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REGULAR ARTICLE

On application of the precautionary principle to ban GMVs: an evolutionary model of new seed technology integration

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Abstract

Since the 1990s, agri-biotech multinationals have introduced a radical innovation in the form of seeds derived from genetically modified plant varieties or GMVs. However, on the basis of the 'precautionary principle' that advocates ensuring a higher environmental protection through preventative decision-taking, many countries have banned the cultivation of GMVs within their territories. Thus, the objective of the present paper is to attempt to explore the rationale for application of the precautionary principle. This is done through development of an evolutionary model of farmers' technology choice incorporating intrinsic features of agriculture such as the technological obsolescence of seed varieties, impact of environmental degradation engendered by new seed technology adoption and farmers' compliance choice vis-à-vis sustainability guidelines. Further, instead of a unique representative farmer, two types of farmers are considered. The first type is driven by short term profit maximization, while the second type aims to be sustainable, by maximizing profit over the life time of the technology. Integrating the above elements and considering two possible rules for application of the precautionary principle, the paper explores the conditions under which the precautionary principle can be implemented. It demonstrates that, even under complete and perfect information the need to exercise such caution depends principally on four factors: the economic gains from GMVs, the possibilities for sustaining the production of the conventional variety in the post-GMV period via compliance, the distribution of farmers over types and the compliance-contamination burden.

Keywords GMV seed · Farmer heterogeneity · Technology obsolescence · Irreversibility · Evolutionary model · Precautionary principle · Ecology

JEL classification K32 · O30 · Q12 · Q15 · Q16

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1 Introduction

Worldwide, farmers are burdened with an ever-pressing need to increase productivity. This often drives them to apply more chemical inputs such as fertilizers and pesticides, which in turn lead to substantial environmental degradation and lower soil fertility. In response, since the 1990s, agri-biotech multinationals such as Monsanto, Dupont and Syngenta have introduced a radical innovation in the form of seeds derived from genetically modified plant varieties or GMVs. With desirable traits such as pest resistance, GMVs reduce the need for agrochemicals and lessen soil and water contamination. However, many countries, notably in Europe, have banned the cultivation of GMVs within their territories on the basis of the 'precautionary principle' that advocates taking preventative measures to tackle potential threats to society. In this setting, the objective of the present paper is to attempt to explore the rationale for application of the precautionary principle to ban the diffusion of innovations such as GMVs.

The precautionary principle, which forms a part of Article 191 of the Treaty on the Functioning of the European Union, is to enable a policy response to economic activity that can pose a possible danger to human, animal or plant health, or the environment. It advocates that whenever scientific data does not permit a complete evaluation of risk, the precautionary principle may be applied as a preventive measure to curb the concerned economic activity. In other words, if an objective evaluation of a phenomenon, product or process indicates that it may pose a threat to living beings and/or the environment, the scientific uncertainty is high and/or the evaluated risk is elevated, then the precautionary principle can be evoked to address the concerned challenge.

While the precautionary principle in general is accepted worldwide, it is interpreted differently in different countries. For instance, with respect to new crop plant varieties, Europe follows a process based regulatory framework wherein the techniques used to create the innovation also determine the form of regulation, in contrast to a product-based regulatory framework, followed in the USA and Canada, which focuses only on the inherent risk of the final product. The precautionary principle can also be reinterpreted as investment in monitoring and generating knowledge about a new technology that can have unintended consequences (Miller and Engemann 2019). However, such a tailored and rationalized application assumes the existence of monitoring, regulatory and scientific capabilities, which are inadequate in many countries, especially developing ones (Adenle et al. 2018). Such diverse policy stances stem from differing scientific capabilities, regulatory prowess and societal concerns over the medium term and/or long term returns and risks of GMV.

It is important to review the precautionary principle discourse anew with respect to agriculture, because the agri-biotechnology revolution is scaling new heights with gene editing. New genome editing techniques such as 'zinc finger nucleases', 'TALENS' and 'CRISPR Cas9' allow scientists to change, delete or replace DNA more easily than ever before. It is expected that they would revolutionize agriculture and enable increases in yield, nutritive value and pest resistance, while making plants more robust to deteriorating agroecological conditions and climate change (Voytas and Gao 2014). While the final product may be even closer to the original due to gene editing, the risks of unpredictable consequences related to the process of new plant variety creation through gene editing remain similar (Caplan et al. 2015).

Presently, the European stance is supported by studies confirming that diffusion of GMVs has led to genetic contamination of conventional plants and the emergence of super weeds with increased resistance to herbicides (Gilbert 2013). It takes the perspective of Weaver and Morris (2005) who explain that while such risks of genetic contamination are present with conventional varieties also, it is essentially the process of creation of GMVs that increases the risk of unpredictable consequences. They point out that genetic modification is often to enable the targeted plant to produce proteins that they would not otherwise produce, but this creates a risk that the GMVs may also produce proteins that were not intended, and such effects may be manifested with a time lag longer than that required for safety tests.

In sum, the application of the precautionary principle to ban a new technology is founded upon the threats posed by its possible but uncertain and irreversible impact (Sandin 1999). We aim to make a contribution to this discourse in the context of GMVs by demonstrating that even in the absence of informational constraints, the precautionary principle may be called upon under certain conditions pertaining to the economic gains opened up by the new technology versus its ecological impact. For this, we develop an evolutionary model of farmer behavior. There are two types of farmers, differentiated by their criteria for new technology adoption. The first type is driven by short term profit maximization, while the second type aims to maximize profit over the life time of the technology. Further, agriculture specific features that are under examined in innovation studies are integrated. These include the natural built-in technological obsolescence of seeds, the environmental degradation engendered by new seed technology adoption, and farmer choice vis-à-vis compliance with sustainability guidelines. Then the rationale for the application of the precautionary principle is explored.

The present paper makes a twofold contribution to the existing literature. First, it provides an explanation for why some countries have opted for GMVs, whereas others have refused them. At present, while the literature provides justification for one or the other stance, there is no unifying theoretical framework that demarcates the contexts under which each stance can be rationalized. The model developed in this paper is an attempt to fill this gap. It incorporates agriculture specific features such as possibilities for contamination and irreversibility, the role of science, compliance burden, farmer types and farmer choices, in order to highlight the nature of their influence on the applicability of the precautionary principle. It demonstrates that even if uncertainty were to be absent, the nature of the context-specific trade-offs between the economic opportunities and ecological impact may justify the implementation of the precautionary principle in the corresponding regions.

Second, this work also adds to the literature on new technology adoption in agriculture by introducing farmer heterogeneity and studying the consequences of technology-compliance choices on Nature. By Nature, we refer to the local ecological conditions or “the state of ecological systems, which includes their physical, chemical, and biological characteristics and the processes and interactions that connect them…. An ‘ecological system’ (ecosystem) is a biological community consisting of all the living organisms (including humans) in a particular area and the nonliving components, such as air, water, and mineral soil, with which the organisms interact.” (https://www.epa.gov/report-environment/ecological-condition). This approach is distinct from the majority of papers on agricultural innovations, which consider a unique representative farmer and focus on the impact of new technology introduction on total factor productivity.

The remainder of this paper is organized as follows. Section 2 presents a brief survey of prominent findings of the relevant literature. Section 3 contains the evolutionary model. Section 4 presents its results and Section 5 discusses them in the light of the rationale of the precautionary principle. Section 6 concludes.

2 Precautionary principle, new technology integration in agriculture and Nature

> There is an extensive literature on the rationale for application of the precautionary principle. Starting with Henry (1974) and Arrow and Fisher (1974), it has been demonstrated that even for risk neutral agents, if there is a possibility of negative irreversible outcomes, then it is worthwhile to wait to gain more information about the outcomes. A decision takes on the characteristics of irreversibility to the extent that it shrinks the space of available options in present or future. In other words, an irreversible decision is one which, if taken, results in not being able to exercise (for a long time or forever) some option that was available earlier. Henry (1974) put forward the link between irreversibility, uncertainty and information explicitly in a proposition called the 'irreversibility effect'. This states that an irreversible decision that yields better payoffs as compared to a reversible decision under a particular situation, may with more information (and under the same situation) yield lower payoffs than the reversible decision. 'More information' here connotes an increased capability to anticipate with greater accuracy and precision the state of the world tomorrow. Through different analyses these authors arrived at the same normative conclusion, that in the face of anticipated increases in information, it might be better to take a reversible rather than an irreversible decision (Gollier et al. 2000). For instance, the precaution exercised against GMVs stems from the possible irreversible nature of their introduction into the ecology.

