Congestion effects, spatial externalities, and inefficient crop diversification

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Abstract

Crop diversification helps maintain yields while reducing pesticides' and fertilizers' use, and is, therefore, an essential tool for more sustainable agriculture. Despite extensive support for this practice among agronomists, crop diversity appears more limited than what is justified by technical benefits to specialization. We study barriers to diversification that can arise from farmers' equilibrium choices. Farmers choose their land allocation across two crops, where one is intrinsically more productive than the other. A congestion effect arises: the productivity of each crop decreases when its proportion increases. We investigate whether the crop with the highest achievable revenue over-dominates, with and without spatial externalities. Mental accounting, lack of coordination, and non-internalization of spatial effects help understand under-diversification. Lack of agrobiodiversity can arise even though we consider only the monetized value of diversity (e.g., its private impact on yields) and neglect other social benefits.

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1 Introduction

The loss in plant biological diversity is in part due to human activities that impact ecosystems. Among those activities some come very directly from human choices: Farmers select particular crops (and within crops, particular varieties), with immediate consequences for diversity. While many consequences of the loss in biodiversity are difficult to quantify, agricultural crop diversity has direct economic impacts for farmers, that translate into incentives for seeds manufacturers.

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This paper focuses on a setting in which a farmer can use two crops, and the revenue derived by each crop is decreasing in the fraction of land allocated to that crop. Due to this feature, a "congestion effect", a crop that has a lower attainable yield may still be cultivated, as it helps maintain the yield of a superior crop. We analyze the farmer's land allocation choice, given the congestion effect. We assume that there are spatial externalities in congestion (as evidenced by Donfouet et al., 2017), so that the yield from one crop for a given farmer depends not only on the proportion of her own land that is dedicated to this crop, but also on the land allocation choices of neighboring farmers.

Crop diversification. Crop diversification refers to the addition of more crops to an existing cropping system. This includes crops rotation, intercropping and growing several crops rather than specializing the whole farm activity on a single one. Its benefits on farmers' revenues are now well established (e.g., Garbelini et al. 2022), especially for smaller farms. They are such that crop diversification has been advocated as a way to alleviate poverty for farmers in poorer countries (Antonelli et al., 2022, Birthal, Jha, Joshi and Singh, 2006, Bozzola and Smale, 2020, Feliciano, 2019). Diversification is considered to be an ecological, cost-effective and easy way of reducing revenue uncertainty but also of increasing yields (Makate et al., 2016, Bowles et al., 2020, Vilatte et al., 2023). It improves output stability and resilience, including in long-term studies (Sanford et al., 2021). Lack of diversity and shorter rotations are associated to lower yields (Bennet et al., 2012). For instance, the yield of oil-seed grape in monoculture declines by 25% (Hilton et al., 2013). This reduction in yields is due to several factors, including higher vulnerability to pests (Altieri, 1999, Lin, 2011, Tooker and Frank, 2012, Peralta et al., 2018)[1] and loss of soil quality (McDaniel et al. 2014)[2]. Conversely, crop diversification is positively associated to yield (Tamburini et al. 2020, Bowles et al., 2020), low yield variability (Gaudin et al., 2015) and farm income in a number of studies.[3]

Despite these benefits of crop diversification, three crops (maize, rice, and wheat) account

[1] Monocultures are more vulnerable to pests when an attack occur, but are also more likely to suffer an attack, since monocultures benefit less from natural ennemies to their pests than polycultures (see e.g., Altieri, 1999). In addition, monocultures favor the dissemination of pests, as they can easily move from one area to a close one where the same crop is grown.

[2] On a meta-analysis of 112 studies, McDaniel et al. (2014) find that crop rotations very significantly increased the soil microbial biomass carbon (20.7%) and nitrogen (26.1%) pools. They also improve microbial biomass. Weisberger, Nichols and Liebman (2019) also use a meta-analysis to conclude that diversifying crop rotations helps suppress weeds, reducing their density by 49%.

[3] Bowles et al. (2020) find that crop rotation can increase yield by 28% for maize in North America. Bravo-Ureta et al. (2006) find a 21% average increase in farm income on sampled farmers in El Salvador and Honduras; Perz (2004) similarly obtain a strong positive association between diversification and farmers' income in the Brazilian Amazon.

for more than half of the calories and proteins that humans get from plants worldwide[4]. And if one adds soya, the four crops account for nearly half of worldwide farmland (Martin et al., 2019). Economic factors, including the cost of machinery for each crop (different types of sowers, harvesting tools...) and returns to scale in commercialization, favor specialization (see Lin, 2011, Bowman and Zilberman, 2013, or Weisberger et al., 2021, whose survey research stresses the lack of adequate markets for small crops). Aguilar et al. (2015) find that the number of crops grown in most parts of the US has decreased between 1978 and 2012 due to farmers' specialization. This loss in diversity applies not only to the number of crops grown, but also in the range of varieties crop: there is less diversity both at the species and the genetic level (see Bradshaw, 2017, for a historical perspective). Martin et al. (2019) find that while the number of different crops grown has increased over the world between 1960 and 2015, both the dominance of the major crops and the genetic similarity in grown varieties have noticeably increased.

A more diverse crop allocation provides financial diversification to risk-averse farmers. Smaller farms are likely to find this benefit more attractive than larger farms that are able to hedge through other means (including financial markets). The financial insurance provided by diversification can therefore depend on the size of the farm. The other benefits to specialization relate to yields and pest resistance. Our analysis incorporates both types of benefits, but we tend to focus more, in our interpretation, on the yield aspects and on crop market price aspects.

Spatial externalities to crop choices. Neighboring farms can exert externalities on one another via their crop choices. A first reason is that the effects of congestion that are present at a farm's level also apply, possibly to a lesser extent, to closely located land acres. So if closely located farmers all cultivate the same crop, the productivity of this crop will tend to decrease compared to a situation of more diverse crops in the area. Other farmers' decisions related to crop choices – most especially pesticides use – also exert externalities (e.g., Grogan, and Goodhue, 2011, 2012, Zheng and Goodhue, 2021).

Donfouet et al. (2017) estimate production functions and find that crop diversity increases crop production, with significant spatial effects.[5]

In their 34-year study of crop diversity in the US, Aguilar et al. (2015) find that counties tend to cluster in either high-diverse or low-diversity areas, which can be due to spatial effects that impact

[4]An explanation for why these three crops became so dominant is that they rely on wind for pollination, and are therefore not dependent on specific insects, which increases their resilience to natural conditions (Allard, 1999, Warren, 2016).

[5]They also highlight that the benefits of diversity on production are more pronounced in situations of limited rainfall, for the regions and crops considered.

land allocation choices. They also find that the number of high-diversity counties has decreased.

Our approach. We analyze the incentives of farmers who must allocate their land between two crops, under the existence of congestion effects: Growing more of a crop reduces its attainable yield. The congestion effect is amplified by a lack of diversity in neighboring farms: There are spatial externalities in congestion, which affects each farmer's crop allocation choice in a Nash equilibrium. A breeder or seed supplier can adjust the price of seeds in order to maximize profits, anticipating these externalities.

In a Nash equilibrium, farmers choose their land allocation in a way that can lead to either too much or too little diversity, depending on relative seeds prices. A monopoly seed producer may however counter the externality effect by an adequate input pricing.

We do not consider the social value associated to more diversity. This value undeniably exists and the loss of genetic crop diversity is a global concern (Fowler and Mooney, 1990). However, we investigate whether crop choice can be inefficient even when only the private, monetized, value of diversity is considered. We therefore identify sources of inefficiencies in addition to the more evident inefficiencies arising from the gap between private and social values to biodiversity.

2 The model

A farmer must choose her land allocation over two cash crops, A and B. We do not consider cover crops or sequentially cultivated crops, so that any acre allocated to crop A cannot be allocated to crop B and vice versa. The important elements of the farmer's decision are the following: i) Each crop exerts an externality on the other crop that is related to the crop's dominance on the land, and ii) crops differ in their maximum potential yield (the "attainable yield").

