_1+bcr-LNc\alpha-ANb\alpha+AN^2c\alpha^2\beta\Big)\\ &* \frac{-b^3\gamma+b^2-Nc^2m\alpha^2\beta+N^2bc^2\alpha^2\beta\gamma}{\gamma b\left(Lb-bcB_1+bcr-LNc\alpha-Ab\alpha N+AN^2c\alpha^2\beta\right)\left(-b^2+N^2c^2\alpha^2\beta\right)}\end{aligned}$$

Therefore,

$$y_{2NA}^{*}=\frac{-b^3\gamma+b^2+Nc^2\alpha^2\beta\left(-m+Nb\gamma\right)}{b\gamma\left(-b^2+N^2c^2\alpha^2\beta\right)}x_{2}^{*}$$

The numerator and denominator of the previous ratio are negative because of concavity conditions. Moreover

$$\frac{-b^3\gamma+b^2+Nc^2\alpha^2\beta\left(-m+Nb\gamma\right)}{b\gamma\left(-b^2+N^2c^2\alpha^2\beta\right)}<1$$

$\iff \frac{-b^3\gamma+b^2+Nc^2\alpha^2\beta(-m+Nb\gamma)}{b\gamma(-b^2+N^2c^2\alpha^2\beta)}-1=\frac{b^2-Nc^2m\alpha^2\beta}{b\gamma(-b^2+N^2c^2\alpha^2\beta)}<0.$

For the numerator, $b^2-Nc^2m\alpha^2\beta>0 \iff \frac{b^2}{Nm\alpha^2\beta}>c^2$

For the denominator,

$-b^2+N^2c^2\alpha^2\beta<0 \iff \frac{b^2}{N^2\alpha^2\beta}>c^2$

The previous conditions are satisfied because $\frac{b^2}{Nm\alpha^2\beta}>\frac{b^2}{N^2\alpha^2\beta}>c^2$ due to concavity conditions. Therefore,

$$y_{2NA}^{*}<x_{2}^{*}$$

Now, concerning the sign of $y_{2NA}^{*}-y_{2}^{*}$,

$$
\begin{aligned}
\frac{y^*_{2NA}}{y^*_2} &= \frac{\frac{b(L-D_2)-Nc\alpha(L-AN\alpha\beta)}{b^2-N^2c^2\alpha^2\beta}}{\frac{-b(b\gamma-1)(-L+D_2+An\alpha)+c\alpha N((b\gamma-1)(-L+AN\alpha\beta)-cn\alpha\beta\gamma(D_1-D_2+A\alpha(m-n)))}{b^2(b\gamma-1)+c^2\alpha^2\beta N(m-b\gamma N)}} \\
&= \frac{\frac{b(L-(AN\alpha+cB_1-cr))-Nc\alpha(L-AN\alpha\beta)}{b^2-N^2c^2\alpha^2\beta}}{\frac{-b(b\gamma-1)(-L+(Am\alpha+cB_1-cr)+An\alpha)+c\alpha N((b\gamma-1)(-L+AN\alpha\beta)-cn\alpha\beta\gamma((An\alpha+cB_1-cr)-(Am\alpha+cB_1-cr)+A\alpha(m-n)))}{b^2(b\gamma-1)+c^2\alpha^2\beta N(m-b\gamma N)}} \\
&= \left(Lb-bcB_1+bcr-ANb\alpha-LNc\alpha+AN^2c\alpha^2\beta\right) \\
&* \frac{-b^2(b\gamma-1)+Nc^2\alpha^2\beta(-m+Nb\gamma)}{(b\gamma-1)\left(Lb-bcB_1+bcr-LNc\alpha-Ab\alpha(m+n)+AN^2c\alpha^2\beta\right)\left(-b^2+N^2c^2\alpha^2\beta\right)} \\
&= \left(Lb-bcB_1+bcr-ANb\alpha-LNc\alpha+AN^2c\alpha^2\beta\right) \\
&* \frac{-b^2(b\gamma-1)+Nc^2\alpha^2\beta(-m+Nb\gamma)}{(b\gamma-1)\left(Lb-bcB_1+bcr-LNc\alpha-Ab\alpha N+AN^2c\alpha^2\beta\right)\left(-b^2+N^2c^2\alpha^2\beta\right)}
\end{aligned}
$$