At the same time, it is recognized that the existence of ecological hazards per se cannot be used as a reason to stop innovations altogether (Giampietro 2002). For example, in addition to irreversibility, the future strategic flexibility provided by an option must be examined, and if the gain from expected flexibility can compensate for the expected losses, then an irreversible decision might be welfare enhancing (Ramani and Richard 1993). Firms whose innovations pose environmental risk can be nudged to acquire more information and voluntarily take measures to limit potential damages (Orset 2014). Given the diversity of contexts, applying the precautionary principle in a one size fits all approach may not be efficient and stand in the way of welfare enhancing initiatives (Immordino 2003).

The application of the precautionary principle to the European risk regulation of genetically modified crops has led to a better understanding of the diverse cognitive framing of the relevant uncertainties corresponding to different framing visions for agriculture (Levidow 2001). As such, researching the ecological basis for sustainable agriculture wherein the needs of the present vis-à-vis agriculture are met without compromising the ability of future generations to meet their own needs is a recent phenomenon (Gliessman 1990). It has been fuelled by the realization of the negative impact of the Green Revolution,[1] which while saving many developing countries from famine, also led to degradation of the soil and groundwater resources, given its water intensive and chemicals intensive production technology (Murgai et al. 2001) and caused a significant loss of bio-diversity (Shiva 1989). Moreover, recent 'accidents' such as 'Starlink', in 2000, whereby many food products containing genetically modified corn that had not yet been approved for human consumption were recalled, seem to be nudging policy makers to hold a more cautious view (Prakash and Kollman 2003). In developing countries also, controversies about GMVs are centered on these possible negative ecological consequences rather than immediate economic effects (Ramani and Thutupalli 2015). Scholars note that effective systemic dialogue with all societal stakeholders about the impact of new technology will help to minimize the risk of applying the precautionary principal wrongly, thereby foregoing valuable opportunities that may be opened with application of the new technology (Ishii 2018; Bogner and Torgersen 2018; Pant 2019).

Such controversies have also led to the recognition of farmer heterogeneity in terms of preferences for ecological sustainability that have been corroborated by empirical studies in the form of choice-experiments, in different parts of the world and for different solution packages. Innovation for the agriculture sector can take the form of a combination of improved inputs such as seeds, fertilizers or pesticides or mechanical equipment or new routines i.e. novel agro-ecological practices. With respect to new technology adoption in agriculture, there is a very extensive literature on the determinants of their economic impact in terms of higher profits and/or improved factor productivity (e.g. Sunding and Zilberman 2001; Feder and Umali 1993). The relationships between the nature and magnitude of innovation rent and systemic features such as actor-strategy, policy design and contextual factors (Klerkx et al. 2012), the nature of markets (David 1975), farmer and farm characteristics (Feder et al. 1985), public investment (Hayami and Ruttan 1971) and a combination of the above (Szirmai 2005) have been highlighted. That said, starting from the seminal work of Griliches (1957), most scholars assume that for farmers, the main driver of adoption of new technology in agriculture is the expectation of higher profit it carries in its wake.

In the existing literature on new technology adoption in agriculture, what is striking is that barring exceptions, Nature or ecology is taken as given. Turning to these exceptions, there are a few articles that highlight how Nature is impacted by farmer technology choices. Noailly (2008) develops a model where farmers in a region choose their pesticide dosage, which in turn determines the evolution of resistance to the pesticide in the pest. Farmers can choose between a low or high level of pesticide, the higher the sum of the pesticides use in the region, the higher is the resistance of the pest to the same. When pests develop resistance to the pesticide, their population grows and lowers the revenues of all farmers.

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[1] The Green Revolution was a technology package involving improved quality seeds, controlled irrigation and measured doses of fertilizers. Created by the agricultural scientist Norman Borlaug, these modern variety seeds were a new dwarf variety of wheat, with "short legs" that could support a greater amount of wheat grains on any stalk. The hybrid dwarf variety clearly yielded more than the conventional varieties of wheat of that time. While the Green Revolution heralded a veritable increase in yields with respect to cereals, and saved developing countries, especially India, from famine, it led to very intensified use of water and application of agro-chemicals causing soil degradation and groundwater depletion.

Noailly (2008) shows that there can be many initial configurations under which the pesticide use can converge to its maximal level, while a lower use could yield higher incomes for all farmers. Thus, as a policy recommendation, they invoke the precautionary principle whereby the natural environment is exploited less than it could be.

It would seem that the main reason for the non-inclusion of Nature as an actor in the innovation system is because unlike economic actors who are driven by objectives set by self-interest, Nature's strategy is not governed by standard economic rationale, but by biophysical laws as responses to the strategies of other economic players, especially farmers. Nature does not seek to optimize, i.e. to maximize self-payoffs vis-à-vis the moves of other players, but it responds with passive actions of self-organization (or changes to itself) as dictated by universal biophysical laws to the strategies of economic players. However, given the complexity of the ecological system, Nature's responses constitute uncertainty for the economic actors. While the short run responses of Nature can be forecast using the existing scientific knowledge base to some extent, there is real scientific uncertainty about the long term consequences of adoption of new techniques in agriculture. That said, the evolutionary response of Nature to achieve biophysical efficiency is analogous to the evolutionary behavior of economic actors trying to achieve economic efficiency. We thus propose that Nature must also be considered as a non-economic actor in the agriculture innovation system.

Incorporating Nature, we further integrate the evolutionary and systemic features associated with agriculture. We take into account the fact that farming practices such as application of agrochemicals and utilization of water impact Nature. For instance, farmers can decide whether or not to invest in preserving Nature by preserving soil fertility, minimizing water contamination, nurturing bio-diversity etc. In most countries, farmers receive guidance from a variety of agriculture extension services on how this can be achieved. The mission of the latter is to transfer useful knowledge generated by public and private research to farmers and educate and accompany them to improve their livelihoods. While it is well known that national agriculture extension services were responsible for the success of the Green Revolution, with the acceptance of economic liberalization, there is a sea of change. Worldwide, public sector extension services are increasingly being supported or replaced by public-private partnerships or private providers (Anderson and Feder 2004).

In the context of GMV production, farmers also come under regulators' purview. For instance, there are GM crops, called Bt crops, containing genes from the bacterium *Bacillus thuringiensis*, which express a toxin that kills insect pests popularly known as bollworms. When bollworm pests attack a Bt crop, they are killed by the toxin. As acreage under Bt crops increases, there is a risk that bollworms might develop resistance to the toxin. To minimize this, farmers are requested to plan a refuge of non-Bt crop around Bt crop fields to ensure the survival and maintenance of susceptible insect populations on the non-Bt crop. To date, there has been regulatory swings vis-à-vis refuge. In the USA, for example, planting of refuges around Bt corn was initially voluntary and then mandatory, with clear definitions of accountability of farmer and seed company (Huang et al. 2011). In developing countries such as India, on the other hand, planting of refuges around Bt cotton is voluntary and it has been noted that there is mainly non-compliance (Singla et al. 2013). By and large, worldwide, for farmers, compliance to sustainability guidelines is voluntary rather than mandatory.

We now turn to the model.

3 Farmer technology and compliance choices: a model

3.1 Systemic setting

Three main actor-groups are considered, namely farmers, Nature and the regulator. Both the regulator and Nature are taken to be non-strategic in the sense that they do not align their strategies to maximize personal payoffs.

At the start, all farmers have access to only conventional variety seeds. Then a new genetically modified variety or GMV seed is submitted to the regulator for possible introduction into the market. The GMV is an innovation proposed in the system. The GMV comes along with a set of compliance measures to contain environmental degradation once cultivated. Input and output prices are the same for both seed varieties. Finally, all actors, farmers and the regulator have perfect and complete information.