We only consider in the main text the situation where farmers cultivate all the land they own (so that the share of land allocated to B is one minus the share allocated to A). In the appendix however (sections A.2. and A.3.), we study decisions with potential partial cultivation (and show that it cannot be efficient).

2.1 Crop yield and congestion effects

Attainable revenues. Crop B has a maximum potential ('attainable') revenue $y_B \equiv y$, and crop A is potentially more efficient: $y_A = (1 + a)y$. Parameter a, $a \in]0, 1[$, measures the relative advantage of cultivating crop A: Crop A has a higher attainable revenue, ceteris paribus. While this advantage would lead to using primarily crop A, it is mitigated by a 'congestion' effect that increases with the loss of crop diversity.

Congestion. Lack of diversity has a direct impact on profits: The larger the share of a crop, the lower its revenue will be (per unit of surface cultivated). The congestion / depreciation rate is α, $\alpha \in]0,1[$. It is proportional to a crop's share, and applies to the attainable revenue. Therefore, congestion is $\alpha y_A = \alpha(1+a)y$ for one more 'unit' of crop A in land allocation, and $\alpha y_B = \alpha y$ for one more 'unit' of crop B.

We describe the impact of spatial externalities on congestion in Section 3. Locally, two different channels can create congestion. One is an "intra-crop congestion": cultivating more of a crop increasingly drains specific soil nutrients, and favors pests and diseases propagation. The other channel is an "inter-crop congestion relief": cultivating more of an adequately selected secondary crop allows benefiting from agronomic complementarities.[6]

Since A has a higher potential revenue, it is also more affected, ceteris paribus, by the congestion effect associated to crop dominance. However, proportionality also implies that the value (gross of seeds price) made from crop A remains above that on crop B.

Yields and revenues. We confound in the following yields and monetary profits from a crop: So we may refer to $y_B = y$ and $y_A = (1+a)y$ as "yields" although they are actually the *revenues* the farmer derives from her crops. In doing so, we de facto normalize the market price for each crop to one. However, we could easily relax this assumption since parameter a could account for the impact, not only on yield but also on market prices, of diversity. The assumption has no impact, except that it helps avoid confusion: In the remainder of the article, when we refer to prices, we will be referring to the input prices that the farmer faces, that is: the seeds price

In addition, elements of costs are incorporated in the analysis: If a farmer is faced to increased pest pressure, it may be possible to maintain yield by using pesticides, but this entails treatment and application costs, so that revenues are still reduced per acre, compared to the 'ideal' situation of no congestion. Similarly, if the farmer needs to use more fertilizers to maintain yields despite soil nutrients depletion, this involves some loss of revenues. So while we will tend to use 'yield' in the following as it is the object of study of many agroecological research, our work actually applies more broadly to congestion impacts that may go through prices and costs.

The farmer's profits. The seeds for crops A and B are sold by a single (monopoly) seed breeder, at respective prices w_A and w_B. Assuming that seeds are sold by a monopoly allows us

[6] Cultivating another cash crop also provides financial diversification. Since we consider a risk-neutral farmer, we do not model the consequences of yield variability and revenue diversification.

to abstract from strategic competition between seeds suppliers, in order to focus on the farmer's choice.

The farmer's profit is

$$\Pi^F \equiv \theta[(1+a)y(1-\alpha\theta) - w_A] + (1-\theta)[y(1-\alpha(1-\theta)) - w_B]$$

It is helpful to rewrite profits (divided by the revenue from crop B) to highlight the specific role of crop allocation θ:

$$\begin{aligned}\Pi^F/y &= 1-\alpha - w_B/y + \theta[a + \alpha(1-\theta(1-a)) - \Delta w/y] \\ &= [1-\alpha-w_B/y] + \theta[a+2\alpha-\Delta w/y] - \theta^2[\alpha(2+a)]\end{aligned}$$

with $\Delta w \equiv w_A - w_B$ the seeds price difference between the two crops. Profits are a concave (quadratic) function of the crop allocation θ: while crop A has a higher potential yield, cultivating too much of it reduces this value.

Crops' substitutability / complementarity. Because of this specific feature of agricultural crops, two crops can be substitutes or complements from the point of view of the farmer: Crops are substitutes to the extent that any land allocated to one crop cannot be allocated to another; Yet crops can be complementary in the sense that increasing the production of one raises the marginal yield on the other.

2.2 Benchmark: The case of a single farmer

2.2.1 The farmer's choice

The farmer's problem consists in maximizing profits over crop allocation. The choice of crop allocation depends on the seeds *price difference* but not on absolute price levels. Absolute seed price levels play a role in determining whether profits are positive (the term w_B enters as a constant in profits). The equilibrium allocation value is:

$$\theta^*(\Delta w) = \frac{a+2\alpha-\Delta w/y}{2\alpha(2+a)} = \frac{1}{2+a}\left[1 + \frac{a-\Delta w/y}{2\alpha}\right]$$

provided that this value belongs to $[0,1]$ and that the farmer's participation constraint is met (i.e., that her profits are positive).

For an interior equilibrium value, the profit of the farmer is $\Pi^F(\theta^*) = y(1-\alpha) - w_B + y\frac{(a+2\alpha-\Delta w/y)^2}{4\alpha(2+a)}$. The participation constraint, $(PC)^F: \quad \Pi^F(\theta) \geq 0$, thus translates into an upper bound on the seed price of crop B, given the price differential Δw:

$$(PC)^F: \quad w_B \leq \overline{w}_B(\Delta w) \equiv y\Big[1-\alpha+\frac{1}{4\alpha(2+a)}(a+2\alpha-\Delta w/y)^2\Big]$$

The higher the revenue y derived from crop B (and therefore from crop A, which is always higher), the larger the seed price compatible with this condition. A higher price differential (a higher seed price for crop A) reduces the maximum seed price for crop B that keeps farming profits positive: $\overline{w}_B(\Delta w)$ is a decreasing function of Δw.

We assume (for now) that the participation constraint is satisfied.

Lemma 1. *A single farmer grows both crops whenever $a - 2\alpha(1+a) < \Delta w/y < a + 2\alpha$. She then chooses her crop allocation as a function of the seed price differential:*

$$\theta^*(\Delta w) \equiv \frac{a+2\alpha-\Delta w/y}{2\alpha(2+a)}$$

. The farmer grows only A if $a - 2\alpha(1+a) > \Delta w/y$ and only B if $a + 2\alpha < \Delta w/y$.

In the absence of the congestion effect, increasing the share of crop A by one unit would increase the seed price paid by Δw (reducing profits by the same amount) and would increase crop revenues by ay, given the superiority of crop A. The value of $\theta^*(\Delta w)$ would simply be 1 if $ay \geq \Delta w$, and 0 otherwise. The farmer would always cultivate a single crop. The congestion effect creates a much more complex problem where any increase in the share of crop A modifies the profitability of both crops. It makes it attractive to grow both crops.

If $a + 2\alpha < \Delta w/y$, then $\theta^* = 0$: Seed A is sold at a too high premium compared to its added benefits (which are its superior yield measured by a, and its beneficial reduction of the congestion on B, measured by 2α). The farmer then grows only B.

Conversely, if $a - 2\alpha(1+a) < \Delta w/y$, growing only crop A becomes very attractive despite its negative congestion effect on the return to crop A (measured by $2\alpha(1+a)$).

