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Leveraging Parrondo's paradox for sustainable agriculture

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Abstract

Rotating crops is a sustainable agricultural technique that has been at the disposal of humanity since time immemorial. Switching between cover crops and cash crops allows the fields avoid overexploitation due to intensive farming. How often the respite is to be provided and what is the optimum cash cover rotation in terms of maximising yield schedule is a long-standing question tackled on multiple fronts by agricultural scientists, economists, biologists and computer scientists, to name a few. Dealing with the uncertainty in the field due to diseases, pests, droughts, floods, and impending effects of climate change, is important to consider when designing the cropping strategy. Analysing this time-tested technique of crop rotations with a new lens of Parrondo's paradox allows us to improve upon the technique and use it in synchronisation with the burning questions of contemporary times. By calculating optimum switching probabilities in a randomised cropping sequence, suggesting the optimum deterministic sequences and judicious use of fertilisers, we propose methods for improving crop yield and the eventual profit margins for farmers. Overall we also extend the domain of applicability of the seemingly unintuitive paradox by Parrondo, where two losing situations can be combined eventually into a winning scenario.

Keywords: crop rotation, Parrondo's game, fluctuating selection, population dynamics, crop yield, soil quality, fertilisers.

Introduction

"In an April speech to Congress [...] President Biden suggested paying farmers to plant cover crops, which are grown not for harvest but to nurture the soil in between plantings of cash

crops.” [1].

In the coming thirty years the world will be facing a severe dearth of food [2]. Nourishment will be hard to provide unless crop yields improve. Furthermore, farmers have to face the consequences of climate change, resistant pathogens and recurrent diseases. Fixing the dire situation using intensive cropping techniques and blanket use of fertilisers is a short term solution and not sustainable. For example, the intense use of inorganic fertilisers feed-back negatively into the ecosphere accelerating climate change [3]. While most of the classical “old-fashioned” strategies such as tilling and slash and burn agriculture are not scalable and climate friendly, perhaps some of the strategies can be upgraded for the future. Already for hundreds of years, farmers have been rotating crops as a sustainable strategy. The approach has been augmented technologically [4, 5] and analysed computationally [6] to provide better crop rotation schedules. Crop rotations are akin to fluctuating selection regimes where the soil quality changes with the planted crops affecting the yield of the following crop. In very simplistic terms, a cash crop yields profit whereas a cover crop does not. Cover crops can act as carbon sequestration tools and generally enriching the soil with nutrients and preventing their leaching in water. Although cover crops improve soil health and prepare it for easy exploitation for the cash crops, the covers themselves are typically an economic dead-end for the farmers.

We look at crop rotation from the point of view of a different discipline. Game-theoretically, in terms of profit making, planting cash crops is a winning game while cover crops are not. In the long run, however, even cash crops are a losing venture as the soil quality depletes beyond repair. We use this simplicity of logic as a starting point to connect this obviously complex scenario to a well studied, seemingly unintuitive phenomenon - Parrondo’s paradox [7, 8]. When a combination of two losing strategies results in a winning strategy, this situation is referred by Parrondo’s paradox. This seemingly paradoxical behaviour exists in other fields as well. Numerous situations exist across the complexity of life where particular traits, strategies, or behaviours can be detrimental to the organism when implemented over long periods. However, combining the individually harmful strategies in a specific manner, a sustainable method emerges [9, 10]. Starting at the genetic scales, [11] show how an autosomal allele with lower fitness advantage can persist and even continue to fixation via its epistatic interactions with alleles at other loci. At the population level, persistence in sink environments is possible if offspring are distributed over different habitats that fluctuate temporally [12]. In [13] it is shown how environmental sensors with low accuracy can indeed be selected under certain environmental conditions. In a similar vein, [14] shows how switching between two evolutionary strategies, nomadism and colonialism, that individually leads to extinction, can lead to population persistence and long-term growth. Concerning grasslands, a Parrondo like

effect explains the persistence of rare forb species existing in competition with the dominant grasses in California under fluctuating environmental conditions [15]. The “storage effect” was the key determinant for this co-existence, with forbs using their seed banks differently in different climatic conditions. In this study, we leverage this theoretically versatile framework of Parrondo’s paradox to devise profitable and sustainable agricultural practices.