Farmer types and strategy space The region contains farmers who can be one of two types: type 1, who is 'short term profit driven' or type 2, who is 'sustainability driven'. They start with the same amount and quality of endowments. At every time period t, type 1 farmer strives to maximize profit at time t, while type 2 farmer seeks to maximize profit over the lifetime of possible technological choices starting from time t. Let the technology or seed choice of farmer i at time t be given by $s_i^t = \{0, 1\}$ such that, if $s_i^t = 1$, it implies that the GMV seed has been chosen for cultivation; and if $s_i^t = 0$, the conventional variety has been picked by farmer i. At every planting season t, each farmer i also decides on the allocation of his land between two seed technologies, the conventional variety and the GMV. If a farmer i opts for GMV at time t, then he has to decide whether or not to comply with sustainability guidelines, i.e. choose between $c_i^t = 1$ and $c_i^t = 0$. Whatever properties are specified for farmer i hold similarly for farmer j and so we drop the farmer index j whenever possible.

The above framing reflects heterogeneous farmer preferences that have been observed vis-à-vis land management practices to preserve the quality of local water sources in the UK (Beharry-Borg et al. 2013), subsidy schemes for pesticide-free buffer zones in Denmark (Christensen et al. 2011), design of agri-environment schemes in UK (Aslam et al. 2017) and across Europe, (Ruto and Garrod 2009) and crop rotation to preserve soil fertility in Malawi (Ortega et al. 2016) etc.

Another way of understanding the difference between the two farmer types is in terms of their rate of discount d of future payoffs. The profit driven farmer discounts future payoffs very highly, at $d = 1$; while the sustainability driven farmer does not discount future payoffs, at $d = 0$. Considering d to be either 0 or 1 also permits analytical tractability, which would not be possible otherwise.

Compliance-contamination burden To preserve the state of Nature or local ecological conditions, the GMV comes with voluntary compliance measures that involve a fixed cost. In keeping with the discussion of the previous section, compliance refers to costly agro-ecological practices that maintain soil fertility over the long run. Let the compliance burden per unit of land cultivated with GMV be given by B.

Furthermore, whenever a farmer adopts GMV and does not comply, he might decrease the profit of the neighboring farmer through contamination. While, in reality, contamination would depend on individual farmer type and the number and type of his neighbors, in order to construct a tractable analytical model, we consider each farmer to be affected only by one neighbor. Thus, in what follows, we consider two neighboring farmers i and j who might be both of type 1 (i.e. profit driven) or both of type 2 (i.e. sustainability driven) or mixed (i.e. one profit driven, one sustainability driven).

Let the additional contamination burden to farmer i at time t by his neighbor j be given by $s_j^t B\theta\left(1-c_j^t\delta\right)$, where θ is the degree of contamination and δ is the efficiency of existing science to preserve the original state of Nature through compliance. Let $\theta \in [0, 1]$ and $\delta \in]0, 1[$. For example, if the neighbor cultivates GMV without complying then there is an additional loss in profit due to contamination given by $B\theta$. On the other hand, if the neighbor complies then the profit loss due to contamination is less at $B\theta(1-\delta)$, with the decrease depending on the efficiency of science δ.

Then, the compliance-contamination burden per unit of land of farmer i at time t, $B_i^t = B_i\left(s_i^t, c_i^t, s_j^t, c_j^t, \theta, \delta\right)$, is given by Eq. (1) and illustrated in Table 1.

$$B_i^t = B_i\left(s_i^t, c_i^t, s_j^t, c_j^t, \theta, \delta\right) = B\left(s_i^t c_i + \theta s_j^t\left(1-c_j\delta\right)\right). \tag{1}$$

For ease of notation, in what follows we will refer to the compliance-contamination burden for farmer i when he adopts GMV without compliance at time t as $B_i\left(1, 0, s_j^t, c_j^t, \theta, \delta\right) = B_i^{gm}(t)$. Similarly, the burden for GMV adoption with compliance will be given by $B_i\left(1, 1, s_j^t, c_j^t, \theta, \delta\right) = \widehat{B}_i^{gm}(t)$ and the burden for farmer i when he does not adopt GMV is given by $B_i\left(0, 0, s_j^t, c_j^t, \theta, \delta\right) = B_i(t)$. This short hand will be used only whenever possible.

Ecological impact The state of Nature is given by the ecology index, which captures the fit of the seed to the ecological conditions at time t and determines farmland productivity. At the start $t = 1$, the ecology index is the same for all farmers, being ξ. But, over time, it evolves differently for each farmer according to his seed and compliance choices. The evolution of the ecology index of farmer i over time, $\xi_i(t)$, is determined by the interaction between the seed and compliance choices of the farmer and Nature as:

Table 1 Compliance-contamination cost burden matrix

Farmer i, Farmer j	$s_j = 1 =$ gmv; $c_j = 0 =$ non-compliance	$s_j = 1 =$ gmv; $c_j = 1 =$ compliance	$s_j = 0 =$ conventional
$s_i = 1 =$ gmv; $c_i = 0 =$ non-compliance	$-\theta B, -\theta B$	$-B\theta(1-\delta), -B(1+\theta)$	$0, -\theta B$
$s_i = 1 =$ gmv; $c_i = 1 =$ compliance	$-B(1+\theta), -B\theta(1-\delta)$	$-B(1+\theta(1-\delta)),$ $-B(1+\theta(1-\delta))$	$-B, -B\theta(1-\delta)$
$s_i = 0 =$ conventional	$-\theta B$, 0	$-B\theta(1-\delta), -B$	0, 0

$$\xi_i(t) = \xi_i(t-1)\psi(t)^{\left(s_i^{t-1}\right)\left((1-\delta)^{c_i^{t-1}}\right)}. \tag{2}$$

Let $\psi(t) \in]0, 1[$ represent the yearly degradation of the ecology index due to the use of GMV such that the resulting function $\xi_i(t)$ is a downward sloping concave function. Recall that whenever compliance is observed with GMV cultivation, δ indicates the efficiency of science to preserve the state of Nature. According to Eq. (2), if farmer i cultivates the conventional variety (i.e $s_i^{t-1} = 0$) or observes compliance when cultivating a GMV ($s_i^{t-1} = 1$ and $c_i^{t-1} = 1$) and science is very effective, i.e. $\delta \to 1$, then there is practically no degradation of the ecological conditions.

This is in keeping with acknowledged findings that the 'vigor' of the seed falls regularly and over a span of years, the plant also becomes vulnerable to new pests and pathogens, leading to diminishing returns in yield (Peng et al. 1999; Swanson 2002; Peng et al. 2010). Nature also responds to the agro-ecological practices of the farmers in terms of their technology and compliance choices according to bio-physical and biochemical laws in a cumulative manner (Van der Werf and Petit 2002). Finally, as Tisdell (2010) explains, GMVs designed by human ingenuity independently of natural environmental forces are more fragile than conventional varieties and are likely to lose their ecological fitness at a faster rate. Thus, by Eq. (2), whenever GMVs are cultivated, the ecology index falls, while conventional variety cultivation does not lower it.

Irreversibility of ecological impact via GMV One of the issues raised with respect to GMVs is the possible irreversible impact they may engender. Hence, we consider a reversibility index $\gamma \in [0, 1]$ where $\gamma = 0$ indicates total irreversibility and any $\gamma > 0$ means some degree of reversibility to move back to cultivation of the conventional variety after the GMV has been adopted. Let $\bar{s}^t$ be an indicator of the past cultivation of GMV i.e. $\bar{s}^t$ is either 1 or 0. Then, at time t, if $\bar{s}^t = 1$, i.e. the farmer has cultivated GMV prior to time t and he switches back to the conventional variety, then he will get only γ of the profit associated with cultivation of the conventional variety. We detail this further in the next section.