The participation constraint, at this equilibrium, can be expressed as a maximum seed price for

B, that is (weakly) decreasing in the seed price differential:

$$(PC)^F : w_B \leq \overline{w}_B(\Delta w) \equiv \begin{cases} y\Big[1-\alpha+\dfrac{1}{4\alpha(2+a)}(a+2\alpha-\Delta w/y)^2\Big] \\ \qquad\qquad\qquad \text{if } a-2\alpha(1+a) < \Delta w/y < a+2\alpha \\ (1-\alpha)y \qquad\qquad \text{if } \Delta w/y \geq a+2\alpha \\ (1-\alpha)(1+a)y-\Delta w \quad \text{if } \Delta w/y \leq a-2\alpha(1+a) \end{cases}$$

The higher the revenue y derived from the crops, the larger the seed price compatible with this condition. A higher price differential (a higher seed price for crop A compared to crop B) reduces the maximum seed price for crop B, w_B, that keeps farming profits positive.

2.2.2 The breeder's problem

The breeder is a monopoly and we normalize its production costs to zero. Its profits are therefore equal to sales revenues, $\pi^B \equiv w_A\theta + w_B(1-\theta) = w_B + \Delta w \cdot \theta$. The breeder maximizes its profits, anticipating the equilibrium allocation chosen by the farmer, under the constraint that the letter buys (the farmer has no alternative provider):

$$\max_{\Delta w} \{w_B + \Delta w \cdot \theta^*(\Delta w)\} \quad \text{s.t.} \quad (PC)^F$$

The breeder's best interest lies in setting maximum seed prices compatible with the farmer's participation constraint: Because of this, the seed price for crop B will be set at $w_B = \overline{w}_B(\Delta w)$. A monopoly seeds breeder chooses seeds prices that appropriate the full farmer's profit at the equilibrium crop allocation.

The breeder's problem therefore simplifies into chosing the seed price differential Δw that induces the most beneficial crop allocation from its point of view. Replacing the equilibrium value for $\theta^*(\Delta w)$ by its expression for an internal equilibrium, the breeder's program becomes

$$\begin{array}{cc} \displaystyle\max_{(\Delta w, w_B)} & \{w_B + \Delta w \dfrac{a+2\alpha-\Delta w/y}{2\alpha(2+a)}\} \\ \text{subject to} & (PC)^F : w_B \geq \overline{w}_B(\Delta w) \end{array}$$

- *Interior allocation.* When the equilibrium allocation is interior, the participation constraint is binding and the program is equivalent to

$$\begin{aligned}
& \max_{\Delta w} \quad \{\overline{w}_B(\Delta w) + \Delta w \frac{a+2\alpha-\Delta w/y}{2\alpha(2+a)}\} \\
\Leftrightarrow \quad & \max_{\Delta w} \quad \{y\Big[1-\alpha+\frac{(a+2\alpha-\Delta w/y)^2}{4\alpha(2+a)}\Big] + \Delta w \frac{a+2\alpha-\Delta w/y}{2\alpha(2+a)}\} \\
\Leftrightarrow \quad & \max_{\Delta w} \quad \{y\Big[1-\alpha+\frac{1}{2\alpha(2+a)}[1/2(a+2\alpha)^2-(\Delta w/y)^2]\Big]\} \\
\Leftrightarrow \quad & \max_{\Delta w} \quad \{-(\Delta w/y)^2\Big]\}
\end{aligned}$$

The solution consists in selecting the smallest value (0) for the squared price differential: $\Delta w = 0$. The breeder prefers to price both seeds at the same level, despite the superior attainable yield of crop A.

Consistency requires that the farmer indeed chooses the interior allocation at $\Delta w = 0$, that is: $a - 2\alpha(1+a) < 0 < a + 2\alpha$, which reduces to the constraint that $a - 2\alpha(1+a) < 0$ or equivalently $\alpha > \frac{a}{2(1+a)}$ (congestion must be strong enough). If this condition is not satisfied, the equilibrium is necessarily one with a corner allocation.

- *Corner allocations.*

If $\Delta w/y \leq a - 2\alpha(1+a)$, the farmer grows only crop A. The breeder's profit is $\pi^{Br} = w_A = w_B + \Delta w$, which is maximized for the highest seed prices compatible with the participation constraint, that is: $w_A = (1-\alpha)(1+a)y$. This corresponds to $w_B = \overline{w}_B(\Delta w) = (1-\alpha)(1+a)y - \Delta w$ and Δw is irrelevant (and indeterminate in equilibrium, provided that it is lower than $y(a - 2\alpha(1+a))$. The breeder's profits are $(1-\alpha)(1+a)y$.

If $\Delta w/y \geq a + 2\alpha$, the farmer cultivates only crop B and Δw is irrelevant (provided that it remains above $a+2\alpha$). Then $w_B = \overline{w}_B(\Delta w) = (1-\alpha)y$ (for this range of parameter, this maximum price is independent of Δw. The breeder's profits are $\pi^{Br} = w_B = (1-\alpha)y$. This corresponds to a dominated choice of price differential by the breeder, as it generates less profit than inducing the cultivation of crop A.

The situation where only crop A is cultivated leads to a lower profit than the one for an interior allocation, whenever the latter situation is indeed an equilibrium ($\alpha > \frac{a}{2(1+a)}$). If it is not, then inducing the cultivation of only crop A maximizes the breeder's profit (with $w_A = (1-\alpha)(1+a)y$).

Lemma 2. *A monopolistic seed breeder appropriates all the social surplus and leaves no profit to the farmer.*
The equilibrium is interior if congestion is strong enough ($\alpha > \frac{a}{2(1+a)}$). In that case the breeder chooses $w_A = w_B = y\Big[1-\alpha+\frac{(a+2\alpha)^2}{4\alpha(2+a)}\Big]$. The seeds for the crop with the highest attainable yield

(A) are not priced higher than the less efficient crop's seeds ($\Delta w = 0$).
The equilibrium leads to cultivating only A when $\alpha \leq \frac{a}{2(1+a)}$.

2.2.3 The social optimum

There are no externalities, so social welfare simply consists in the sum of the farmer's profits and the seed breeder's profits. Here, all the benefits from diversity are monetized through the farmer's yield. The breeder, thanks to its monopoly position, appropriates the full profit of the farmer, as seen above. Its profits are the full surplus generated by cultivation, and it chooses seed prices that lead to surplus maximization.

Result 1. *With a single farmer and a monopolistic seed breeder, crop diversity is socially efficient. The equilibrium crop allocation is the first-best one: $\theta^{FB} = \frac{a+2\alpha}{2\alpha(2+a)}$ when $\alpha > \frac{a}{2(1+a)}$ and $\theta^{FB} = 1$ otherwise.*

This result is not in line with the concern expressed by experts about the concentration of agriculture on very few crops. However it depends on the assumption of a monopolistic seed breeder, and more fundamentally, on the ruling out of social benefits to diversity that would not accrue to the farmer.

To better understand limits to diversification that are specifically due to farmers' choices, we consider below the situation in which congestion also depends on neighboring farms.

3 Spatial externalities between farmers

When farms are close enough, crops yields and revenues on a given farm can be affected not only by the farm's crop allocation, but also by decisions made by neighbors.[7]. Such spatial externalities are especially likely if congestion is due to an increased vulnerability to pests – that disseminate across fields. There is then a diffusion of the congestion effect of a crop's dominance beyond a farm's boundaries. Spatial externalities are of much less relevance if congestion is mostly due to soil exhaustion – that is more local.

Under spatial externalities, the congestion due to a crop's dominance is a function not only of the farmer's crop allocation but also of the average crop allocation on the relevant geographical area.

[7] We do not consider the standard externality that other sellers, local or not, exert on crop prices through the total volume sold.

3.1 The diffusion effect

Assume that there are $n+1$ identical farmers in a given area, F^0, F^1 ..., F^n. The congestion due to a crop's dominance is determined in part by the farmer's crop allocation. But it is also affected by the average crop allocation chosen by the n other farmers in the area. More precisely, the rate of congestion α in farm F^i, $i = 0, ..., n$, is determined by the weighted average $(1-d)\theta^i + d\frac{\sum_{j\neq i}\theta^j}{n}$ for crop A. The equivalent term for crop B is $(1-d)(1-\theta^i)+d(1-\frac{\sum_{j\neq i}\theta^j}{n}) = 1-((1-d)\theta^i+d\frac{\sum_{j\neq i}\theta^j}{n})$. Parameter d, $d \in]0,1[$, represents the relative strength of diffusion effects, that is the impact of others' choices relative to one's own allocation choice, on own yield. It can be seen as a diffusion parameter. Assumption $d \leq 1/2$ represents situations in which the farmer's own choices have more impact than her neighbors' while $d > 1/2$ would mean that diffusion externalities are very strong (e.g., because each farm is 'small' in a geological basin where diffusion is easy).