Cash and cover crops act as games in our model. The farmer is interested in generating a profit. Consistently planting cover crops while increasing soil quality is assumed not to provide any monetary gains. Similarly, sequentially planting only cash crops will deplete the soil quality over time, making the field barren. Numerous approaches have been proposed before as means of increasing the crop yield, optimising the rotation patterns between cash and cover crops empirically as well as computationally [4, 5, 16]. These models can be incredibly complicated, considering the spatial and temporal variation in the planted crops, market effects of demand and supply trends, pathogen evolution dynamics and weather conditions. However, not all of such approaches are agriculturally sustainable as we move forward [17]. Crop rotations have been proposed as a means of tackling multiple issues of modern-day agriculture, being able to - control insects, pests and diseases of crops, weed control, increase crop yields, lower economic risk, reduce toxic substance accumulations in soils, achieve abundant and lasting soil cover, maintain or increase soil organic matter content, provide alternating root systems allowing for a stable extraction of nutrients favouring soil equilibrium, improve soil structure and ultimately promote greater biological diversity [18]. Crop rotations are thus a sustainable way towards conservation agriculture. However, a significant obstacle lies in deriving optimum rotation schedules.

Visualising crop rotations through the lens of Parrondo’s paradox allows us to derive the optimum rotation frequency of cash and cover crops for randomised cropping sequences. With fertilisers, we show that we can increase range of the profitable rotation frequency given the appropriate cash crops. This helps us identify the profitable fertiliser-cash crop combinations. The result depends on the specific properties of the cash and cover crops, such as the threshold soil quality required to grow the cash crop and how fast the cover crop can replenish the soil quality. Even for deterministic sequences, we observe a Parrondo-like effect. Our study thus provides a novel take on determining the optimum crop rotations schedules for maximising the profit for farmers while simultaneously being a sustainable agricultural strategy. We have also extended the domain of applications of Parrondo’s paradox and demonstrated its utility in translational studies.

Figure 1: **Crop rotations, soil quality and profit margins.** Cash and cover crops are highlighted in an exemplar rotation sequence on top. A) for each event of cash or cover crop, the soil quality decreases or increases by a unit amount. B) the cumulative soil quality over the duration of the sequence is shown. The threshold soil quality required for generating a possibly profitable cash crop is set to $\theta = 2$. C) To capture the fickle nature of agricultural outcomes due to various factors, the probabilities of profits possible for the cover crop is set to $p = 0.2$ and for the cash crop in poor soil is $p_1 = 0.5$ and $p_2 = 0.9$ otherwise. Using these probabilities the trajectories show the results of a 1000 independent runs with the red lines (16/1000) end up in making a cumulative profit.

From soil to profit

The quality of the soil has a profound effect on the yield of the crops. Reaping crops for nutritional benefit inherently strips the soil of essential nutrients. Under crop rotations typically two types of crops are considered - “cover” crops and “cash” crops. Cover crops provide a low yield, if any, but increase the quality of the soil. Alternatively, they are used as fodder for animals. Cash crops are the main profit generating crops such as essential grains as wheat, maize. If the soil quality is above a certain threshold value, then the cash crops can maximally extract the nutrients. We define this threshold soil quality to be θ . Thus profits are more probable if cash crops are grown in a field with a good soil quality (soil quality $> \theta$). For an example cropping sequence between cash and cover crops, Fig. 1 shows the effect on how the soil quality changes with every cropping season as well as the cumulative effect on the field. Profit can be generated (with a certain probability) if the soil quality is higher than the threshold θ required by the cash crop (shown by $\theta = 2$ in Fig. 1 panel B).

The crop yield does not solely depend on the soil quality but also on other complex ex-

ternal factors, e.g. climate conditions, pathogen co-evolution and market volatility. We have captured these complex interactions by introducing probabilistic outcomes. We denote p as the probability of obtaining financial profit from a cover crop (usually minimal). For the cash crops, p_1 and p_2 as probabilities of obtaining profits when the soil quality value is bad (soil quality $< \theta$) or suitable (soil quality $> \theta$), respectively. These decision trees for the cash and cover crops are visualised in Fig. A.1. Typically we will have $p_1 < 0.5$ and $p_2 > 0.5$. The effect of including the probabilities of profit for a given rotation sequence is shown in Fig. 1 panel C.

So what should be the ideal rotation sequence that maximises profit? In a previous study [6], the optimum sequence was found by performing an exhaustive search of all possible sequences of a given length. Various computational and empirical approaches have striven to answer this pertinent question [4, 5, 19, 20]. While the space of possible sequences can be ample, randomised switching provides an excellent analytical handle helping us understand different regions of the parameter space of our model.