Role of the regulator Let the time period 0 to T be the lifetime of a conventional seed. Similarly, let the time periods from 0 to $\widehat{T}^{gm}$ and T^{gm} be the lifetime of GMV with and without compliance, with $\overline{T} = Max\left(T^{gm}, \widehat{T}^{gm}, T\right)$. With respect to the regulator, the focus is on his choice as to whether or not allow the commercialization of GMV at $t =$ 1. The objective of the regulator is to safeguard of livelihoods of the farming community.

3.2 Properties of profit functions (net of production costs)

We start by defining the profit functions of farmers net of production costs and distinguish these from farmer payoffs obtained by further subtracting their compliance-contamination burden.

For a configuration $s_i^t, c_i^t, s_j^t, c_j^t, \xi_i^t, \delta, \theta, \gamma, \bar{s}_i^t$ let the yield maximizing inputs combination for farmer i at time t be x_i. Let the input prices and output price be the same for both the varieties and unchanging over time, being given by w and p, respectively. Let the production or yield function for the GMV be given by f^{gm} and, for the conventional variety, by f. They are common to both farmers as they are assumed to have the same knowledge base. The agricultural yield functions is assumed to be strictly concave over inputs x_i, and, as mentioned earlier, increase with ecology index ξ_i. Then the profit net of production costs of farmer i at time t for GMV or conventional variety cultivation is given respectively by:

$$\begin{aligned} &pf^{gm}(x_i^{gm}(t),\xi_i(t)){-}wx_i^{gm};\\ &pf(x_i(t),\xi_i(t)){-}wx_i. \end{aligned} \tag{3}$$

The yields f^{gm} and f depend on the state of ecology, $\xi_i(t)$ which in turn depends on the farmer's history of technology and compliance choices. For any configuration, $s_i^t, c_i^t, s_j^t, c_j^t, \xi_i^t, \delta, \theta, \gamma, \overline{s}_i^t$ let the profit function per unit land of farmer i at time t on land allocated to conventional variety and GMV be $\pi_i(t)$, $\pi_i^{gm}(c_i, t)$ respectively. For notational convenience, let $\pi_i^{gm}(0, t) = \pi_i^{gm}$ refer to GMV cultivation without compliance and let $\pi_i^{gm}(1,t) = \widehat{\pi}_i^{gm}(t)$ refer to GMV cultivation with compliance. By construction all these profit functions are downward sloping and concave over time. Let the total quantity of land be normalized to 1. Then from the definition of $\xi_i(t)$ two properties of the profit functions (given by Eqs. (4) and (5)), which are independent of the strategies of neighboring farmer, can be noted.

Advantages from compliance are directly proportional to the prior time period over which compliance has been practiced. Let $\widehat{\pi}_i^{gm}\left(t|t_{start}=\widetilde{t}\right)$represents the profit of a late complier who begins adopting guidelines at time $\widetilde{t}>0$. Then:

$$\widehat{\pi}_i^{gm}\left(t|t_{start}=\widetilde{t}\right) > \widehat{\pi}_i^{gm}\left(t|t_{start}=\overline{t}\right) for\ \widetilde{t} < \overline{t} \leq t. \tag{4}$$

If the GMV engenders significant environmental degradation such that its yields fall as compared to those of the conventional technology, then with prior compliance this would occur at a later time; or:

$$\text{If at time } T*,\ \ \pi_i^{gm}(T*) = \pi_i(T*) \Rightarrow \widehat{\pi}_i^{gm}\left(T*|t_{start}=\overline{t}\right) > \pi_i(T*) for\ \overline{t} < T*. \tag{5}$$

3.3 Properties of payoff functions

Now, as GMVs come with a compliance-contamination burden, this value has to be deducted from the production profit to arrive at payoffs. Thus, the payoff of farmer i at time t when he cultivates GMV without compliance is $\pi_i^{gm}(t){-}B_i^{gm}(t)$; with compliance it is $\widehat{\pi}_i^{gm}(t){-}\widehat{B}_i^{gm}(t)$and, for conventional variety cultivation, it is $\pi_i(t) - B_i(t)$. Then, given a compliance burden, B, a rate of contamination, θ, the efficiency of science, δ, a reversibility index γ and prior cultivation of GMVs, $\overline{s}_i^t$, the payoffs to farmer i at time t will be given by:

$$\left(s_i^t\cdot\left(\pi_i^{gm}\left(c_i^t,t\right)-B_i\left(1,c_i^t,s_j^t,c_j^t,\theta,\delta\right)\right)\right)$$
$$+\left(\left(1-s_i^t\right)\cdot\left(\pi_i(t)\left(\gamma\overset{t}{\overline{s}}_i+\left(1-\overset{t}{\overline{s}}_i\right)\right)-B_i\left(0,0,s_j^t,c_j^t,\theta,\delta\right)\right)\right). \qquad (6)$$

The first term models returns from GMV. The second term indicates that once the GMV is adopted, the profit from cultivation of conventional variety also depends on the degree of reversibility. For instance, if $\overline{s}_i^t = 1$, i.e. the land had been used to cultivate GMV in a previous time period, then the returns to the conventional variety from the next period onwards will be $\gamma(\pi_i - B_i)$, where γ is the index of reversibility. This payoff structure is further illustrated in Table 2.

Three assumptions, A1-A3 based upon the findings of the literature further define the properties of the payoff functions[2].

A1: When a GMV seed is introduced, it is a viable alternative to the conventional one with or without compliance. The GMV yields high enough yields to bear any own compliance burden and any imposed through contamination from a neighboring farm:

$$\pi_i^{gm}(t)-B_i^{gm}(t) > \pi_i(t)-B_i(t) \;\text{ and }\; \widehat{\pi}_i^{gm}(t)-\widehat{B}_i^{gm}(t) > \pi_i(t)-B_i(t) \;\text{ at }\; t=1. \qquad (7)$$

Empirical studies on the economic impact of GMVs (Areal et al. 2013; Carpenter 2010) confirm its higher profit as the main reason for its commercial success and this is also confirmed by reports on the ‘Global Status of Commercialized Biotech/GM Crops’ (ISAAA 2018).

A2: However, for GMV seeds, sustainability guidelines ensure higher cumulative payoffs for farmer *i* when he practices compliance from the start rather than from time $\widetilde{t} > 1$whatever the strategies chosen by the neighboring farmer:

$$\sum_{t=1}^{T^{gm}}\left(\widehat{\pi}_i^{gm}(t)-\widehat{B}_i^{gm}(t)\right) > \left(\sum_{t=1}^{\widetilde{t}-1}\pi_i^{gm}(t)-B_i^{gm}(t)+\sum_{t=\widetilde{t}}^{T^{gm}}\left(\widehat{\pi}_i^{gm}(t)-\widehat{B}_i^{gm}(t)\right)\right). \qquad (8)$$

A3: For farmer *i*, compliance lowers returns at the start, as it involves a fixed cost. Then as ecology gets less damaged, it yields higher returns, implying there exists a time T_1 beyond which returns from compliance are higher, for all farmer *j*’s strategy profile histories:

$$\begin{aligned}\pi_i^{gm}(t)-B_i^{gm}(t) &> \widehat{\pi}_i^{gm}(t)-\widehat{B}_i^{gm}(t) \text{ for } t < T_1;\\ \text{but } \pi_i^{gm}(t)-B_i^{gm}(t) &< \widehat{\pi}_i^{gm}(t)-\widehat{B}_i^{gm}(t) \;\text{ for } t > T_1.\end{aligned} \qquad (9)$$

Identification of contamination by GMVs, its measurement and its containment are subjects of scholarly enquiry (Ceddia et al. 2007, 2009; Belcher et al. 2005; Friesen et al. 2003). Further, the impact of cultivation of GMV and contamination depends on soil conditions of farmlands, ecological conditions, plant variety, spatial arrangements of lands, their sizes etc.

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[2] Interested readers can obtain examples of precise functional forms of the profit and payoff functions that satisfy these properties from the authors.