The profit of a firm F^i is

$$\begin{aligned}\pi^{F^i} &= \theta^i(1+a)y\Big[1-\alpha\Big((1-d)\theta^i + d\frac{\sum_{j\neq i}\theta^j}{n}\Big)\Big] - \theta^i w_A \\ &\quad +(1-\theta^i)y\Big[1-\alpha\Big(1-((1-d)\theta^i + d\frac{\sum_{j\neq i}\theta^j}{n})\Big)\Big] - (1-\theta^i)w_B.\end{aligned}$$

3.2 The benchmark of perfect coordination

Assume that farmers are able to coordinate perfectly their crop choices. They maximize the sum of their profits:

$$\max_{\theta^0,\dots\theta^n} \sum_{i\geq 0} \pi^{F^i}\Big(\theta^i, \frac{\sum_{j\neq i}\theta^j}{n}\Big)$$

Given that the profit function is concave in its arguments, the optimal allocations are symmetric: By equally splitting production of each crop, a cooperative lessens the costs of yield depreciation.[8]

The problem is therefore identical to maximizing $n+1$ times the profit of a farmer in the absence of spatial externalities. If interior, the best cooperative level is that each farmer allocates land according to

$$\theta^c = \frac{a + 2\alpha - \Delta w/y}{2\alpha(2+a)}$$

The cooperative level is independent from the diffusion effects d. The average crop allocation of neighbors is equal to each farmer's crop allocation.

[8]The full proof is in the appendix. To get an idea of the structure of the problem, consider the case with only two farmers, 0 and 1. The maximization problem over the couple (θ^0, θ^1) bears over a global profit function of the form $K(\theta^0+\theta^1) + L((\theta^0)^2 + (\theta^1)^2) + M\theta^0\theta^1$. The first-order conditions yield $\theta^0 = \theta^1 = (K-2L)/C$. Choosing identical crop allocations maximize the sum of the farmers' profits.

Lemma 3. *Under perfect cooperation, equilibrium crop allocation is given by* $\theta^c = \theta^* = \frac{a+2\alpha-\Delta w/y}{2\alpha(2+a)}$. *It is*

- *independent from the relative strength of externalities* d,
- *identical to the allocation* (θ^*) *that a single farmer owning all the land would choose or that a farmer would choose in the absence of externalities* ($d = 0$).

The above result implies that the case of a single farmer is more general than it seems: It also represents the situation of a group of farmers able, by whatever mechanism (including possibly a cooperative structure) to fully coordinate their decisions.

Because coordination bears on production decisions, however, they may raise issues with respect to antitrust rules, depending on the countries considered. Agriculture benefits from block exemptions in many countries, as in the E.U. (European Commission, 2011), but these are limited to specific activites that are considered to generate sufficient positive effects to overrule the usual harms associated to producers coordination. In the E.U., the exemptions do not explicitly include coordination on crops cultivated surfaces and some judicial uncertainty remains.[9] We therefore consider below the case of no coordination, and that of imperfect coordination.

3.3 The Nash equilibrium with spatial externalities

Let us now consider the (non-cooperative) choice made by farmer F^0 (the problem is symmetric). Her profit is

$$\begin{aligned}\pi^{F^0} &= \theta^0(1+a)y\Big[1-\alpha\Big((1-d)\theta^0 + d\frac{\sum_{j\neq 0}\theta^j}{n}\Big)\Big]\\ &\quad +(1-\theta^0)y\Big[1-\alpha\Big(1-((1-d)\theta^0 + d\frac{\sum_{j\neq 0}\theta^j}{n})\Big)\Big]\\ &\quad -\theta^0 w_A - (1-\theta^0)w_B.\end{aligned}$$

Let us define $\tilde{\Theta}_{-i} \equiv \frac{\sum_{j\neq i}\theta^j}{n}$, the average crop allocation among all other farmers than F^i.

Optimization with respect to θ^0 yields the following best response:

$$\theta^0\left(\tilde{\Theta}_{-0}\right) = \frac{a+(2-d)\alpha-\Delta w/y}{2\alpha(2+a)(1-d)} - \frac{1}{2}\frac{d}{1-d}\tilde{\Theta}_{-0}$$

[9] in the E.U., the 2015 guidelines for the application of antitrust to arable crops (European Commission, 2015) list the following as beneficial activities: Joint distribution, joint promotion, joint organization of quality control, joint use of equipment or storage facilities, joint procurement of inputs. It does not include coordination on crops' surfaces. However, art. 209 of Regulation 1308/2013 indicates that "Article 101(1) TFEU [on horizontal agreements] shall not apply to agreements [...], which concern the production or sale of agricultural products [...] unless the objectives set out in Article 39 TFEU are jeopardised". Coordination on prices remains prohibited.

with a symmetric expression for the other n firms. The number of firms plays no role as it is the average allocation (over a given geographical area) that matters for depreciation. For the same reason, the detailed allocation for each farmer does not matter, the best response only depends on its average. One can check that this best response is identical to the choice of a single farmer (θ^*) whenever there are no spatial effects ($d = 0$).

The first term measures the relative value of crop A (that has an additional potential yield of ay but loses αy from depreciation and has an excess cost $w^A - w^B = \Delta w$ compared to crop B). The second term measures the adverse impact of other farmers' choices to grow crop A, and is weighted by half of $d/(1-d)$, the relative strength of spatial externalities.[10]

In a symmetric equilibrium, all allocations are identical and their average is equal to each: $\frac{\sum_{j \neq i} \theta^j}{n} = \tilde{\Theta}_{-i} = \frac{n\theta^i}{n} = \theta^i$. The definition of the best response, at the symmetric equilibrium, yields $\theta^i = \theta^i(n\frac{1}{n}\theta^i) = \theta^i(\theta^i)$. Using this equality, we can rewrite the best response for each firm F^i, $i = 0, ..., n$, as

$$\theta^i = \theta^i(\theta^i) = \frac{a + (2-d)\alpha - \Delta w/y}{2\alpha(2+a)(1-d)} - \frac{1}{2}\frac{d}{1-d}\theta^i$$

which yields the symmetric non-cooperative equilibrium allocation, $\theta^{nc}(d)$ (which is the solution to $\theta^i = \theta^i(\theta^i)$), if interior:

$$\theta^{nc}(d) = \frac{a + (2-d)\alpha - \Delta w/y}{(2-d)\alpha(2+a)}.$$

Lemma 4. *In a symmetric non-cooperative equilibrium with externalities:*

- Each farmer grows both crops whenever $a - \alpha(1+a)(2-d) < \Delta w/y < a + (2-d)\alpha$. Each then chooses the same non-cooperative share:

$$\theta^{nc}(d) = \frac{a + (2-d)\alpha - \Delta w/y}{(2-d)\alpha(2+a)}.$$

- Each farmer grows only A if $\Delta w/y \leq a - \alpha(1+a)(2-d)$ and only B if $\Delta w/y \geq a + (2-d)\alpha$.

To highlight the role of d, let us write the conditions for the allocation to be interior as $\Delta w/y \in]d\alpha(1+a) + a - 2\alpha(1+a), -d\alpha + a + 2\alpha[$. This interval gets reduced, both at its lower and its higher bound, when d increases (which makes it more likely that $\Delta w/y$ is not in it).[11]

Result 2. *An increase in the strength of externalities, d, enlarges the set of seed prices for which all farmers concentrate on a single crop in a symmetric non-cooperative equilibrium.*

[10] The multiplier 1/2 is the usual one, seen for instance in Cournot competition, that reflects that the farmer does not internalize the full effect of the average of others' choices, as it is not a choice variable for her.