Randomised cropping sequences

We model the effect of different crops on soil quality as a discrete-space discrete-time random walk problem. The soil quality can vary from 0 to a maximum possible value of K . We generate a random sequence of cash and cover crops. The probability of choosing the cover crop in the coming season is γ . Thus a cover crop is chosen with probability γ , and it is assumed to increase the soil quality by a units. Conversely, with probability, $1 - \gamma$ cash crop is chosen for the next season, depleting the soil of nutrients reducing the quality by b units at the end of the season, see Fig. A.2. Fig. A.1 illustrates this choice based on γ between the cash and cover crop decision trees. From the Markov chain analysis, the probability of making a profit for the randomised switching is then:

$$P_{\text{win}}^R = q_1 \sum_{i=0}^{\theta} x_i^* + q_2 \sum_{i=\theta+1}^K x_i^*, \quad (1)$$

where, $q_{1/2} = \gamma p + (1 - \gamma)p_{1/2}$ (see App. A.3) and x_i^* is the steady-state probability of soil quality being equal to i units. When γ is 0 or 1, we have cash or cover crops monoculture. For only cash (cover) crop, we have $P_{\text{win}}^R = p_1$ (p). It is so because, when only growing cash crops, the field will ultimately become barren. Thus the probability of making a profit becomes p_1 (set to $p_1 = 0$). On the other hand, with prolonged use of cover crops, although the soil quality reaches the carrying capacity K , the probability of winning remains p (set to $p = 0.4$). Since both p and p_1 are less than half, we always lose when under monoculture all

Figure 2: **Optimum cover crop frequency and threshold dependence.** Left: the probability of profiting is plotted as a function of the frequency of cover crops used to generate a randomised sequence. We designate a ‘win’ when this probability is more than 50%. The range of the frequency of cover crops where the profit is a ‘win’ is bounded by $\gamma_{\min}$ and $\gamma_{\max}$. This range is shown for a given threshold value of soil quality $\theta = 3$. Right: As the threshold soil quality for a cash crop to generate profit increases, the range of $\gamma_{\min} - \gamma_{\max}$ shrinks. Other parameter values are $K = 10, p = 0.4, p_1 = 0, p_2 = 0.8$.

seasons. We highlight the losing probabilities in the Fig. 2 panel (A), as the extremes of the curve representing the cash monoculture (p_1 - yellow marker) and cover monoculture ($p = 0.4$ - purple marker). However, something unintuitive happens for the intermediate values of γ . For a given set of parameters, we find that $P_{\text{win}}^R > 0.5$ for a certain range of γ , the blue shaded region of Fig. 2 panel (A). That is, we can make a profit by randomly switching between two crops which individually results in a loss, see Fig. A.4. This effect is quite similar to famous Parrondo’s paradox[7], where two individually losing games combine to form a winning game.

We further find that the range of γ for which $P_{\text{win}}^R > 0.5$, shrinks with the increase in the soil quality threshold θ . It can be seen in Fig. 2 panel (B) that $\gamma_{\min}$ increases with θ while $\gamma_{\max}$ remains almost constant. For all values of γ , $q_1 < q_2$ (except for $\gamma = 1$ when $q_1 = q_2$). On increasing θ , we increase the magnitude of the first term on the right-hand side on Eq. 1. However, it is the second term that has a substantial contribution to P_{win}^R . To compensate for the effect of increasing θ , $\gamma_{\min}$ also increases, putting more weight in the tail of the soil quality distribution and hence the second term of Eq. 1.

Let us define a quantity θ^* , critical θ , such that if $\theta \leq \theta^*$, $P_{\text{win}}^R > 0.5$ for some values of γ . From Fig. 2 panel (B), we find that both $\gamma_{\min}$ and $\gamma_{\max}$ take values close to 0.5 for $\theta \leq \theta^*$ indicating that one needs to switch often between the cash and cover crop to make profit. The equal switching regime also agrees with the classical Parrondo’s game. Switching between

games is often done to exploit the asymmetry in the winning probabilities of the sub-games. If the cash crop depletes the soil quality at a very high rate, it is more difficult to profit. This can be seen from Fig. A.6, where θ^* decreases with the increase in b/a .

Nevertheless, what if the required soil quality threshold, θ for a given cash crop, is above θ^* ? How do we make a profit in that case? The answer can lie in the efficient use of fertilisers. Using suitable fertilisers depending on the crop system, one can increase the θ^* .

