Modelling crop diversification and association effects in agricultural systems

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Abstract:

The need to redesign more sustainable agricultural systems able of producing more, especially through intercropping or agroforestry, cannot be achieved without taking into account the essential aspect of production variability. Yet, although many studies have focused on the effect of intercropping on overall production, the particular issue of production variability in such systems remains relatively unstudied. The approach we propose, for a shift towards sustainable intensification of agricultural systems, considers the dual dimensions of yield and risk in a combined framework for the assessment and the comparison of two diversification strategies: (i) a simple diversification strategy (SDS) considered as an increasing number of crops grown on separate plots within a farm and (ii) an intercropping strategy (IC) considered as a within-plot increased diversity, where more than one species is grown at the same time and place. The two perspectives examined here were Modern Portfolio Theory and Land Equivalent Ratio. The former quantifies the effect of diversification on risk, the latter measures the effect of association on production. This research merges both approaches in a combined framework in order to assess intercropping system performances. By applying our framework to cases selected from the literature, we explored and compared the potential benefits of these two strategies in terms of yield and risk. Results showed that intercropping, in addition to being interesting with regard to yield, can have an additional risk reduction effect compared to a simple diversification strategy. Conversely, some crop mixtures maintained or even increased yield variability. Our work contributes to a better understanding of the possible impacts of diversification strategies on trade-offs between yield and risk, but also underlines the importance of taking yield variability into account in further studies.

1. Introduction

Agricultural systems are facing a productive challenge, the necessity to ensure a sufficient quantity of goods for a growing population (Fischer et al., 2014; Tilman et al., 2011; Tscharntke et al., 2012). However, this productivity issue cannot be decoupled, even more so today, from the necessity of stability of this provision service (Hardaker et al., 2015; OECD, 2011). Indeed, weather and climate being significant drivers of agricultural production systems, food security seems doomed to deteriorate on a global scale, despite advances in technology and other fronts (Matiu et al., 2017; Osborne and Wheeler, 2013; Ray et al., 2015). In addition, the ecologization of agriculture limits the pool of management options available for farmers or their efficacy to control system variability, indicating the importance of finding farm-level responses (HLPE, 2019; Reidsma et al., 2010).

The dual productivity-stability issue therefore seems essential for designing and evaluating sustainable agricultural systems in a situation of increasing uncertainties (Muller et al., 2017; Urruty et al., 2016). Production stability depends on scale in nested systems. Although greater stability through crop diversity can be achieved at a national level (Renard and Tilman, 2019) it seems that farm-scale is a crucial level to achieve this property (Reidsma et al., 2007). In this context, new farming organizations have emerged in the last decades, creating diversified systems based on the agroecological paradigm (Krebs and Bach, 2018; Wezel et al., 2014, 2009). Among these diversified systems, we can identify two diversification pathways. The first one, called Simple Diversification Strategy (SDS) corresponds to an increased cultivated diversity, that is to say, an increased number of species grown within a farm (Malézieux et al., 2009; Ratnadass et al., 2012). Because different crops are grown in different fields, (i.e., spatial diversification) biological interactions between crops do not occur. The other diversification strategy is called intercropping (IC) and refers to the spatial association of crops on the same plot and involves a diversity of ecological interactions between crops (Lovell et al., 2017; Torquebiau, 2000; Vandermeer, 1989). In the case of tree-crop interactions, this system is also referred to as agroforestry.

In contrast to monocultures, both strategies lead to a more diversified production system, but while SDS relies on diversification to reduce risks, IC relies also on spatial association to benefits from the biological interactions between crops. Therefore, these two diversification strategies rely on two stacked paradigms in managing the balance between risk and yield, and a comparison of both approaches regarding risk-yield trade-offs is still lacking.

A relevant tool to address this issue is the Modern Portfolio Theory (MPT). The MPT has been initially developed in finance (Markowitz, 2010, 1952) and recently used in agricultural sciences to select relevant crop combinations in a portfolio under uncertainty (Barkley and Peterson, 2010; Fraser et al., 2005; Nalley and Barkley, 2010; Paut et al., 2019; Van Noordwijk et al., 1994). The central point of this theory is based on the fact that if productions of the two crops are not perfectly correlated with each other, combining these crops in a portfolio, which corresponds to a diversified land use, makes it possible to reduce the risk associated with crop production. Specifically, there may be large potential gains from combining varieties or species that are characterized by inverse yield responses to environmental fluctuations such as droughts, pests or diseases.