[11] Note that this interval always exists, although $\Delta w/y$ may not be in it, since the lower bound is indeed lower than the higher one for $d \leq 2$, and therefore for $d \in [0, 1]$.

The interior equilibrium allocation is a monotonous function of the strength of spatial externalities: $\theta^{nc}(d) = \frac{a+(2-d)\alpha-\Delta w/y}{(2-d)\alpha(2+a)} = \frac{1}{2+a} + \frac{a-\Delta w/y}{(2-d)\alpha(2+a)}$. The allocation is increasing in d when $\Delta w/y \leq a$ and decreasing otherwise.[12]

This expression can be written as a function of the allocation that would prevail under full cooperation or under no spatial externalities:

$$\theta^{nc}(d) = \theta^c + \frac{d}{2-d}\frac{1}{2\alpha(2+a)}[a - \Delta w/y].$$

The sign of the difference $\theta^{nc}(d) - \theta^c$ is that of $a - \Delta w/y$. If the seed breeder does not charge more for crop A, relative to crop B, that its superiority in revenues (ay), then the non-cooperative allocation is higher than the fully cooperative level.

Proposition 1 (Cooperative and non-cooperative equilibria with spatial externalities and a given price difference Δw)**.** *If both the non-cooperative and the cooperative equilibria with spatial externalities entail corner allocations, they are identical.*
Otherwise, the following results apply: The non-cooperative equilibrium share of the dominant crop, A, is too high relative to the cooperative share when $\Delta w/y < a$. It is too low if $\Delta w/y > a$.
The non-cooperative equilibrium is identical to the fully cooperative one if and only if the seed price differential equals the crops yield differential: $\Delta w/y = a$.

The intuition behind this proposition is the following: When $ay > \Delta w$, the seed price differential is below the crop differential in attainable yield. Crop A is therefore more attractive than B, ceteris paribus. The farmer would like to grow much crop A; but due to congestion effects, this becomes less and less attractive when the surface allocated to crop A (i.e., θ) increases. When there are no externalities, the congestion is entirely due to the farmer's own crop choice, so that she gets the full benefit of limiting the surface dedicated to A. However, when there are externalities, reducing one's surface for A is less beneficial, since congestion may remain high due to other farmers' choices: Reducing θ is a less effective way of reducing congestion than without externalities. This is a classic situation in which the farmer bears the full cost of her efforts at reducing congestion while obtaining only a fraction of the benefits. It is thus optimal for the farmer to select a higher share of the most profitable crop.

Corollary 1. *Equal seed prices ($\Delta w = 0$) induce a socially optimal equilibrium when there are no externalities or perfect coordination; Otherwise they induce a non-cooperative equilibrium with too much concentration on crop A (unless the allocation is the corner one).*

[12] $\frac{\partial \theta^{nc}}{\partial d} = \frac{\partial}{\partial d}\frac{a+(2-d)\alpha-\Delta w/y}{2-d} = \frac{a-\Delta w/y}{(2-d)^2}$, which is of the sign of $a - \Delta w/y$.

For $\Delta w \neq ay$, the gap between interiors non-cooperative and cooperative allocations is non null and its absolute value increases in the strength of the diffusion effect, d.

Imperfect coordination. Imperfect coordination can arise if there is a risk that the negotiation between neighbors breaks down. Denote ρ the probability that the fully cooperative agreement is reached and carried on. The average crop allocation under spatial externalities and imperfect coordination is $\theta^* + (1-\rho)\frac{d}{2-d}\frac{a-\Delta w/y}{2\alpha(2+a)}$. It is above the cooperative level if $a > \Delta w/y$ and below otherwise.[13]

Parameter ρ can be used to better describe a variety of social environments, in which farmers may be more or less willing and able to coordinate. The existence of a cooperative, or facilitating governmental measures, can lead to an increase in ρ and therefore to an allocation closer to the efficient one.

3.4 Incorrect perceptions of spatial externalities

Assume that equilibrium levels are such that crop A covers more than half of acres.

Because yield depends on many factors (including climate, pest pressure, cross-crop effects,...), it may be difficult for a farmer to precisely estimate the degree to which her yields are affected by spatial externalities. This holds even after several years of observation, given the high heterogeneity in farming conditions. Therefore, farmers may overestimate or underestimate the strength of externalities, even if they use the best information at their disposal.

We have seen that the non-cooperative equilibrium $\theta^{i*}(d)$ is increasing in d if $ay > \Delta w$. If a farmer is not aware of the full impact of her neighbors' choices on her yield in the sense that she *underestimates* d, she will grow less of crop A.

Lemma 5. *In a non-cooperative set-up, if $ay > \Delta w$, farmers who underestimate the strength of spatial externalities (d) will use less of the dominant crop A than if they had correct beliefs.*

If all farmers underestimate spatial externalities, they will make choices closer to the cooperative one (a lower proportion of A): they will behave as if they internalized better their impact on others. This is because, if they underestimate the impact of externalities, they overestimate the impact of their own cultivated surface on their own returns. This leads them to choosing a lower surface for

[13] With probability ρ, the agreement is readched. Each farmer then chooses the cooperative allocation, $\theta^c = \theta^*$, defined previously. With probability $1-\rho$, negotiations break down and each farmer chooses the non-cooperative crop allocation. The average crop allocation under the risk of negotiation break-down is the weighted average of the two allocations, where the weights are defined by the probability of reaching an agreement. It equals $\rho\theta^* + (1-\rho)\left[\theta + \frac{d}{2-d}\frac{a-\Delta w/y}{2\alpha(2+a)}\right] = \theta^* + (1-\rho)\frac{d}{2-d}\frac{a-\Delta w/y}{2\alpha(2+a)}$.

A in order to limit congestion, when crop A is more attractive than B (that is: when the price differential Δw is lower than the excess attainable yield on A, ay).

Note that farmers may also have an incorrect perception of the degree of congestion, α, since they may not have enough data to eliminate noise. For interior solutions, they will choose the same allocation as under full cooperation if they believe that the degree of congestion is equal to some $\tilde{\alpha} \equiv \frac{2\alpha}{2-d}$.

3.5 Spatial externalities with more diverse crops

We have assumed up to now that there is a strong concentration on crops, in the sense that all farmers only cultivate the same two crops in the relevant area. This simplification provides an adequate approximation of crop choices in a number of regions, where dominant crops such as wheat and maize or rice represent most of the cultivated surfaces. In other regions, there may be much concentration on the dominant crop A, but farmers may also cultivate a variety of other crops on the remainder of their land. It is hoped that the development of ancient varieties and new varieties based on wild relatives, could increase agrobiodiversity.

To represent the impact of spatial externalities on the dominant crop when there is a diversity of other cultivated crops, we consider the following situation: Farm F^0 cultivates crops A and B, and other farms cultivate A and other crops than B. Then, congestion on crop A depends on the weighted average of this crop in the relevant area, as before. But the congestion on crop B only depends on the land allocation in the farm F^0.

We will refer to this situation as to a 'diverse environment' (even though there is a dominant crop, A, that is considered for cultivation by all farmers in the area).

The farmer's profit is

$$\begin{aligned}\pi_{div}^{F^0} &= \theta^0(1+a)y\Big[1-\alpha((1-d)\theta^0+d\tilde{\Theta}_{-0})\Big] \\ &\quad +(1-\theta^0)y\Big[1-\alpha\Big(1-\theta^0\Big)\Big]-\theta^0\Delta w-w_B.\end{aligned}$$

The best response, if interior, is

$$\theta_{div}^0\left(\tilde{\Theta}_{-0}\right)=\frac{a+2\alpha-\Delta w/y-d\alpha(1+a)\tilde{\Theta}_{-0}}{2\alpha[1+(1-d)(1+a)]}.$$

This best response compares to $\theta^0(\tilde{\Theta}_{-0})=\frac{a+(2-d)\alpha-\Delta w/y-d\alpha(2+a)\tilde{\Theta}_{-0}}{2\alpha(2+a)(1-d)}$ for concentrated crops.