Simplifying,

$$\frac{y^*_{2NA}}{y^*_2} = \frac{-b^3\gamma+b^2-Nc^2m\alpha^2\beta+N^2bc^2\alpha^2\beta\gamma}{(b\gamma-1)(-b^2+N^2c^2\alpha^2\beta)} > 0$$

and,

$$\frac{-b^3\gamma+b^2-Nc^2m\alpha^2\beta+N^2bc^2\alpha^2\beta\gamma}{(b\gamma-1)(-b^2+N^2c^2\alpha^2\beta)} - 1 = Nc^2\alpha^2\beta\frac{N-m}{(-b^2+N^2c^2\alpha^2\beta)(b\gamma-1)} < 0$$

due to concavity conditions. As

$$\frac{-b^3\gamma+b^2-Nc^2m\alpha^2\beta+N^2bc^2\alpha^2\beta\gamma}{(b\gamma-1)(-b^2+N^2c^2\alpha^2\beta)} < 1,$$

$$y^*_{2NA} < y^*_2$$

Finally, concerning the sign of $(Ny^*_{1NA}+Ny^*_{2NA})-(nx^*_1+my^*_1+nx^*_2+my^*_2)$, First, as $x^*_1 = y^*_1$,

$$
\begin{aligned}
&(Ny^*_{1NA}+Ny^*_{2NA})-(nx^*_1+my^*_1+nx^*_2+my^*_2) \\
&= (Ny^*_{1NA}+Ny^*_{2NA})-(Nx^*_1+nx^*_2+my^*_2)
\end{aligned}
$$

where

$$
\begin{aligned}
Ny^*_{1NA} &= N\frac{(b\gamma-1)(b(L-AN\alpha\beta)-cN\alpha\beta(L-D_2))}{(b\gamma-1)(b^2-N^2c^2\alpha^2\beta)} \\
&= N\frac{(b\gamma-1)(b(L-AN\alpha\beta)-cN\alpha\beta(L-(AN\alpha+cB_1-cr)))}{(b\gamma-1)(b^2-N^2c^2\alpha^2\beta)},
\end{aligned}
$$

$$
\begin{aligned}
Ny_{2NA}^{*} &= N\frac{b\left(L-D_2\right)-Nc\alpha\left(L-AN\alpha\beta\right)}{b^2-N^2c^2\alpha^2\beta} \\
&= N\frac{b\left(L-\left(AN\alpha+cB_1-cr\right)\right)-Nc\alpha\left(L-AN\alpha\beta\right)}{b^2-N^2c^2\alpha^2\beta},
\end{aligned}
$$

$$
\begin{aligned}
Nx_1^{*} &= N\frac{\left(b\gamma-1\right)\left(b\left(-L+AN\alpha\beta\right)-cm\alpha\beta\left(-L+D_2+An\alpha\right)\right)-bcn\alpha\beta\gamma\left(-L+D_1+Am\alpha\right)}{-b^2\left(b\gamma-1\right)+c^2\alpha^2\beta N\left(-m+b\gamma N\right)} \\
&= N\frac{\left(b\gamma-1\right)\left(b\left(-L+AN\alpha\beta\right)-cm\alpha\beta\left(-L+\left(Am\alpha+cB_1-cr\right)+An\alpha\right)\right)-bcn\alpha\beta\gamma\left(-L+\left(An\alpha+cB_1-cr\right)+Am\alpha\right)}{-b^2\left(b\gamma-1\right)+c^2\alpha^2\beta N\left(-m+b\gamma N\right)} \\
&= N\frac{\left(b\gamma-1\right)\left(b\left(-L+AN\alpha\beta\right)+cm\alpha\beta\left(L+c\left(r-B_1\right)-A\alpha\left(m+n\right)\right)\right)+bcn\alpha\beta\gamma\left(L+c\left(r-B_1\right)-A\alpha\left(m+n\right)\right)}{-b^2\left(b\gamma-1\right)+c^2\alpha^2\beta N\left(-m+b\gamma N\right)} \\
&= N\frac{\left(b\gamma-1\right)\left(b\left(-L+AN\alpha\beta\right)+cm\alpha\beta\left(L+c\left(r-B_1\right)-A\alpha N\right)\right)+bcn\alpha\beta\gamma\left(L+c\left(r-B_1\right)-A\alpha N\right)}{-b^2\left(b\gamma-1\right)+c^2\alpha^2\beta N\left(-m+b\gamma N\right)},
\end{aligned}
$$