Table 2 Payoff matrix of farmers at time *t*

Farmer i, Farmer j	$s_j = 1 = $ gmv; $c_j = 0 = $ non-compliance	$s_j = 1 = $ gmv; $c_j = 1 = $ compliance	$s_j = 0 = $ conventional;
$s_i = 1$ $c_i = 0$	$\pi_i^{gm}(t) - B\theta$, $\pi_j^{gm}(t) - B\theta$	$\pi_i^{gm}(t) - B\theta(1-\delta)$, $\widehat{\pi}_j^{gm}(t) - B(1+\theta)$	$\pi_i^{gm}(t)$, $\gamma\overline{s}_j^t\pi_j(t) + \left(1-\overline{s}_j^t\right)\pi_j(t) - \theta B$
$s_i = 1$ $c_i = 1$	$\widehat{\pi}_i^{gm}(t) - B(1+\theta)$, $\pi_j^{gm}(t) - B\theta(1-\delta)$	$\widehat{\pi}_i^{gm}(t) - B(1+\theta(1-\delta))$, $\widehat{\pi}_j^{gm}(t) - B(1+\theta(1-\delta))$	$\widehat{\pi}_i^{gm}(t) - B$, $\gamma\overline{s}_j^t\pi_j(t) + \left(1-\overline{s}_j^t\right)\pi_j(t) - B\theta(1-\delta)$
$s_i = 0$	$\gamma\overline{s}_i^t\pi_i(t) + \left(1-\overline{s}_i^t\right)\pi_i(t) - \theta B$, $\pi_j^{gm}(t)$	$\gamma\overline{s}_i^t\pi_i(t) + \left(1-\overline{s}_i^t\right)\pi_i(t) - \theta B(1-\delta)$, $\widehat{\pi}_j^{gm}(t) - B$	$\gamma\overline{s}_i^t\pi_i(t) + \left(1-\overline{s}_i^t\right)\pi_i(t)$, $\gamma\overline{s}_j^t\pi_j(t) + \left(1-\overline{s}_j^t\right)\pi_j(t)$

Assumptions 2 and 3 reflect the scientific rationale of compliance measures such as planting a refuge around a field of GMVs (Reisig and Kurtz 2018; Tabashnik and Carrière 2017; Jin et al. 2015; Catarino et al. 2015; Tabashnik et al. 2008). The purpose of refuges is twofold. First, it is to delay build-up of resistance in the GMVs. Second, it is to prevent the emergence of insect species that are not susceptible to the expressed toxin, which can develop into secondary pests (Lu et al. 2010). Field outcomes documented by scholars confirm that refuge strategy, namely a generous border of non-GMV host plants around GMV fields can substantially address the above risks, and yield better performance in the long run (Anderson et al. 2019). Thus, we assume that complying with guidelines will protect farmers' livelihoods over the lifetime of the technology.

3.4 Game setting

Starting from time $t = 1$, farmers have to decide between GMV or conventional variety and, in the case of the former, also choose whether or not to comply. Recall that $\overline{s}^t$ is simply an indicator function of past cultivation of GMV. Suppose $\prod_{i=profit}^{t}(.)$ is the payoff of a type 1 profit driven farmer i at time t. Then, his objective at time t is to maximize immediate profit as given below:

$$\begin{gathered}\underset{s_i^t, c_i^t}{Max} \prod_{i=profit}^{t}\left(s_i^t, c_i^t, s_j^t, c_j^t, \theta, \delta, \overset{t}{\overline{s}_i}\right) \text{ where} \\ \prod_{i=profit}^{t}(\cdot) \\ = \left[\left(s_i^t \cdot \left(\pi_i^{gm}\left(c_i^t, t\right) - B_i\left(1, c_i^t, s_j^t, c_j^t, \theta, \delta\right)\right)\right) + \left(\left(1 - s_i^t\right) \cdot \left(\pi_i(t)\left(\gamma \overset{t}{\overline{s}_i} + \left(1 - \overset{t}{\overline{s}_i}\right)\right) - B_i\left(0, 0, s_j^t, c_j^t, \theta, \delta\right)\right)\right)\right]\end{gathered} \tag{10}$$

Let $\prod_{i=sust}^{t}(.)$ be the payoff of a type 2 sustainability driven farmer i at time t. In this case, the farmer's objective at time t is to maximize profit over the lifetime $\overline{T} = Max\left\{T, T^{gm}, \widehat{T}^{gm}\right\}$ by choosing the optimal sequence s_i^z, c_i^z for $z = t, t+1, \ldots, \overline{T}$; i.e.:

$$\begin{gathered}\underset{s_i^z c_i^z \text{ for } z=t,t+1,\ldots,\overline{T}}{Max} \prod_{i==sust}^{t}\left(s_i^t, c_i^t, s_j^t, c_j^t, \theta, \delta, \overset{t}{\overline{s}_i}\right); \text{where} \\ \prod_{i=sust}^{t}\left(s_i^t, c_i^t\right) \\ = \sum_{z=t}^{\overline{T}}\left[s_i^z \cdot \left(\pi_i^{gm}(z) - B_i\left(1, c_i^z, s_j^z, c_j^z, \theta, \delta\right)\right) + \left(\left(1 - s_i^z\right) \cdot \left(\pi_i(z)\left(\gamma \overset{z}{\overline{s}_i} + \left(1 - \overset{z}{\overline{s}_i}\right)\right) - B_i\left(0, 0, s_j^z, c_j^z, \theta, \delta\right)\right)\right)\right]\end{gathered} \tag{11}$$

A Nash equilibrium of the above dynamic game is an evolutionary trajectory of strategy profiles of farmer pairs i and j or $\left(S_i^t, C_i^t, S_j^t, C_j^t\right)$ for every t where $1 \le t \le \overline{T}$ such that for every farmer i the Nash equilibrium strategy profile $\left(S_i^t, C_i^t, S_j^t, C_j^t\right)$ satisfies:

$$\prod_{i=profit}^{t}\left(S_i^t, C_i^t | S_j^t, C_j^t\right) \ge \prod_{i=profit}^{t}\left(S_i^t, c_i^t | S_j^t, C_j^t\right) \text{ for all possible } \left(s_i^t, c_i^t\right) \text{ at time } t;$$

$$\prod_{i=sust}^{t}\left(S_i^t, C_i^t | S_j^t, C_j^t\right) \ge \prod_{i=sust}^{t}\left(S_i^t, c_i^t | S_j^t, C_j^t\right) \text{ for all possible } \left(s_i^t, c_i^t\right) \text{ at time } t.$$

Similarly for farmer *j*. Do such Nash equilibrium strategies exist? We attempt to answer this question in the next section.

4 Co-evolutionary dynamics: Discussion of results

We start with an observation on compliance choices.

Result 1: On compliance choices

1.1 Whenever a profit driven farmer adopts GMV, his dominant strategy is to start without compliance and then comply after a time, say T_1.

1.2 Whenever a sustainability driven farmer adopts GMV, his dominant strategy is to comply from the start.

Proof: 1.1. From Table 1, for any farmer, the contamination-compliance burden is greater when compliance is observed than not, whatever his neighbor's strategies. By assumption 3, a profit driven farmer *i* would start without observing compliance, and beyond time period T_1, as the ecological conditions get eroded, he would begin complying. By Table 2, clearly the time he starts complying will be later if his neighbor is a sustainability driven farmer as his compliance-contamination burden will be less then. □.