Applied to agricultural sciences, MPT makes it possible to define the best crop combinations when the expected yields, the individual risks of each crop, as well as the correlations between crops are known (Knoke et al., 2015; Paut et al., 2019). Although other definitions of risk exist in agricultural studies the MPT considers risk as the unpredictability of yields (i.e. standard deviation of yield) rather than the probability of not reaching a stated goal (Van Noordwijk and Van Andel, 1988; Van Winsen et al., 2013). Thus the overall yield and risk of a crop portfolio, considered as a group of physically separated plots, can be assessed (Castro et al., 2015; Fraser et al., 2005). This approach therefore seems to be more appropriate for a simple diversification strategy (SDS) rather than for the selection of intercropping systems (IC), where interactions between crops are sought and can lead to a non-linear effect on yields (Paul et al., 2017).

Besides, intercropping (IC) is another form of diversification in which interactions between crops are prevalent. Crop interactions that may lead to an increasing productivity are often assessed by the so-called Land Equivalent Ratio (LER) (Willey, 1979a). The LER compares the land-use efficiency of crops grown in intercropping systems with sole crops. It is a widespread and useful indicator to assess the benefits of intercropping in terms of production, but it is generally used in a way that does not consider a possible decrease of the yield variability that could result from intercropping (Fukai, 1993; Lithourgidis et al., 2011; Rao and Willey, 1980).

Yet, from a biological perspective, it seems that mixed systems are better able to buffer environmental variations. Beyond the diversification effect above-mentioned, ecological interactions can generate a combination of stabilizing mechanisms such as complementarity in resource use, i.e. the ability of one component to use resources not needed by another one, which leads to a compensation in the ecosystem functions they provide and promotes stability (Bedoussac et al., 2015; Grman et al., 2010; Tilman, 1999). Facilitation mechanism can also occur when certain species mitigate harsh environmental conditions or provide resources for others (Hooper et al., 2005; Mulder et al., 2001; Vandermeer, 1989). Such mechanisms obviously cannot occur if the crops are grown separately. However, even though biological diversity has been reported to be important in yield stability, there is still limited experimental evidence of this relationship in the specific case of crops interacting with each other (Blandon, 2004; Francis, 1989; Willey, 1979b) and some conflicting reports. The early research on intercropping suggested that these systems are likely to be more stable (Rao and Singh, 1990; Vandermeer and Schultz, 1990) but there is still little quantitative information on the extent or the operational significance of this improved performance. In some cases, intercropping systems can have more stable yields over time and can serve as a risk mitigation strategy due to the relative sensitivity of their component crops to temperatures fluctuations, drought or pests and diseases (Francis, 1989). Inversely, the production variability can increase due to the existence of shared pests and diseases, e.g. polyphagous insects, fungal diseases (Schroth et al., 2000) or the microclimate created by one plant on the other (Jose et al., 2004; Monteith et al., 1991). In the end, in many situations it remains unclear whether increased stability can be achieved effectively and whether this stability is due to the diversification effect or to biological interactions between crops (Blandon, 2004, 1985; Paul et al., 2017; Rao and Singh, 1990; Rao and Willey,1980).

To summarize, Modern Portfolio Theory and Land Equivalent Ratio are relevant frameworks to analyze different mechanisms associated with diversified cropping systems. MPT makes it possible to formalize the risk reduction effect of crop diversification, but does not, in its standard application, consider ecological interactions between crops neither spatially nor temporally. LER provides a standardized basis to assess mean production of intercropping systems, but does not account for the risk-reduction effect of such diversification (although it could also be applied to any parameter of a statistical distribution rather than the mean, e.g. to an X% percentile). The aim of the present study is therefore to combine these two theoretical approaches in a unified framework to formalize the effect of intercropping on both production and risk (Fig. 1).

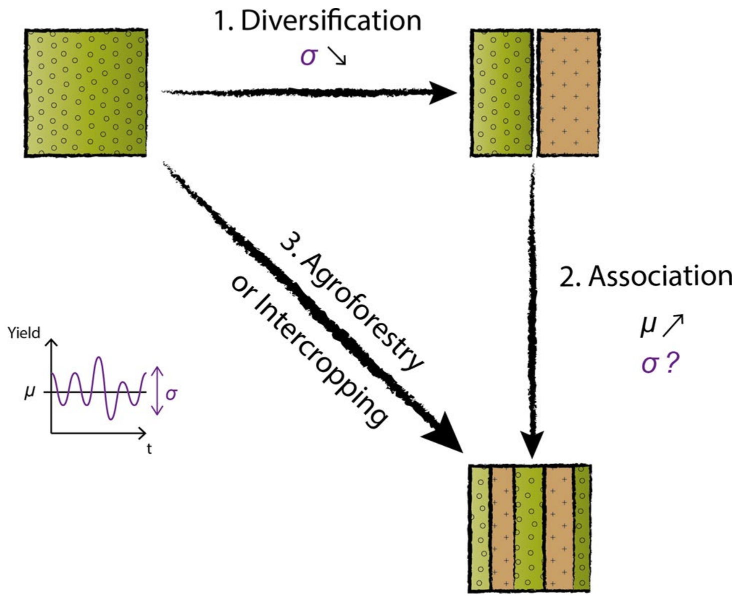

Fig. 1. Graphical summary of the approach, with μ standing for mean crop production and σ its standard deviation.