Smart fertiliser use

Continuous exploitation of pristine soils leads to nutrient depletion. Leaving the land fallow for a while or actively planting nutrient enriching cover crops can help recover the soil quality. Even crop rotations are typically not enough to maintain stable productivity over several years; interventions to add nutrients are therefore necessary [18]. Thus, fertilisers can be applied to minimise the amount of time the land is left fallow. Often, fertilisers are tailored towards particular cash crops, and an optimal fertiliser-crop combination can lead to enhanced profits. In our case, we see fertilisers maintaining the soil quality above the threshold value required by the cash crop. Hence, one can keep making a profit without switching back often to the cover crop. Precisely, in the context of randomised crop switching, fertilisers can manipulate soil quality probability distribution to help increase the θ^* . The effective increase in the θ^* due to fertilisers is illustrated in panel (B) of Fig. 3. The minimum amount of soil quality required by the cash crop is the fixed amount θ . If the soil quality is less than θ , the addition of fertilisers aims to increase it beyond θ . However, the actual effect of the fertiliser is perceivable with the complete knowledge of the crop (θ), the rate of change of soil quality due to rotation (a and b) and the effective soil quality distribution.

In this work, we only explore the effect of adding fertilisers on a crop rotation system that is already in a steady-state. We model the change in the steady-state soil quality distribution due to fertilisers as follows:

$$x_i^* \rightarrow x_i'^* = \frac{x_i^* + f_i}{\sum_{i=0}^K (x_i^* + f_i)} = \frac{x_i^* + f_i}{1 + \sum_{i=0}^K f_i}, \quad (2)$$

where, the distribution f quantifies the sole effect of fertilisers on the soil quality. For illustration, we choose distribution f to be a skewed normal distribution:

$$f_i = \frac{e^{-\frac{(i-\mu)^2}{2\sigma^2}} \text{Erfc}\left[-\frac{\alpha(i-\mu)}{\sqrt{2}\sigma}\right]}{\sqrt{2\pi}\sigma}, \quad (3)$$

Figure 3: **Choosing fertilisers according to crop properties.** The way in which the range of γ for which $P_{\text{win}} > 0.5$ changes after adding fertilisers to a system of crops rotating for a long time is shown. We see that depending upon the system of crops (b/a), θ^* can either increase, see panel (B), or decrease, see panel (A). Parameters are $K = 40$, $p = 0.4$, $p_1 = 0$, $p_2 = 0.8$.

where, μ is the mean effect of the fertilisers, σ is the corresponding uncertainty measure, and α represents the skewness in uncertainty towards increased soil quality.

The rates of increase and decrease of the soil quality (a and b) are intrinsic properties of the crops (cash and cover). We find it might be economically more profitable to change the crop system rather than invest in adding fertiliser to an existing crop system. For example, panel (A) of Fig. 3 shows the disastrous results of adding fertilisers to an $a = b$ system. Concerning the threshold value, the region is reduced from around 31 (without fertilisers) to 20 (with fertilisers). In the right panel for a $b = 1.5a$ crop system, the addition of fertilisers increases the region from around 15 to 19. Here, the addition of fertilisers has helped increase the θ^* above the threshold value where profit is possible. To understand the differential results of adding fertilisers, we scrutinise the precise location where the fertilisers take effect - the soil quality. The addition of fertilisers can change the weights associated with the two sums in Eq. (1) in a manner to increase the contribution of the second sum. The second part of Eq. (1) is associated with the profit, i.e. when the soil quality is higher than the threshold. The (sometimes) increased contribution of the second sum due to the addition of fertilisers is discussed in detail in the Appendix and highlighted in Fig. A.7. From an economic standpoint, everything else being equal, it might be better to invest in an $a = b$ system with no fertilisers than an $b = 1.5a$ system that would incur the additional cost of fertilisers. Hence the choice of cash-cover crops and an ad hoc assessment of the impact of fertilisers can play an essential role in reaching decisions in fertiliser investment.

Figure 4: **Best deterministic sequences.** Deterministic sequences are given by (α_1, α_2) where α_1 is the number of consecutive cover crops followed by α_2 time the cash crops before the sequence repeats, as shown in the inset bottom right. The left panels explore the $\alpha_i = 1, \dots, 4$ and, for a variety of b/a ratios, the rate at which cover crops replenish the soil quality depleted by the cash crops. For select extreme threshold values $\theta = 1$ and $\theta = 9$ we report the top five sequences that give the best probability of winning P_{win} (ranked from dark to light green) if they exist above 0.5 (with precision set up to two decimal values). As b/a increases, we see that the best deterministic sequences are not the ones with higher values of α_1 and α_2 but the sequences where the crops switch often. On the right we show only the best P_{win} for all combinations of θ and b/a ratios. $K = 10, p = 0.4, p_1 = 0, p_2 = 0.8$