$$
\begin{aligned}
nx_2^{*} &= n\gamma\frac{-b^2\left(-L+D_1+Am\alpha\right)+c\alpha N\left(b\left(-L+AN\alpha\beta\right)+cm\alpha\beta\left(D_1-D_2+A\alpha\left(m-n\right)\right)\right)}{b^2\left(b\gamma-1\right)+c^2\alpha^2\beta N\left(m-b\gamma N\right)} \\
&= -n\gamma b\frac{Lb-bcB_1+bcr-LNc\alpha-Ab\alpha\left(m+n\right)+AN^2c\alpha^2\beta}{-b^3\gamma+b^2-Nc^2m\alpha^2\beta+N^2bc^2\alpha^2\beta\gamma} \\
&= -n\gamma b\frac{Lb-bcB_1+bcr-LNc\alpha-Ab\alpha N+AN^2c\alpha^2\beta}{-b^3\gamma+b^2-Nc^2m\alpha^2\beta+N^2bc^2\alpha^2\beta\gamma} \text{ and,}
\end{aligned}
$$

$$
\begin{aligned}
my_2^{*} &= m\frac{-b\left(b\gamma-1\right)\left(-L+D_2+An\alpha\right)+c\alpha N\left(\left(b\gamma-1\right)\left(-L+AN\alpha\beta\right)-cn\alpha\beta\gamma\left(D_1-D_2+A\alpha\left(m-n\right)\right)\right)}{b^2\left(b\gamma-1\right)+c^2\alpha^2\beta N\left(m-b\gamma N\right)} \\
&= -m\left(b\gamma-1\right)\frac{Lb-bcB_1+bcr-LNc\alpha-Ab\alpha\left(m+n\right)+AN^2c\alpha^2\beta}{-b^3\gamma+b^2-Nc^2m\alpha^2\beta+N^2bc^2\alpha^2\beta\gamma} \\
&= -m\left(b\gamma-1\right)\frac{Lb-bcB_1+bcr-LNc\alpha-Ab\alpha N+AN^2c\alpha^2\beta}{-b^3\gamma+b^2-Nc^2m\alpha^2\beta+N^2bc^2\alpha^2\beta\gamma}
\end{aligned}
$$

Then by substituting and simplifying,

$$
\begin{aligned}
&\left(Ny_{1NA}^{*}+Ny_{2NA}^{*}\right)-\left(nx_1^{*}+my_1^{*}+nx_2^{*}+my_2^{*}\right) \\
&= bn\left(-b+Nc\alpha\beta\right)\frac{L\left(b-Nc\alpha\right)+bc\left(r-B_1\right)-AN\alpha\left(b-Nc\alpha\beta\right)}{\left(-b^2+N^2c^2\alpha^2\beta\right)\left(-b^2\left(b\gamma-1\right)+Nc^2\alpha^2\beta\left(-m+Nb\gamma\right)\right)}
\end{aligned}
$$

The numerator of previous expression is negative as $\left(-b+Nc\alpha\beta\right)<0$ and $L\left(b-Nc\alpha\right)+bc\left(r-B_1\right)-AN\alpha\left(b-Nc\alpha\beta\right)>0$.