As before, we focus on interior solutions in symmetric equilibria. In a symmetric equilibrium, the average share of crop A is equal to the share in F^0, from which we deduce the equilibrium (using $\theta^0 = \theta^0_{div}(\theta^0)$). If interior, the equilibrium allocation with diverse crops is:

$$\theta^{div}(d) = \frac{a + 2\alpha - \Delta w/y}{\alpha[2 + (2-d)(1+a)]} = \frac{a + 2\alpha - \Delta w/y}{\alpha[2(2+a) - d(1+a)]}.$$

The solution is interior if $0 < a + 2\alpha - \Delta w/y < \alpha[2 + (2-d)(1+a)]$. If $a + 2\alpha - \Delta w/y leq 0$, then $\theta^{div}(d) = 0$. If $a + 2\alpha - \Delta w/y \geq \alpha[2 + (2-d)(1+a)]$, then $\theta^{div}(d) = 1$.

The question we are interested in is whether a 'diverse' environment increases or decreases the share of the dominant crop.

For interior allocations, the sign of the difference between $\theta^{div}(d)$ and $\theta^{nc}(d)$ is:[14]

$$\begin{aligned} sign\Big(\theta^{div}(d) - \theta^{nc}(d)\Big) &= sign\Big(\frac{a + 2\alpha - \Delta w/y}{\alpha[2 + (2-d)(1+a)]} - \frac{a + (2-d)\alpha - \Delta w/y}{(2-d)\alpha(2+a)}\Big) \\ &= sign\Big((a + 2\alpha - \Delta w/y)(-d) + \alpha d[2 + (2-d)(1+a)]\Big) \\ &= sign\Big(-d\Big[a + 2\alpha - \Delta w/y - \alpha[2 + (2-d)(1+a)]\Big]\Big) \end{aligned}$$

This is always positive under the conditions for which $\theta^{div}(d)$ is below one ($a + 2\alpha - \Delta w/y \geq \alpha[2 + (2-d)(1+a)]$).

Note that the condition for the share of crop A to be non-negative is stricter in a concentrated environment ($a + (2-d)\alpha - \Delta w/y \geq 0$) than in a diverse one. It may be the case that crop A is cultivated in a diverse environment but not in a concentrated one. If $a + 2\alpha - \Delta w/y \leq 0$, the dominant crop is not cultivated in either environments.

Proposition 2 (Diversity vs. dominance)**.** *If $0 < a + 2\alpha - \Delta w/y < \alpha[2 + (2-d)(1+a)]$, the dominant crop (A) is not the only cultivated crop in a Nash equilibrium under diverse alternative crops. Its share is then strictly larger than in the concentrated environment: $\theta^{div}(d) > \theta^{nc}(d)$.*
A greater number of varieties can indirectly lead to a greater dominance, in terms of land usage, of the higher-revenue crop.

Somewhat paradoxically, *more variety* in the alternative crops leads to *more specialization* on the dominant one, in terms of cultivated surfaces.

Because neighbors cultivate other alternatives than B, the reduction in B's yield due to congestion is fully internalized by the farmer (and it is independent from neighbors' choices). To the

[14] If $d = 0$, the two allocations are identical. Developing the denominators for computation, we can rewrite the difference between the two allocations as follows: $\theta^{div}(d) - \theta^{nc}(d) = \frac{a+2\alpha-\Delta w/y}{\alpha[4+2a-d-ad]} - \frac{a+(2-d)\alpha-\Delta w/y}{\alpha[4+2a-2d-ad]}$. Since both denominators and α are positive, the sign of the difference is that of $[a+2\alpha-\Delta w/y][(4+2a-2d-ad)-(4+2a-d-ad)]-(-d\alpha)[4+2a-d-ad] = -d[a + 2\alpha - \Delta w/y] + d\alpha[4 + 2a - d - ad] = -d[a + 2\alpha - \Delta w/y - \alpha[2 + (2-d)(1+a)]]$.

contrary, in a concentrated environment, congestion on B depends not only on the farmer's own land allocation but also on neighbors' (as for congestion on A, in both environments). This externality effect leads the farmer to cultivate less of crop B in the diverse environment, where she fully internalizes its impact on congestion.

Empirical relevance. While Proposition 2 may seem paradoxical, it is consistent with observed worldwide evolutions. Martin, Cadotte et al. (2019) provide detailed evidence that the number of available varieties has increased worlwide, especially in the 1980s. However they also show that genetic diversity has decreased and that land use has been increasingly concentrated over very few crops,. Nine crops account for 2/3 of all cultivated land worldwide, and 4 of them, account for nearly 1/2. The reduction in diversity is observable both in terms of increased dominance of major crops and of increased genetic similarity.

The increase in the number of varieties in no way guarantees that land allocation will entail more diversity.

Martin et al. (2019) suggest that the increased dominance of the major crops is due to the fact that they have been highly subsidized. In our model, this corresponds to a value a, measuring the superior revenues from the dominant crop, that is inflated by government decisions.

4 Seed prices under spatial externalities

We now turn to the problem of seed breeders who are faced with non-cooperative farmers exerting spatial externalities on one another.

4.1 The case of a monopoly

Let us consider, as in the benchmark case of a single farmer, that seeds are supplied by a single monopoly, who can choose both prices w_A and w_B.

The breeder's problem is as before (the participation constraints are all identical in a symmetric equilibrium):

$$\begin{aligned} \max_{\{\Delta w, w_B\}} \quad & \{w_B + \theta^{nc}(\Delta w) \cdot \Delta w\} \\ \text{s.t.} \quad & w_B \leq \overline{w}_B(\Delta w). \end{aligned}$$

The farmers' participation constraint is always binding, so that the problem is

$$\max_{\{\Delta w\}} \{\overline{w}_B(\Delta w) + \theta^{nc}(\Delta w) \cdot \Delta w\}$$

Replacing the non-cooperative equilibrium allocation by its value, one can re-write the maximum seed price for B and the breeder's profit at this price.[15] Maximizing it over the seed price differential yields

$$\Delta w^* = \frac{ad}{2} y$$

which is the level that aligns the farmers' non-cooperative choices with surplus maximization: $\theta^{nc}(\frac{ad}{2}y) = \frac{a+2\alpha}{2\alpha(2+a)} = \theta^{coop}$. The breeder appropriates the full cultivation surplus, and chooses input prices to maximize it.

Result 3. *A monopolistic breeder will choose a seed price differential which eliminates the impact of the spatial externality:* $\Delta\theta^* = y\, ad/2$ *and* $\theta^{nc}(\Delta\theta^*) = \theta^{coop}$.
By increasing the price of the dominant crop, a monopolistic breeder favors diversity.

The breeder overprices seed A relative to B (compared with the single farmer's case, where it would choose $\Delta w = 0$). This indeed counters the farmers' excess cultivation of A in a non-cooperative equilibrium. The breeder is able to fully offset the inefficiencies due to spatial externalities.

4.2 A competitive market for seed B

Let us now consider the case where the superior crop, A, is sold by a monopoly, while the alternative crop, B, is sold on a purely competitive market at a fixed price $\hat{w}_B$.

The monopoly supplies both seeds and has a local advantage that allows it to obtain the whole market when selling at the same price as competitors. However its seed price for B is above the international price, it will not sell. And it cannot price below $\hat{w}_B$ without breaching antidumping regulations.

Now, the monopoly serves the full market but may not be able to appropriates the full cultivation surplus.