Deterministic sequence

So far, the crop rotation was done in a randomised manner. Reflecting closer to reality, we analyse patterns of crop rotations such that the order of crops is predetermined. To define a deterministic sequence, we use the following notation, $(\alpha_1, \alpha_2, \dots, \alpha_n)$ where $\alpha_i \in \mathbb{Z}_0^+$. For odd i , α_i denotes the number of times covered crop is grown, whereas even i denotes the number of times a cash crop is grown. One cycle of implementing a deterministic sequence takes $\alpha_1 + \alpha_2 + \dots + \alpha_n$ time units. The probability of winning corresponding to a given sequence, P_{win} is found from the slope of the average capital trajectory using Eq. A.9 by implementing the sequence for sufficiently long times.

We scanned all the sequences of type (α_1, α_2) with $\alpha_i \in [0, 1, \dots, 4]$. From Fig. 4, we confirm Parrondo like effect for the case of deterministic sequences. If $\alpha_i = 0$ for any i ,

there is no sequence such that $P_{\text{win}} > 0.5$, i.e. growing only one type of crop is a losing strategy. However, there exist some sequences with both α_1 and α_2 not equal to zero. For those sequences, we have $P_{\text{win}} > 0.5$, i.e. specific combinations of two losing strategies yield a winning one. We observe that the number of such sequences reduces with increasing θ and b/a . We also find that for large θ , one needs to switch often between crops to make a profit, especially when b/a is high. These findings are in agreement with our results from the randomised cropping case.

Discussion & Conclusion

Combining two losing games to create a winning scenario seems initially counterintuitive. Parrondo invented this setup initially intending to explain the dynamics of an imaginary machine that could convert the Brownian motion of particles into work - the Brownian ratchet [21]. The process highlights the positive role of noise in generating ordered structures. Parrondo's paradox was suggested to have implications in several fields such as economics, biology, and social evolution, given the inherent presence of noise in such adaptive systems. Over the past twenty years, this prediction has borne fruit with applications ranging from the classical to the quantum world [22]. Herein we have introduced Parrondo-like thinking in the field of eco-evolutionary agriculture [6].

Rotating crops between cash and cover crops is a time tested strategy [23]. Designing a successful rotation schedule is extremely important in yield-maximisation and avoiding over-exploitation of the field in the long run. We show that leveraging the noise coming from randomised cropping sequences identifies the frequency of cover crops to maximise the profit. The region where the two losing games combine to form a winning game can be extended by fertilisers, but not always. We have shown an example where the addition of fertilisers to the wrong crop system can even decrease the profit margin. We thus highlight the importance of identifying crop-fertiliser pairs before investing in cash crops.

At first glance, our observation of the Parrondo effect in our system is similar to the classical Parrondo's paradox [7]. However, an important distinction lies between the conventional Parrondo's effect and the effect that we encounter in our system. In a conventional Parrondo game, the separatrix defining the winning and losing region of the probability space is not a hyperplane (theorem 3.1 of [24]), whereas in our case, it is (see Fig. A.8). In our set-up, the requirement for a cash crop to be a losing strategy is when $p_1 < \frac{1}{2}$, resulting in the separatrix to be a line. Nevertheless, we observe a Parrondo type effect. We thus see that non-linearity in the games, as seen in the winning probability space, is not a requirement for observing a Parrondo like effect.

Intending to increase yield, we observe that allowing for mixing games does not lead to a monoculture of the cash crops. The optimal sequences already involve an adequate amount of cover crops so that the soil is not rendered barren. Thus while selecting only for one observable, the cash yield, we have inadvertently also optimised the appropriate soil quality. Furthermore, our model implementation is probabilistic in nature; that is, the cash crop does not always provide a stable return, and the cover crop may not always be a loss-making crop. These uncertainties reflect the unstable nature of the agriculture market economics, weather and climate effects and the possibilities of crop loss due to disease and pests. Cover crops can replenish the soil and prevent unwanted weed growth, pests or enhance beneficial insects such as pollinators. While we have not explicitly modelled the impact of such specific processes, it would be a profitable future research project to co-evolve disease evolution and winning probabilities. In particular, inclusion of pathogen evolution á la [6] will complete the eco-evolutionary picture from a Parrondo's paradox point of view.