1.2. Suppose the sustainability driven farmer *i* adopts GMV at $t = 1$. By assumption A3 (or Eq. 9) on this land, compliance yields higher payoff each period beyond time T_1. As the life time of the GMV cannot decrease with compliance, i.e. $\widehat{T}^{gm} \geq T^{gm}$, assumption 3 assures that after T_1, a sustainability driven farmer will always comply:

$$\sum_{t'=T_1+1}^{\widehat{T}^{gm}} \left(\widehat{\pi}_i^{gm}(t) - \widehat{B}_i^{gm}(t)\right) > \sum_{t'=T_1+1}^{\widehat{T}^{gm}} \left(\pi_i^{gm}(t) - B_i^{gm}(t)\right) . \tag{12}$$

Then what about the time before T_1 when payoff without compliance is higher? We prove the result by contradiction. Consider a time $t' < T_1$. As the objective of the sustainability driven farmer *i* is to maximize payoffs over the horizon $t = 1$ until $\overline{T}$, he will not comply at $t' < T_1$ if:

$$\sum_{t=t'}^{\widehat{T}^{gm}} \left(\widehat{\pi}_i^{gm}(t) - \widehat{B}_i^{gm}(t)\right) < \sum_{t=t'}^{\widehat{T}^{gm}} \left(\pi_i^{gm}(t) - B_i^{gm}(t)\right) \text{ for } \widehat{T}^{gm} \geq T_1 > t' \geq 1 \tag{13}$$

Now let us add $\sum_{t=1}^{t'-1} \left(\widehat{\pi}_i^{gm}(t) - \widehat{B}_i^{gm}(t)\right)$ where $1 \leq t' < T_1$ to both sides of Eq. (13) to get:

$$\sum_{t=1}^{\widehat{T}^{gm}} \left(\widehat{\pi}_i^{gm}(t) - \widehat{B}_i^{gm}(t)\right) < \sum_{t=t'}^{\widehat{T}^{gm}} \left(\pi_i^{gm}(t) - B_i^{gm}(t)\right) + \sum_{t=1}^{t'-1} \left(\widehat{\pi}_i^{gm}(t) - \widehat{B}_i^{gm}(t)\right). \tag{14}$$

Splitting the first term on the right hand side of Eq. (14) we can write:

$$\sum_{t=1}^{\widehat{T}^{gm}} \left(\widehat{\pi}_i^{gm}(t)-\widehat{B}_i^{gm}(t)\right) < \sum_{t=t'}^{T_1}(\pi_i^{gm}(t)-B_i^{gm}(t)) + \sum_{t=T_1+1}^{\widehat{T}^{gm}} (\pi_i^{gm}(t)-B_i^{gm}(t)) + \sum_{t=1}^{t'-1} \left(\widehat{\pi}_i^{gm}(t)-\widehat{B}_i^{gm}(t)\right). \tag{15}$$

Now according to assumption (3):

$$\sum_{t'=T_1+1}^{\widehat{T}^{gm}} (\pi_i^{gm}(t)-B_i^{gm}(t)) < \sum_{t'=T_1+1}^{\widehat{T}^{gm}} \left(\widehat{\pi}_i^{gm}(t)-\widehat{B}_i^{gm}(t)\right) \text{ and } \sum_{t=1}^{t'-1} \left(\widehat{\pi}_i^{gm}(t)-\widehat{B}_i^{gm}(t)\right) < \sum_{t=1}^{t'-1} (\pi_i^{gm}(t)-B_i^{gm}(t)).$$

Substituting the above terms into (15), we can re-write it as:

$$\sum_{t=1}^{\widehat{T}^{gm}} \left(\widehat{\pi}_i^{gm}(t)-\widehat{B}_i^{gm}(t)\right) < \sum_{t=t'}^{T_1}(\pi_i^{gm}(t)-B_i^{gm}(t)) + \sum_{t'=T_1+1}^{\widehat{T}^{gm}} \left(\widehat{\pi}_i^{gm}(t)-\widehat{B}_i^{gm}(t)\right) + \sum_{t=1}^{t'-1} (\pi_i^{gm}(t)-B_i^{gm}(t)).$$

Or

$$\sum_{t=1}^{\widehat{T}^{gm}} \left(\widehat{\pi}_i^{gm}(t)-\widehat{B}_i^{gm}(t)\right) < \sum_{t=1}^{T_1}(\pi_i^{gm}(t)-B_i^{gm}(t)) + \sum_{t'=T_1+1}^{\widehat{T}^{gm}} \left(\widehat{\pi}_i^{gm}(t)-\widehat{B}_i^{gm}(t)\right). \tag{16}$$

But Eq. (16) contradicts assumption 2 that sustainability guidelines ensure higher payoffs for farmer i when compliance is practiced from the start at $t = 1$ over the life time T^{gm} rather than from time $T_1 > 1$whatever the strategies chosen by the neighboring farmer.

It suffices to note here that our model accords an inbuilt ‘bonus’ to sustainability driven farmers. The returns to GMV for a sustainability driven farmer will fall more slowly over time than for a profit driven farmer because the ecology deteriorates less due to compliance observance. Hence, result 1.2 is proved.□.

Without detailing the functional forms of the profit trajectories, it is impossible to identify the optimal sequence of strategies s_i^t for $t = 1, 2, \ldots, \overline{T}$ for a sustainability driven farmer that explain when he would adopt the GMV or the best time for switching to conventional post-adoption. However, we can identify the necessary and sufficient conditions for repeated adoption of GMV by the two farmer types.

Result 2: On GMV adoption by a sustainability driven farmer: Whenever $\widehat{\pi}_i^{gm}(t) - B > \pi_i(t)\ \forall t$ the dominant strategy of the sustainability driven farmer is to adopt the GMV at the start.

Proof: At the outset, note that if a sustainability driven farmer i does not adopt the GMV at the start, he will not adopt it thereafter. However, the opposite is not true. The argument can be proved as follows. By assumption 1, the payoff from GMV is higher than from conventional varieties even with compliance, i.e. $\widehat{\pi}_i^{gm}(1) - \widehat{B}_i^{gm}(1) > \pi_i(1) - B_i(1)$. A sustainability driven farmer adopts GMV at the start, $t = 1$, if the area under the payoffs function to GMVs is greater than that from conventional variety (taking into account his neighbor's type and strategy sequences). As the profit functions are downward sloping and concave, the difference in the areas under the payoff function to GMVs and conventional varieties will decrease over time. Thus, if the area under the GMV payoff function is not greater to start with, it cannot become so over time. In other words, if a sustainability driven farmer opts for the conventional variety at $t = 1$, he will continue with it thereafter.

Now, from Table 2, whatever the neighbor type, for a complying sustainability driven farmer, the strategy of GMV adoption and cultivation at every time period (i.e. $s_i^t = 1 \quad \forall t$) would yield higher payoffs than from the conventional variety (i.e. $s_i^t = 0 \quad \forall t$) if:

$$\sum_{t=1}^{\overline{T}} \left(\widehat{\pi}_i^{gm}(t) - B \right) > \sum_{t=1}^{\overline{T}} \pi_i(t) \tag{17}$$

Thus, if $\widehat{\pi}_i^{gm}(t) - B > \pi_i(t) \forall t$, Eq. (17) holds and the sustainability driven farmer would adopt GMV at $t = 1$. □.

Result 3: On repeated adoption of GMV by both farmer types: Let T_1 be the time when complying yields higher payoff than non-complying for a profit driven farmer *i* as a function of neighbor type *j*. If the following conditions hold, then the dominant strategy of the profit driven farmer and the sustainability driven farmer is to adopt the GMV repeatedly from the start:

(i) $\widehat{\pi}_i^{gm}(t) - B > \pi_i(t) \forall t$; and,
(ii) $\widehat{\pi}_i^{gm}(t | t_{start} = T_1) - B(1 + \theta(1 - \delta)) > \gamma \pi_i(t)$ for all $t \geq T_1 > 1$.

The Nash equilibrium is then $\left(S_{i=1}^t = 1, C_{i=1}^t = 0, S_{i=2}^t = 1, C_{i=2}^t = 1 \right)$ for $1 \leq t < T_1$ and $\left(S_{i=1}^t = 1, C_{i=1}^t = 1, S_{i=2}^t = 1, C_{i=2}^t = 1 \right)$ for $t \geq T_1$.

Proof: For a profit driven farmer *i*, by assumption 1, the GMV yields higher payoff than the conventional seed with or without compliance. Hence, the profit driven farmer will adopt the GMV, without observing compliance, whatever his neighbor type.

By assumption 3, payoff from compliance becomes higher than that without compliance after time T_1. As the sustainability driven farmer always complies (by result 1), whatever the neighbor type, the profit driven farmer will now get $\widehat{\pi}_i^{gm}(t | t_{start} = T_1) - B(1 + \theta(1 - \delta))$ from GMV cultivation. Thus, if this remains above what he would get from conventional variety cultivation, namely $\gamma \pi(t)$, then he will continue to cultivate GMV.