Assume that $\overline{w}_B(y\, a\, d/2) > \hat{w}_B$. The breeder cannot appropriate the full surplus because that

[15] The maximum seed price for B at the non-cooperative equilibrium is $\overline{w}_B(\Delta w) = y(1-\alpha+\frac{(a+(2-d)\alpha-\Delta w/y)}{\alpha(2+a)(2-d)^2}[(a+2\alpha-\Delta w/y)(2-d) - [a+(2-d)\alpha - \Delta w/y])$. The profit of the breeder at this maximum seed price is $\frac{\Delta w(a+(2-d)\alpha-\Delta w/y)}{\alpha(2+a)(2-d)} + y\Big(1-\alpha+\frac{(a+2\alpha-\Delta w/y)(a+(2-d)\alpha-\Delta w/y)}{\alpha(2+a)(2-d)} - \frac{(a+(2-d)\alpha-\Delta w/y)^2}{(2+a)(2-d)^2\alpha}\Big)$.

would require charging a seed price for B above the competitive level and farmers would buy from competitors. If the breeder chooses the seed price differential that nullifies the impact of externalities, it must leave some profit to the farmers.

Assume that $\overline{w}_B(y\,a\,d/2) < \hat{w}_B$. The breeder cannot appropriate the full surplus either because such this price differential is incompatible with the farmers' participation constraints at the competitive price $\hat{w}_B$. The breeder needs to choose a different price differential, and therefore cannot fully eliminate the negative impact of spatial externalities.

5 Conclusion

This work has focused on congestion effects, understood as the many processes through which the revenues (profit margins and yields) derived from a crop diminish when the crop becomes too dominant in terms of land usage. These congestion effects are important drivers of diversification strategies, including crop rotations and intercropping. A farm that is isolated from spatial externalities will base its diversification decisions on seed prices and attainable yield/revenue differences. Farmers will prefer to grow two crops rather than one only if i) one crop has a superior potential revenue and ii) there are congestion effects limiting the attractivity of this crop. If seeds are sold by a monopoly, this monopoly will set equal prices despite the potential superiority of one crop (the 'dominant' crop), in order to maximize the surplus which this monopoly appropriates.

When there are spatial externalities, so that congestion effects depend on the land use decisions of neighborhing farms, we show that inefficiencies arise, unless farmers are able to perfectly coordinate, or seeds are sold by an unconstrained monopoly (who will then adjust seed prices so as to compensate for the effect of the externality in farmers' decisions). A surprising result if that a dominant crop will be even more dominant in a Nash equilibrium when secondary crops are diverse (in the sense that neighborhing farms may be growing different secondary crops, even if they also grow the same dominant crop). This is consistent with evidence. The emergence of a higher variety of (new, subsidized, ancient, wild...) crops has co-existed with the reinforcement of the share of land allocated to the most dominant crops.

Our work provides a framework that can be extended to include the strategic choice of pesticide prices by firms that may or may not also sell seeds. It can also be adjusted to study the choice of cover crops vs. cash crops in intercropping.

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Appendix

A.1. The cooperative equilibrium with spatial externalities

In a cooperative equilibrium, the farmers choose crop allocations that maximize the sum of their profits:

$$\max_{\theta^0,\dots\theta^n} \sum_{i\geq 0} \pi^{F^i}\left(\theta^i, \frac{\sum_{j\neq i}\theta^j}{n}\right)$$

Denote by $\tilde{\Theta}_{-i}$ the average crop allocation of farmers other than F^i, i.e., $\tilde{\Theta}_{-i} \equiv \sum_{j\neq i} \pi^{F^j}/n$.

The cooperative maximization problem is equivalent to maximizing the sum of profits divided by crop B's revenue y:

$$\begin{aligned}
\sum_{i\geq 0}\pi^{F^i}/y &= \sum_{i\geq 0}\Big[\theta^i(1+a-[1-\alpha((1-d)\theta^i+d\tilde{\Theta}_{-i})])-\theta^i\Delta w/y-w_B/y\\
&\quad +(1-\theta^i)[1-\alpha(1-((1-d)\theta^i+d\tilde{\Theta}_{-i}))]\Big]\\
&= \sum_{i\geq 0}\Big[(1-\alpha-w_B/y)+\tilde{\Theta}_{-i}(\alpha d)-\theta^i\tilde{\Theta}_{-i}[\alpha d(2+a)]-\sum_{i\geq 0}(\theta^i)^2\alpha(2+a)(1-d)\\
&\quad +\theta^i[a+\alpha(2-d)-\Delta w/y]\Big]\\
&= ((n+1)-1)\Big[(1-\alpha-w_B/y)+\tilde{\Theta}_{-i}(\alpha d)\Big]+\sum_{i\geq 0}\Big[\theta^i[a+\alpha(2-d)-\Delta w/y]\\
&\quad -\theta^i\tilde{\Theta}_{-i}[\alpha d(2+a)]\Big]-\sum_{i\geq 0}(\theta^i)^2\alpha(2+a)(1-d)\\
&= n(1-\alpha-w_B/y)+\sum_{i\geq 0}\sum_{j\neq i}\frac{\theta^j}{n}(\alpha d)+\sum_{i\geq 0}\theta^i\Big[a+\alpha(2-d)-\Delta w/y\Big]\\
&\quad -\sum_{i\geq 0}\theta^i\sum_{j\neq i}\frac{\theta^j}{n}\Big[\alpha d(2+a)\Big]-\sum_{i\geq 0}(\theta^i)^2\alpha(2+a)(1-d)
\end{aligned}$$

We have $\sum_{i\geq 0}\theta^i\sum_{j\neq i}\frac{\theta^j}{n}=\frac{1}{n}\Big[\sum_{i\geq 0}\theta^i\sum_{j\geq 0}\theta^j-\sum_{i\geq 0}(\theta^i)^2\Big]$. And $\sum_{i\geq 0}\sum_{j\neq i}\frac{\theta^j}{n}=\sum_i(n+1-1)\frac{\theta^i}{n}=\sum_{i\geq 0}\theta^i$. Replacing these expressions in the sum of profits divided by y yields:

$$\begin{aligned}
\sum_{i\geq 0}\pi^{F^i}/y &= n(1-\alpha-w_B/y)+\sum_{i\geq 0}\sum_{j\neq i}\frac{\theta^j}{n}(\alpha d)+\sum_{i\geq 0}\theta^i\Big[a+\alpha(2-d)-\Delta w/y\Big]\\
&\quad -\frac{1}{n}\Big[\sum_{i\geq 0}\theta^i\sum_{j\geq 0}\theta^j-\sum_{i\geq 0}(\theta^i)^2\Big]\Big[\alpha d(2+a)\Big]-\sum_{i\geq 0}(\theta^i)^2\alpha(2+a)(1-d)\\
&= n(1-\alpha-w_B/y)+\sum_{i\geq 0}\theta^i(\alpha d)+\sum_{i\geq 0}\theta^i\Big[a+\alpha(2-d)-\Delta w/y\Big]\\
&\quad -\frac{1}{n}\sum_{i\geq 0}\theta^i\sum_{j\geq 0}\theta^j\alpha d(2+a)+\frac{1}{n}\sum_{i\geq 0}(\theta^i)^2\alpha d(2+a)-\sum_{i\geq 0}(\theta^i)^2\alpha(2+a)(1-d)\\
&= n(1-\alpha-w_B/y)+\sum_{i\geq 0}\theta^i\Big[a+2\alpha-\Delta w/y\Big]\\
&\quad -\frac{1}{n}\sum_{i\geq 0}\sum_{j\geq 0}\theta^i\theta^j\alpha d(2+a)-\sum_{i\geq 0}(\theta^i)^2\alpha(2+a)(1-d\frac{n+1}{n})
\end{aligned}$$

A.2. Partial land cultivation: The benchmark of a single farmer

Let us consider here the case in which the farmer prefers to left some land uncultivated. This can be an equilibrium outcome when the input seed prices are too high, given the congestion effect.