Further complicated crop rotation sequences can be visualised, such as changing between seasons (summer/winter) and years. For example, growing corn and grey-seeded mucuna in summer and winter, followed by cotton and black oats in the following year. Such patterns will extend the game tree, but as long as we can alternate between these sets, a Parrondo-like region will emerge. The Three Sisters approach practised by the indigenous people of the Americas typically plant corn, squash (or pumpkin) and beans together in mounds. The corn typically provides support for the climbing beans. The beans simultaneously enrich the soil in nitrogen through their association with nitrogen-fixing rhizobacteria, and the squash or pumpkins inhibit the growth of weeds and maintain soil moisture by generating a ground cover [25]. The intercropping technique provides yields that are better than individual monocultures. The mixture of the produce is also nutritionally complementary, providing a wholesome, balanced meal to populations [26]. Analysing intercropping techniques such as the Three Sisters will add a spatial aspect to Parrondo's paradox, with multiple games being played simultaneously [27]. This spatiotemporal cropping technique will be a curious object for future consideration in both the classical Parrondo regime and eco-evolutionary agriculture.

Fluctuating selection regimes play a crucial role in numerous translational biological scenarios. From adaptive cancer treatment, antibiotic treatment schedules, wildlife conservation techniques to agricultural practices, anthropogenic intervention introduces a dynamic selection regime [28, 29]. Human interventions in natural processes (either randomly or deterministically determined) can thus be subject to analysis using Parrondo's paradox. Our study can thus also act as a proof of principle, enhancing the scope and applicability of this approach. We believe that such translation fields are fertile for applying the paradox while simultaneously creating new opportunities to improve our understanding of Parrondo-like processes in nature.

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Data Availability and Analysis All code and preliminary plots are available on GitHub at <https://github.com/tecoevo/agriculturalParrondo>.

Code availability. <https://github.com/tecoevo/agriculturalParrondo>

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A Appendix

A.1 Crop rotations

A cash crop needs soil quality above a threshold value, θ , to make a profit on average. However, cash crops simultaneously deplete the soil quality. Thus, their continuous plantation decreases soil quality beyond the threshold value, making it challenging to generate profits. Similarly, although a cover crop increases the soil quality, it fails to make a profit by itself. However, switching these two types of crops can interestingly result in winning scenarios where one makes a profit. Let p_2 (>0.5) be the probability of making a profit with a cash crop when soil quality is above θ , and p_1 (<0.5) be the winning probability otherwise. When switching, we adopt two strategies: randomised and deterministic switching. This process is summarised in the decision tree, see Fig. A.1. In the following sections, we discuss randomised switching strategy in detail:

Figure A.1: **Rotation sequence generation algorithms.** The probability of generating profit via cash and cover crops follow their independent decision trees. We can generate a rotation sequence by randomising cash and cover with probability γ or picking particular sequences of cash and cover crops in a deterministic manner. Both of these approaches are explored in our analysis.

Figure A.2: **Soil quality dynamics as a one dimensional random walk** For randomised switching, the soil quality dynamics can be modelled as a one-dimensional random walk problem with reflecting boundary conditions. With probability γ , there is a forward state transition, and with probability $1 - \gamma$, there is a backward transition. Here, the forward and backward jump sizes, a and b , are equal.

A.2 Randomised cropping

Randomised switching between cash and cover crop makes the problem effectively a one-dimensional random walk problem in the space of soil quality. Let a be the number of units by which the soil quality increases per season due to cover crops, b be the number of units by which the soil quality depletes per season on growing a cash crop, and K be the highest value of soil quality. The soil quality augments/depletes in a logistic growth manner, but we make a first approximation by considering an increase/decrease of soil quality linearly. We assume reflecting boundary conditions. Following, we analyse this random walk by using discrete Markov chain analysis.

367 A.3 Discrete Markov chain analysis

Here we mainly consider the forward (a) and backward (b) jump size being equal to 1. Let us denote $x_i(t)$ as the probability of soil quality being i units at time t . $x_i(t)$ satisfy the following recursive relations:

$$x_i(t+1) = \gamma x_{i-1}(t) + (1-\gamma)x_{i+1}(t), \quad i \neq 0, K \quad (\text{A.1})$$