We will then apply our framework to horticultural systems, for which the issue of diversification and association is of great relevance. Horticulture, indeed, makes it possible to combine a large number of crops with a wide range of functional traits in both diversification and association configurations. Moreover, there has been a strong development of diversified horticultural systems in recent years, combining an increasing crop diversity (Morel et al., 2017; Morel and Léger, 2016; Navarrete et al., 2015) with intercropping and agroforestry configurations (Léger et al., 2019, 2018; Sieffert et al., 2014). This creates a fertile ground for the application of our conceptual framework to an applied issue relevant to a growing number of farmers. For the application of our conceptual framework, we conducted a literature review from which we extracted the data necessary for the application of this model.

2. Material and Method

2.1 Formalizing the diversification effect through the modern portfolio theory

Markowitz (2010, 1990, 1952) first introduced the so-called Modern Portfolio Theory (MPT) in finance in order to analyze how diversified portfolios of assets could provide a risk reducing effect, as long as assets return are not perfectly correlated. He defined risk as the portfolio standard deviation. In our case, a portfolio diversification consists in moving from a monoculture to a more diversified agrosystem. According to the MPT, the expected yield of a portfolio P is the weighted sum of each individual asset in the portfolio:

$$E(Y_P) = \sum_i w_i E(Y_i) = w_A E(Y_A) + w_B E(Y_B) \qquad (1)$$

where w_i is the weight of crop *i* (that is, the proportion of the cultivated area of crop *i*), $E(Y_i)$ is the expected yield of crop *i* and the sum of w_A and w_B is equal to 1. Notice that in this view, the yield associated with each asset is independent from the composition of the portfolio.

Furthermore, the risk of a portfolio is measured by its standard deviation. The risk of the system composed of two crops (Crop A and Crop B), σ_P, is defined as follows:

$$\sigma_P = \sqrt{\sum_i \sum_j w_i w_j \sigma_{ij}} = \sqrt{w_A^2 \sigma_A^2 + w_B^2 \sigma_B^2 + 2 w_A w_B \sigma_A \sigma_B \rho_{AB}} \qquad (2)$$

where σ_i is the standard deviation of yield for crop *i*, ρ_{AB} is the correlation coefficient of crop *A* and crop *B*. Eq. (2) shows that the standard deviation of the portfolio (σ_P) is the sum of two components: a variance term and a covariance term. It follows that the variability of a portfolio can be reduced in two ways, either by favoring crops with low yield variances, or by choosing crops with a low coefficient of correlation ρ. The effect of different values of ρ is illustrated in Fig. 2.

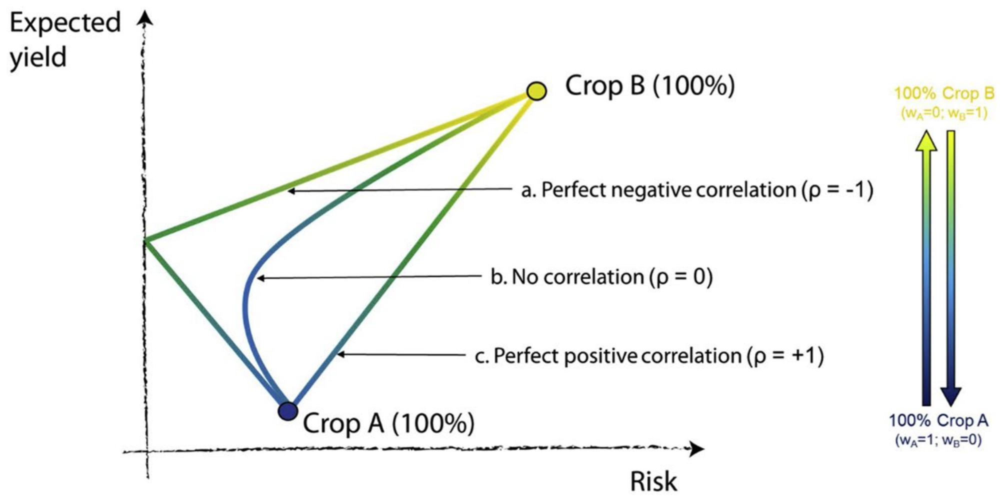

Fig. 2. Possible yield and risk combinations for a two-crops portfolio when: (a) crop yields are perfectly negatively correlated (ρ_{AB} = -1); (b) crop yields are not correlated (ρ_{AB} =0) and (c) crop yields are perfectly correlated (ρ_{AB} = +1).