The farmer allocates a fraction θ^A of her land to crop A, a fraction θ^B to crop B, and leaves

$1-\theta^A-\theta^B$ uncultivated. Her profits are therefore, assuming $\theta^A+\theta^B<1$,

$$\Pi^F = \theta^A[(1+a)y(1-\alpha\theta^A)-w_A]+\theta^B[y(1-\alpha\theta^B)-w_B]$$

and they are maximum for

$$\theta^A = \frac{1}{2\alpha y}(y-\frac{w_A}{1+a}) \quad \text{and} \quad \theta^B = \frac{1}{2\alpha y}(y-w_B).$$

The initial assumption $\theta^A+\theta^B<1$ is satisfied for these values if and only if $y-\frac{w_A}{1+a}-y-w_B-2\alpha y<1$, that is, if and only if $\frac{w_A}{1+a}+w_B>2(1-\alpha)y$.

In that case, the land allocations indeed constitute an equilibrium for the farmer's problem, and we can compute the associated profit:

$$\begin{aligned}
\Pi^F &= \frac{1}{2\alpha y}(y-\frac{w_A}{1+a})\Big[(1+a)y\Big(1-\alpha\frac{1}{2\alpha y}(y-\frac{w_A}{1+a})\Big)-w_A\Big] \\
&\quad +\frac{1}{2\alpha y}(y-w_B)\Big[y\Big(1-\alpha\frac{1}{2\alpha y}(y-w_B)\Big)-w_B\Big] \\
&= \frac{1}{2\alpha}(y-\frac{w_A}{1+a})\Big[(1+a)\Big(1-\frac{1}{2y}(y-\frac{w_A}{1+a})\Big)-\frac{w_A}{y}\Big] \\
&\quad +\frac{1}{2\alpha}(y-w_B)\Big[1-\frac{1}{2y}(y-w_B)-\frac{w_B}{y}\Big] \\
&= \frac{1}{2\alpha}(y(1+a)-w_A)\Big[(1+a)(1-\frac{1}{2})-\frac{w_A}{2y}-\frac{w_A}{y}\Big]+\frac{1}{2\alpha}(y-w_B)\Big[(1-\frac{1}{2})(1-\frac{w_B}{y})\Big] \\
&= \frac{1}{4\alpha}(y(1+a)-w_A)\Big[(1+a)-\frac{w_A}{y}\Big]+\frac{1}{4\alpha}(y-w_B)\Big[1-\frac{w_B}{y}\Big] \\
&= \frac{1}{4\alpha y}\Big[\frac{(y(1+a)-w_A)^2}{1+a}+(y-w_B)^2\Big].
\end{aligned}$$

Lemma 6. *Assume that the farmer does not cultivate all the land she owns. She will choose to cultivate crop A on a fraction* $\theta^A(partial)=\frac{1}{2\alpha y}(y-\frac{w_A}{1+a})$ *of her land and crop B on a fraction* $\theta^B(partial)=\frac{1}{2\alpha y}(y-w_B)$*. This is an equilibrium if* $\frac{w_A}{1+a}+w_B>2(1-\alpha)y$*.*
Her profits under partial cultivation are $\Pi^F(partial)=\frac{1}{4\alpha y}\Big[\frac{(y(1+a)-w_A)^2}{1+a}+(y-w_B)^2\Big]$.

Full vs. partial cultivation. Let us now compare the profits made by the farmer for an interior equilibrium under full cultivation, with the profits made under partial cultivation. The difference in profits, that we denote $\Delta\Pi^F$ is equal to

$$\Delta\Pi^F = y(1-\alpha)-w_B+\frac{1}{4\alpha y}\Big[(y-w_B)^2+(1+a)(y-\frac{w_A}{1=a})^2+\frac{1}{2+a}((a+2\alpha)y-\Delta w)^2\Big].$$

This difference is increasing in y and decreasing in α.[16] It can only be negative, that is: partial cultivation can only be preferred, when w_B is large. However a large value for w_B may not be compatible with the farmer's participation constraint.

To summarize:

- Partial cultivation can be preferred only if w_B is large enough.
- Full cultivation becomes more likely to be chosen by the farmer if the base revenue y increase,
- or if the strength of the congestion effect α decreases.

Social welfare with potential partial cultivation The crop allocation that maximizes social welfare is $\theta^{A^{FB}} = \theta^{FB} = \frac{a+2\alpha}{2\alpha(2+a)}$ and $\theta^{B^{FB}} = 1 - \theta^{FB} = \frac{2\alpha(1+a)-a}{2\alpha(2+a))}$ under full cultivation.

Under partial cultivation, there is no scarcity effect (one can increase one crop's allocated land without reducing the other's). So allocations are independent from the different value of the two crops and depend only on the congestion effect associated to growing more of the crop. Maximizing social welfare under the assumption that $\theta^A + \theta^B < 1$ would yield $\theta^{A^{FB}}(partial) \equiv \frac{1}{2\alpha} = \theta^{B^{FB}}(partial)$. This solution is howevernot coherent with the initial assumption of partial cultivation unless $\alpha > 1$, which is not possible.

Lemma 7. *It is always socially optimal to cultivate the full available land area.*

A.3. Partial land cultivation with spatial externalities

Assume that farmers may choose to cultivate only a part of their land, under spatial externalities. The profits of farmer F^0, when she allocates θ_0^A to crop A and $\theta_0^B < 1 - \theta_0^A$ to crop B, are

$$\Pi^{F^0} = \theta_0^A\Big[(1+a)y\Big(1-\alpha((1-d)\theta_0^A + d\Theta_{-0}^A)\Big) - w_A\Big] + \theta_0^B\Big[y\Big(1-\alpha((1-d)\theta_0^B + d\Theta_{-0}^B)\Big) - w_B\Big]$$

where $\Theta_{-0}^K = \frac{1}{n}\sum_{j\neq 0}\theta_j^K$, for $K = A, B$.

The problem is separable in the two crops (given that the land size constraint is not binding here). The farmer's best response is to choose

$$\theta_0^A(\Theta_{-0}^A) = \frac{1}{1+a}\frac{(1+a)y(1-\alpha d\Theta_{-0}^A) - w_A}{2\alpha(1-d)} \quad \text{and} \quad \theta_0^B(\Theta_{-0}^B) = \frac{y(1-\alpha d\Theta_{-0}^B) - w_B}{2\alpha(1-d)}.$$

In a symmetric Nash equilibrium, we have $\theta_0^K = \Theta_{-0}^K = \frac{1}{n}\sum_{j\neq 0}\theta_0^K$, for $K = A, B$. This yields the

[16] We have $\frac{\partial \Delta\Pi^F}{\partial\alpha} = -\frac{4y}{2+a}((a+2\alpha)y - \Delta w)$ which is negative for an interior value of θ under full cultivation.

following land allocations under partial cultivation:

$$\theta^A(d) = \frac{y - \frac{w_A}{1+a}}{\alpha(2-d)y} \quad \text{and} \quad \theta^B(d) = \frac{y - w_B}{\alpha(2-d)y}.$$

These values indeed constitute an equilibrium with partial cultivation if $\theta^A(d) + \theta^B(d) < 1$. This is the case if and only if $\frac{w_A}{1+a} + w_B > (2(1-\alpha) + \alpha d)y$.

Lemma 8. *Assume that farmers do not cultivate all the land they own. The symmetric Nash equilibrium under spatial externalities entail cultivating crop A on a fraction* $\theta^A(d) = \frac{y - \frac{w_A}{1+a}}{\alpha(2-d)y}$ *of the land and crop B on a fraction* $\theta^B(d) = \frac{y - w_B}{\alpha(2-d)y}$*. This is an equilibrium if* $\frac{w_A}{1+a} + w_B > (2(1-\alpha) + \alpha d)y$*.*

Result 4. *The larger the strength of spatial externalities, d, the less likely it is that farmers will leave some land uncultivated.*

Because farmers underestimate the full impact of growing more of a crop on this crop's yield, under spatial externalities, they also underestimate the value of restricting the cultivated area in order to maintain yields.