$$x_0(t+1) = (1-\gamma)(x_0 + x_1) \quad (\text{A.2})$$

$$x_K(t+1) = \gamma(x_{K-1} + x_K) \quad (\text{A.3})$$

368 In the matrix form, this is represented as:

$$\begin{bmatrix} x_0(t+1) \\ x_1(t+1) \\ x_2(t+1) \\ \vdots \\ \vdots \\ x_{K-1}(t+1) \\ x_K(t+1) \end{bmatrix}^T = \begin{bmatrix} x_0(t) \\ x_1(t) \\ x_2(t) \\ \vdots \\ \vdots \\ x_{K-1}(t) \\ x_K(t) \end{bmatrix}^T \begin{bmatrix} 1-\gamma & \gamma & 0 & \cdots & \cdots & \cdots & 0 \\ 1-\gamma & 0 & \gamma & 0 & \cdots & \cdots & \vdots \\ 0 & 1-\gamma & \ddots & \ddots & 0 & \cdots & \vdots \\ \vdots & 0 & \ddots & \ddots & \ddots & 0 & \vdots \\ \vdots & \cdots & 0 & \ddots & \ddots & \ddots & 0 \\ \vdots & \cdots & \cdots & 0 & 1-\gamma & 0 & \gamma \\ 0 & \cdots & \cdots & \cdots & 0 & 1-\gamma & \gamma \end{bmatrix} \quad (\text{A.4})$$

$$\mathbf{x}(t+1) = \mathbf{x}(t) \cdot \mathbf{T}$$

369 Here $\mathbf{x}(t)$ is the probability row vector at time t and $\mathbf{T}$ is the transition matrix composed of
 370 transition probabilities. It is a right stochastic matrix, and according to the Gershgorin circle
 371 theorem, its largest eigenvalue is 1. For any initial state $\mathbf{x}(0)$ the steady state $\mathbf{x}^*$ converges to
 372 unique stationary state, which turns out to be the eigenvector corresponding to eigenvalue one
 373 (Perron-Frobenius theorem) [30].

$$\mathbf{x}^* = \mathbf{x}^* \cdot \mathbf{T} \quad (\text{A.5})$$

Following we solve for the stationary soil quality distribution. Using the system of Eq. A.4, we find:

$$x_i^* = \left(\frac{\gamma}{1-\gamma} \right)^i x_0^*, \quad i \in [0, K] \quad (\text{A.6})$$

which upon using the normalization constraint, simplifies to:

$$x_i^* = \frac{\left(\frac{\gamma}{1-\gamma} \right)^i}{\sum_{i=0}^K \left(\frac{\gamma}{1-\gamma} \right)^i}, \quad i \in [0, K] \quad (\text{A.7})$$

Figure A.3: **Soil quality equilibrium distribution for different switching frequency.** With $a = 1$ and $b = 1$, the distributions are plotted using relation A.7. The distributions for higher (lower) γ are expectedly skewed to the right (left) of the soil quality spectrum.

374 The steady state soil quality distribution for different values of γ is shown in Fig A.3.

As described earlier, both cover and cash crop strategies as shown in A.1 are individually losing games. However, it is not straightforward to say anything about the randomly mixed game. To find out if the combined game is a winning game or a losing game, we focus on the quantity, P_{win}^R defined as:

$$P_{\text{win}}^R = q_1 \sum_{i=0}^{\theta} x_i^* + q_2 \sum_{i=th+1}^K x_i^* \quad (\text{A.8})$$

375 where, $q_{1/2} = \gamma p + (1 - \gamma)p_{1/2}$.

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In this work, irrespective of the crop type, we assume profit and loss of one unit to the cumulative yield. The average rate of change of the capital is:

$$\left\langle \frac{dX_n}{dn} \right\rangle = 2P_{\text{win}}^R - 1, \quad (\text{A.9})$$

377 where $\langle \dots \rangle$ denotes the ensemble average. This formula is used to compute P_{win}^R , both for
 378 randomised switching as well as deterministic switching, from the slopes of cumulative yield
 379 trajectories. As an example, the Parrondo effect has been explicitly verified for randomised
 380 switching in Fig. A.4 with an agreement between the numerical and simulation analysis.

381 So far, we have considered $a = b = 1$. However, in natural settings, the soil quality is
 382 depleted at faster rates by cash crops than the rate of recovery by the cover crops; for example,
 383 see Fig. A.5. Therefore in the following, we study $a \neq b$ ($a < b$) scenarios.

Figure A.4: **Parrondo effect.** $\theta = 2$, $p = 0.4$, $p_1 = 0$, $p_2 = 0.8$ and $K = 10$ with $a = b = 1$ (equal jump sizes in the forward and backward direction). Profit is characterised by a unit increase in profit, $+1$ and a loss by unit decrease, -1 . Simulation. same parameters as that of part (a) with $\gamma = 0.6$, $n = 1000$ (number of rounds/games played) and $m = 10000$ (number of independent trials). From the fit, we can compare the P_{win}^R from the numerical (turns out to be 0.544) and simulated analysis (0.5372).