Let us now turn to a sustainability farmer *i*. By result 2, given $\widehat{\pi}_i^{gm}(t) - B > \pi_i(t) \forall t$, he can adopt GMV at $t = 1$. But what about thereafter? He would opt for repeated adoption only if the returns from GMV cultivation exceed the stream from conventional, which would be $\gamma \pi_i(t)$ during each period.

After $t > T_1$ we know that $\widehat{\pi}_i^{gm}(t | t_{start} = T_1) - B(1 + \theta(1 - \delta) > \gamma \pi_i(t)$ for all $t \geq T_1$. By advantages of compliance (Eqs. 4 and 5) we have $\widehat{\pi}_i^{gm}(t) > \widehat{\pi}_i^{gm}(t | t_{start} = T_1)$ for all $t > T_1$. Thus, whatever the neighbor type, the dominant strategy for a sustainability driven farmer is repeated adoption after $t > T_1$ (also confirmable by a look at payoffs Table 2).

Then, what about the optimal strategy during $t < T_1$? Consider a time, z, where $z < T_1$. Under this scenario, a profit driven farmer adopts the GMV at the start and continues to cultivate it until the end complying from time $t > T_1$, or $\pi_i^{gm}(t) > \pi_i(t)$ for $t < T_1$ and $\widehat{\pi}_i^{gm}(t|t_{start} = T_1) - B(1 + \theta(1 - \delta) > \gamma\pi_i(t)$ for all $t \geq T_1$. So we can write:

$$\left(\sum_{t=z}^{T_1-1} (\pi_i^{gm}(z) - B) + \sum_{z=T_1}^{\overline{T}} \left(\widehat{\pi}_i^{gm}(z) - B\left(1 + \theta(1 - \delta)\right) \right) \right) > \sum_{t=z}^{\overline{T}} \pi_i(t)\gamma. \tag{18}$$

By result 1, we know that the sustainability farmer complies from the start and by assumption 2, we can write:

$$\sum_{t=z}^{\overline{T}} \left(\widehat{\pi}_i^{gm}(t) - \widehat{B}_i^{gm}(t) \right) > \left(\sum_{t=z}^{T_1-1} (\pi_i^{gm}(z) - B_i^{gm}(z)) + \sum_{z=T_1}^{\overline{T}} \left(\widehat{\pi}_i^{gm}(z) - \widehat{B}_i^{gm}(z) \right) \right) > \sum_{t=z}^{\overline{T}} \pi_i(t)\gamma.$$

Therefore, at $t = z < T_1$, whatever the neighbor type, adoption with compliance from the start is the dominant strategy for the sustainability driven farmer. Hence, the Nash equilibrium. □.

Result 4: On repeated adoption of GMV by the sustainability driven farmer but not the profit driven farmer: The profit driven farmer will start by adopting GMV without compliance, continue to cultivate the GMV with compliance but switch to the conventional after a period of time and, the sustainability farmer will comply from the start and adopt the GMV repeatedly throughout its lifetime if:

(i) $\widehat{\pi}_i^{gm}(t) - B(1 + \theta(1 - \delta)) > \gamma\pi_i(t) \forall t$;
(ii) $\widehat{\pi}_i^{gm}(t|t_{start} = T_1) - B(1 + \theta(1 - \delta)) < \gamma\pi_i(t)$ for all $t \geq T_2 > T_1 > 1$.

In other words, the Nash equilibrium is $(S_{i=1}^t = 1, C_{i=1}^t = 0, S_{i=2}^t = 1, C_{i=2}^t = 1)$ for $1 \leq t < T_1$, $\left(S_{i=1}^t = 1, C_{i=1}^t = 1, S_{i=2}^t = 1, C_{i=2}^t = 1\right)$ for $T_1 \leq t \leq T_2$, and $\left(S_{i=1}^t = 0, C_{i=1}^t = 0, S_{i=2}^t = 1, C_{i=2}^t = 1\right)$ for $T_2 \leq t \leq \overline{T}$:

Proof: Note that whatever the neighbor type, once he starts complying profit maximizing farmer will get $\widehat{\pi}_i^{gm}(t|t_{start} = T_1) - B(1 + \theta(1 - \delta))$. Thus, by condition (ii) he will stop cultivating the GMV after T_2 .

By condition (i) and result 2 the dominant strategy of the sustainability driven farmer is to adopt the GMV at the start. By the same argument as in result 3, we can show that for all time periods $t < T_1$, the sustainability driven farmer will adopt the GMV. From T_1 onwards his payoff is $\widehat{\pi}_i^{gm}(t) - B(1 + \theta(1 - \delta))$and, as this is greater than $\gamma\pi(t)$, by condition (i) he will continue to cultivate GMV. □.

5 Policy reflection: so what about the precautionary principle?

Consider the following thought experiment of a policy maker, who has two identical villages of farmers to administer. The farms are organized in neighboring pairs, comprised of two profit driven farmers, two sustainability driven farmers or one of each type. He has to take a decision on allowing the commercialization of a GMV in the region. To do this, he supposes that he will introduce the GMV in one village, keeping the other village as a control with only the conventional variety to cultivate. He considers two possible rules for application of the precautionary principle. Either he can take a survey at the end of every season to evaluate the livelihoods or payoffs generated for the farmers, or he can conduct a survey at the end of the lifetime of the GMV to assess how the two villages have fared. The former calls for a more stringent application than the latter. Let us refer to the two evaluation routines as rule 1 and rule 2. By farmer livelihoods' in the GMV village, we refer to the sum of the payoffs of all farmers from playing their Nash equilibrium strategies. Similarly, farmer livelihoods' in the non-GMV village is the sum of production profit from cultivating the conventional variety.

The model and results developed in the preceding sections for evaluation of new technology in agriculture lead us to the following inference:

Result 5: On application of the precautionary principle.

5.1. The precautionary principle may be applicable even in the absence of informational constraints and be uninfluenced by the degree of irreversibility under both rule 1 and rule 2

5.2. The likelihood of application would decrease with greater gains from the new technology, lower detrimental ecological impact, lower contamination possibilities, higher effectiveness of science, lower compliance burden, lower irreversibility burden and a greater proportion of sustainability driven farmers. This effect would be greater under rule 1 than rule 2.

Proof: 5.1. Consider the best possible case, wherein the village has only sustainability driven farmers and where the Nash equilibrium is repeated adoption as in results 3 and 4. Then according to payoff matrix of Table 2, at time t every farmer would be earning $\widehat{\pi}_j^{gm}(t) - B(1+\theta(1-\delta))$ in the GMV village and $\pi_i(t)$ in the conventional variety village (or just conventional village henceforth). Then the precautionary principle would not be applied if:

$$\left\{\begin{array}{c} \widehat{\pi}_j^{gm}(t) - B(1+\theta(1-\delta)) \geq \pi_i(t)\ \textit{forany}\ t\ \textit{where}\ 1 \leq t \leq \overline{T}\ \textit{underrule}\ 1. \\ \sum_{t=1}^{\overline{T}} \widehat{\pi}_j^{gm}(t) - B(1+\theta(1-\delta)) \geq \sum_{t=1}^{\overline{T}} \pi_i(t)\quad \textit{underrule}\ 2. \end{array}\right\} \tag{19}$$

Now from results 3 and 4, the necessary condition for repeated adoption of GMV by a sustainability driven farmer is $\widehat{\pi}_i^{gm}(t) - B > \pi_i(t) \forall t$ and the sufficient condition is $\widehat{\pi}_i^{gm}(t) - B(1+\theta(1-\delta)) > \gamma\pi_i(t) \forall t$. Putting these together we have two possibilities:

$$\widehat{\pi}_i^{gm}(t) - B > \pi_i(t) > \widehat{\pi}_i^{gm}(t) - B(1+\theta(1-\delta)) \tag{20}$$

$$\widehat{\pi}_i^{gm}(t) - B > \widehat{\pi}_i^{gm}(t) - B(1+\theta(1-\delta)) > \pi_i(t) \tag{21}$$

The precautionary principle would then be applied under the situation given by Eq. (20) but not (21). Clearly the value of γ does not influence the application of the precautionary principle when the community contains only sustainability driven farmers. This could be because this factor has already been taken into account in their cultivation division. □.