The denominator is positive as $\left(-b^2+N^2c^2\alpha^2\beta\right)<0$ and $\left(-b^2\left(b\gamma-1\right)+Nc^2\alpha^2\beta\left(-m+Nb\gamma\right)\right)<0$. Therefore, the expression is negative and,

$$
\left(Ny_{1NA}^{*}+Ny_{2NA}^{*}\right)<\left(nx_1^{*}+my_1^{*}+nx_2^{*}+my_2^{*}\right).
$$

9.3 Additional figures

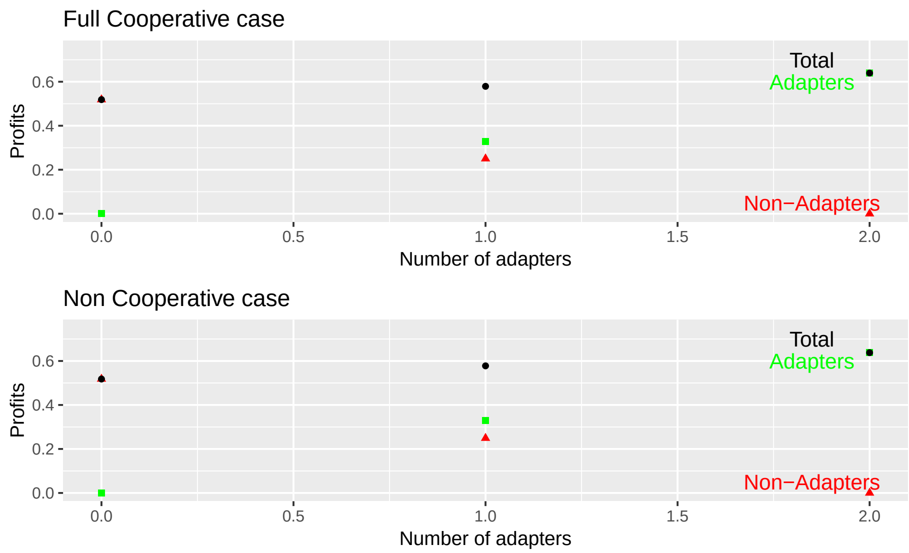

Figure 5: Profits per group (adapters and non-adapters) and total farmers' profits in function of the number of adapting farmers for the different scenarios and $N = 2$.

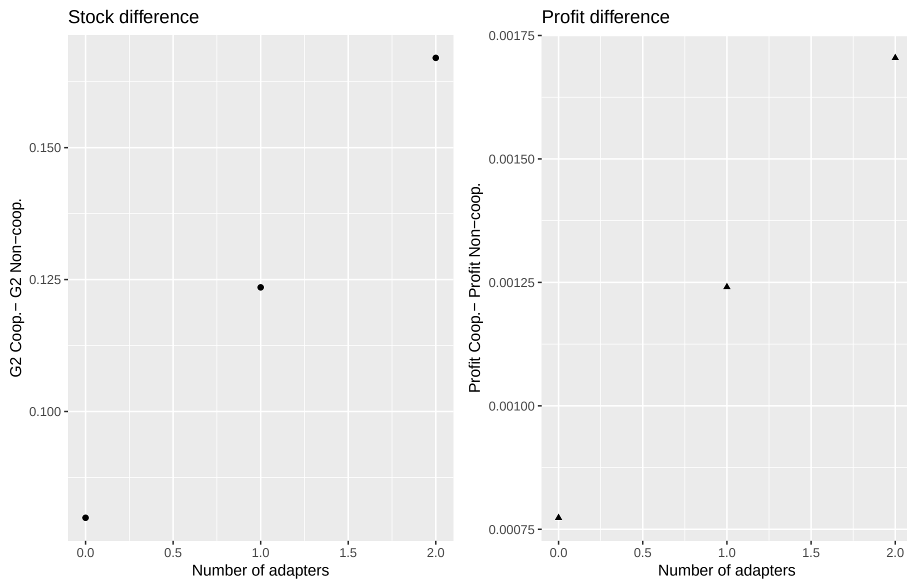

Figure 6: Final stock and profit differences between the cooperative and non-cooperative scenarios, in function of the number of adapting farmers, for the case $N = 2$.