Figure A.5: **Soil quality dynamics under asymmetric crop effects** In this figure, $a = 1$ and $b = 2$.

We use the following system of equation for the time evolution of soil quality probability state vector $\mathbf{x}(t)$:

$$\begin{aligned}
x_0(t+1) &= (1-\gamma)x_0(t) + (1-\gamma) \sum_{i=1}^b x_i(t), \\
x_i(t+1) &= \gamma x_{i-a}(t) + (1-\gamma)x_{i+b}(t), \quad i \in [a, K-b], \text{ bulk} \\
x_i(t+1) &= (1-\gamma)x_{i+b}, \quad i \in [1, a-1], \text{ left boundary} \\
x_i(t+1) &= \gamma x_{i-a}(t), \quad i \in [K-b+1, K-1], \text{ right boundary} \\
x_K(t+1) &= \gamma x_K(t) + \gamma \sum_{i=1}^a x_{K-i}(t)
\end{aligned} \tag{A.10}$$

The transition matrix $\mathbf{T}$ for the case of $a = 1$ and $b = 2$ is written below:

$$\mathbf{T} = \begin{bmatrix} 1-\gamma & \gamma & 0 & \cdots & \cdots & \cdots & \cdots & 0 \\ 1-\gamma & 0 & \gamma & 0 & \cdots & \cdots & \cdots & \vdots \\ 1-\gamma & 0 & \ddots & \ddots & 0 & \cdots & \cdots & \vdots \\ 0 & \ddots & \ddots & \ddots & \ddots & 0 & \cdots & \vdots \\ \vdots & \cdots & \ddots & \ddots & \ddots & \ddots & 0 & 0 \\ \vdots & \cdots & \cdots & \ddots & 0 & 0 & \gamma & 0 \\ \vdots & \cdots & \cdots & \cdots & \ddots & 0 & 0 & \gamma \\ 0 & \cdots & \cdots & \cdots & \cdots & 1-\gamma & 0 & \gamma \end{bmatrix} \tag{A.11}$$

In Fig. A.6 panel (A), we show that θ^* decreases with the increase in the rate at which cash crop depletes soil quality. The value of θ^* can also be visualised from the curve of the second sum, normalised. It is defined as, $(q_2/P_{\text{win}}^R) \sum_{i=\theta+1}^K x_i^*$. It is the second term on the right-hand side of Eq. 1 being normalised, and hence the name second sum normalised. As discussed in the main text, the most contribution to P_{win}^R comes from the second term. The decrease P_{win}^R is accompanied by a decrease in the second term. Until θ^* the second sum normalised hovers around one, and beyond that, it drops quickly. In Fig. A.6 panel (B), θ^* are shown by the vertical black lines for three different cases of b/a . Respective curves drop quickly beyond these lines.

Figure A.6: **Example profit regions.** With the increase in b/a , size of the range $\gamma_{\max} - \gamma_{\min}$ and the corresponding value of θ^* decreases. Second sum normalised can be used to visualise θ^* . Plots on the right for $\gamma = 0.7$. Vertical lines represents θ^* for different value of b/a . $\theta^* = 3, 15$ and 31 for $b/a = 1, 1.5$ and 2 , respectively. Other parameters, $K = 40$, $p = 0.4$, $p_1 = 0$ and $p_2 = 0.8$.

Figure A.7: **Second sum normalised.** Here we illustrate the mechanism by which the profit regions increase/decrease due to the addition of fertilisers. The main contribution to P_{win}^R comes from the second term on the r.h.s of Eq. 1. θ^* corresponding to two cases, namely, with and without fertilisers, are indicated by the black vertical lines. The order of the second sum normalised for these two cases in the region enclosed by two vertical lines dictates which case has more significant profit regions. Parameters are the same as in Fig. 3 while γ is 0.7 for the lower panel figures.

Figure A.8: **Uncurved separatrix.** Here both games are displayed in the joint effective probability space. Red marker represents the cash crop game with $p_1 = 0$ and $p_2 = 0.8$, while blue marker represents the cover crop with $p_1 = p_2 = 0.4$. Randomized switching between these two games results in a plethora of games represented by the straight line joining these two points. As discussed in the main text, the cash crop game is a losing game whenever $p_1 < 0.5$, thus the separatrix separating the winning and losing regions of the probability space is uncurved. However, in the case of conventional capital dependent Parrondo's game, the separatrix is curved, a key ingredient for generating winning outcomes on switching between two losing games. In this sense, the Parrondo type phenomena that we encounter in our work is a different type of Parrondo games mechanism.