5.2. The case of the GMV village also serves to prove the second part. Clearly, Eq. (20) is more likely to hold, when the value of B or θ is higher and the value of δ is lower. Similarly, the higher is the difference between the ecology indices due to continuous cultivation of GMV even with compliance, $\xi_i\left(t, s_i^t = 1, c_i^t = 1\right) - \xi_i\left(t, s_i^t = 0, c_i^t = 0\right)$, the greater is the difference $\pi_i^{gm}(t) - \pi_i(t)$.

To understand the role of irreversibility, let us consider the same context, but with one major difference. Let the village be full of profit driven farmers. According to result 3, farmers will adopt GMV without compliance first, then comply from time T_1 onwards. Here, the necessary and sufficient for GMV cultivation at every time period is: $\widehat{\pi}_i^{gm}(t|t_{start} = T_1) - B(1 + \theta(1 - \delta)) > \gamma\pi_i(t)$.

The policy maker would not call for the precautionary principle if Eq. (22) hold. However, unless reversibility is perfect, i.e. $\gamma = 1$, the required condition would not hold for rule 2 or for rule 1 after time T_1. Hence, the precautionary principle will be applied.

$$\left\{\begin{array}{l} \pi_j^{gm}(t) - B\theta \geq \pi_i(t) \; for \; t \leq T_1 \; and \; \widehat{\pi}_i^{gm}(t|t_{start} = T_1) - B(1 + \theta(1 - \delta)) > \pi_i(t) \; for \; t > T_1 \\ under \; rule \; 1. \\ \sum_{t=1}^{T_1} \pi_i^{gm}(t_1) - B\theta + \sum_{t=T_1}^{\overline{T}} \widehat{\pi}_i^{gm}(t|t_{start} = T_1) - B(1 + \theta(1 - \delta)) > \sum_{t=1}^{\overline{T}} \pi_i(t) \; under \; rule \; 2. \end{array}\right\} \quad (22)$$

Interestingly from *5.1.* we know that if Eq. (20) holds, then for the same context if the village was full of sustainability driven farmers instead of profit driven ones, then the precautionary principle would not be applied. Hence, heterogeneity of farmer type in population matters. □.

6 Concluding remarks

The precautionary principle is a policy response in the context of risk management to any activity that poses a threat to society. It corresponds to an action in the decision-making phase to ban the activity, based on the evaluation of possible irreversible adverse effects, the effectiveness of the present scientific knowledge base to contain them and the extent of scientific uncertainty on both. This has been exemplified, particularly in the European risk regulation of genetically modified crops. In this regard, the present paper sought to develop a framework that would permit a better understanding of the role of different factors specific to new technology introduction in agriculture. An evolutionary model of new seed technology adoption was formulated incorporating novel elements such as farmer heterogeneity, technology obsolescence, ecological impacts, compliance and contamination burdens and the efficiency of the present scientific knowledge base to redress any possible negative effects of new technology adoption. Under assumptions based upon the findings of the literature, the evolutionary model then identified the conditions for repeated GMV adoption and compliance vis-à-vis sustainability guidelines by profit driven and sustainability driven farmers.

Five main results were obtained by solving for the Nash equilibria of the game. Results 1–4 pertained to individual farmer behavior in terms of technology and compliance choices. According to result 1, a sustainability driven farmer would always comply if he adopted GMV, whereas a profit driven farmer would comply only if and when it became necessary. Furthermore, the likelihood of a sustainability driven farmer adopting GMV, result 2 showed, depends on the magnitude of the compliance burden. Only if the burden were sufficiently small so as to make it financially manageable would he adopt GMV, as he would be complying from the start. On the other hand, the profit driven farmer would always adopt GMV by result 3. Thereafter, results 3 and 4 demonstrated that the repeated adoption of GMV would depend on a multiplicity of factors and their interactions such as the ecological impact, the contamination engendered, the compliance and irreversibility burdens and the effectiveness of science as embedded in the compliance routines to counter any possible negative effects. Whatever be the case, result 4 showed that if a sustainability driven farmer adopted GMV, then the duration of his repeated adoption of GMV would be longer than that of a profit driven farmer because he would have protected Nature and soil fertility by being compliant.

The present discourse on application of the precautionary principle rests primarily on scientific uncertainty and irreversibility of possible deleterious impact of an activity. Our exploration at the macro, policy level demonstrated that it could be rationalized even under weaker conditions. To show this, two possible policy rules were considered, one being more stringent than the other, with respect to the application of the precautionary principle. Under the former, the precautionary principle would be applied if cultivation of GMV yielded lower collective farmer payoffs at any harvesting season, while under the latter, it would be evoked only if livelihoods were lower over the lifetime of the GMV – the benchmark being payoffs obtainable from growing the conventional variety. Integrating the above elements and considering these two possible policy rules, result 5 proved that the precautionary principle may be applicable even in the absence of informational constraints and remain uninfluenced by the degree of irreversibility. Result 5 indicated that the likelihood of application of the precautionary principle should increase with lower gains from the new technology, higher detrimental ecological impact, higher contamination possibilities, lower effectiveness of science, higher compliance burden and a lower proportion of sustainability driven farmers.

With this insight, do present patterns of positioning of countries vis-à-vis GMVs seem rational? Since worldwide, the majority of farmers are considered to be profit driven, the application of the precautionary principle would hinge on pessimistic perceptions about the potential for present scientific knowledge to be encapsulated into protocols that can address possible forms of environmental degradation in the future and/or the ability of the regulatory system to nudge or enforce farmers to integrate them into their production systems. Moreover, as regulatory systems are highly developed in both Europe and North America, the difference in their stance towards GMVs seems to lie in their confidence about science being always able to provide solutions to problems, the former being less optimistic than the latter.

A paradox that contradicts the above inference, however, is that at present, GMVs are cultivated more in countries that do not have the scientific, technological and regulatory capabilities of the Western world. Presently, 19 low and middle income[3] countries account for about 53% of the global area devoted to biotech crops (ISAAA 2018). The only way to explain the non-application of the precautionary principle in these countries given a retarding in both technology and regulatory capabilities is that they trust the multinational agribiotech companies to be able to churn out solutions to any major problem that could arise in the future.

Lastly, our model was constrained by its assumptions that had been framed for analytical tractability. We suggest that future research explore how outcomes would change under less restrictive settings. We note several possibilities for future research.

First, using simulation techniques and the existing findings of agricultural scientists, different scenarios for externalities generation from GMVs adoption can be modelled. Externalities generation is likely to depend on the total number of farmers, the composition of farmer types, and their spatial configuration. Impact of technology choice for a farmer would then depend on his own technology and compliance choice as well as those of his neighbors. That said, even at present, there is real uncertainty on the forms of the profit trajectories from different seed technologies, due to a combination of scientific and market uncertainty. Analytical and numerical simulations could be also considered with standard functional forms for profit, to explore the impact of varying the rate of discount among farmer types between 0 and 1, rather than considering only 0 and 1. Finally, monitoring and incentivization schemes can be introduced to arrive at farmer compliance through cooperation and coordination.

Second, our model considered an artificial two farmer world where both are perfectly rational with perfect and complete information for analytical tractability. Multiple farmer types can be introduced and a population of farmers can be considered so that the regional impact is mapped as a function of the size and composition of the population used agent-based modelling techniques. Informational problems can also be introduced in keeping with the reality. The attitudes of different stakeholders such as the regulator, producing agents and consumers can also be integrated in deciding about the implementation of the precautionary principle.

Third, the integration of the ideas developed in this paper can be explored in other contexts where the implementation of the precautionary principle is still being debated such as in medical practices (Gorlin 2019), artificial intelligence (Castro and McLaughlin 2019), international trade negotiations (Cai and Kim 2019) and representations of rationality (Christiansen 2019).

These signal the many avenues for extensions of our model.

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[3] Following the World Bank Country Classification by Income https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups

Compliance with ethical standards

The present paper did not require any interaction or experimentation that demands ethical compliance.

Conflict of interest The authors declare that they have no conflict of interest.

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