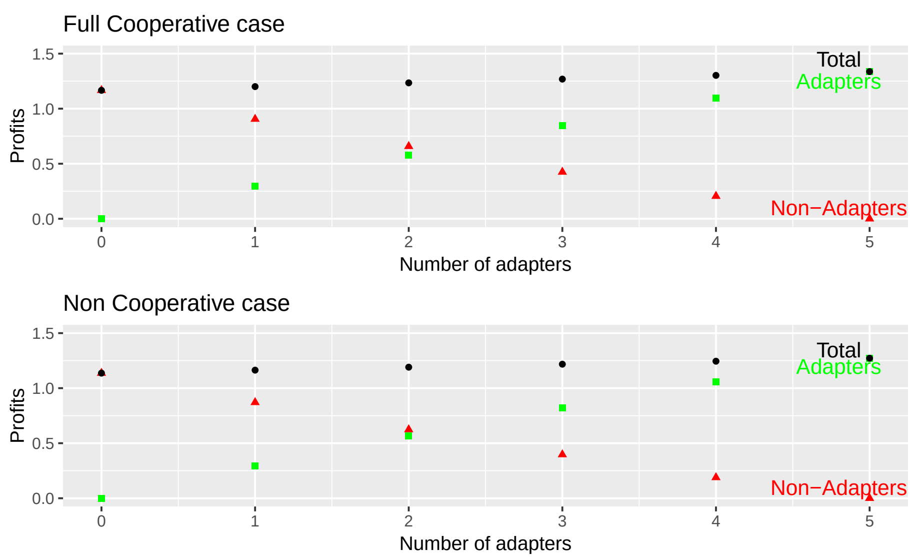

Figure 7: Profits per group (adapters and non-adapters) and total farmers' profits in function of the number of adapting farmers for the different scenarios and $N = 5$.

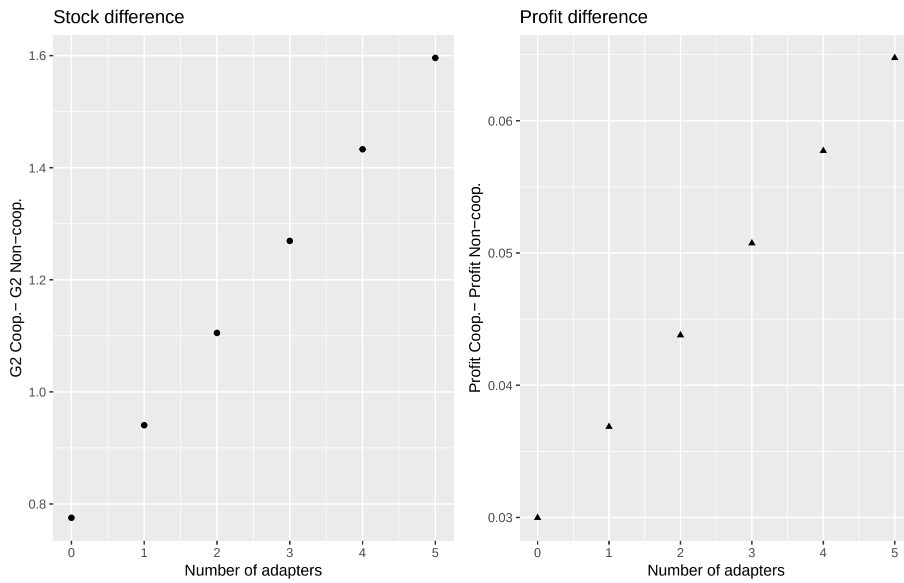

Figure 8: Final stock and profit differences between the cooperative and non-cooperative scenarios, in function of the number of adapting farmers, for the case $N = 5$.

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