2.2 Formalizing the association effect through the Land Equivalent Ratio

When two crops are cultivated simultaneously on the same plot, interactions between these two crops may lead to an overall production different from the weighted sum of the production of each crop cultivated in monoculture. This association effect is classically assessed in the literature by the so-called Land Equivalent Ratio (LER) (Bedoussac and Justes, 2011; Mead and Willey, 1980; Vandermeer, 1989; Willey, 1979a). LER represents the relative area needed for sole crops to produce the same yields as those obtained by an intercropping design. For a given proportion (k) of crop A in the association with crop B, the value of the LER_k it is calculated as the yields of each individual crop in relation to their yield as sole crop (Eq. (3)).

$$LER_k = LER_A^k + LER_B^{1-k} = \frac{Y_A^k}{S_A} + \frac{Y_B^{1-k}}{S_B} \quad (3)$$

Where Y_k^i is the yield of crop i when grown as an intercrop at the proportion of k, S_i is the yield of crop i when grown as a sole crop. An LER greater than 1 means that the intercropping system mixing crop A and crop B produces more than its respective monoculture for the same cultivated area. The value 1 is the critical threshold, above which the intercrop is to be favored, and below which the monocultures may be preferred. Following Vandermeer (1989), we consider only three situations where the LER continuum might be convex (competition), concave (facilitation) or linear (no interaction), presented in Fig. 3.

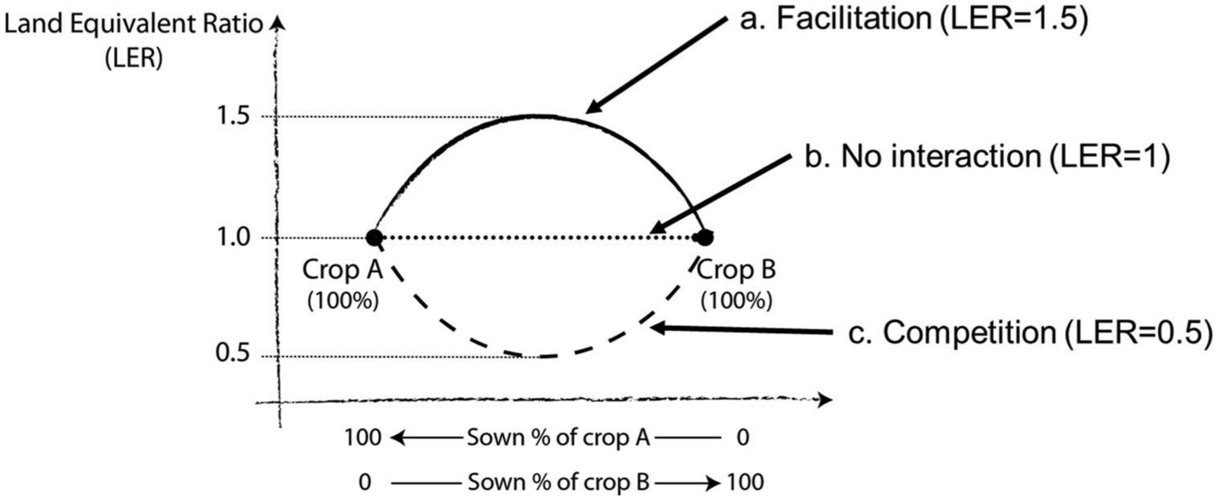

Fig. 3. Examples of three qualitatively distinct forms of the Land Equivalent Ratio distribution. The solid curve represents a situation of facilitation (LER = 1.5); the dotted line represents a situation of independence (LER = 1) and the dashed line represents a situation of competition (LER = 0.5).

2.3 Proposition of a new conceptual framework

As discussed above, despite an emerging consensus on the fact that intercropping can decrease the overall yield variability, this effect has rarely been quantified and no study clearly disentangled diversification effect from association effect on individual crop variability in horticulture (but see Van Noordwijk et al., 1994 for other crops). For the application of our new conceptual framework, this leads us to recompose Eqs. (1) and (2) into Eqs. (4) and (5) respectively. Thus, the intercropping portfolio yield $E(Y_{AB})$ is considered as the weighted average of each crop yield multiplied by its relative yield in intercropping design:

$$E(Y_{AB})^k = LER_A^k w_A E(Y_A) + LER_B^{1-k} w_B E(Y_B) \quad (4)$$

where $E(Y_i)^k$ is the expected yield of crop i and LER_A^k is the partial LER of crop A at the proportion of k in the portfolio.

Besides, the risk of the intercropping portfolio is defined by Eq. (5) as the risk of a two crop portfolio multiplied by two factors. First, as for the yield (Eq. (4)), yield variability is subject to an affine transformation and is multiplied by the LER corresponding coefficient at the proportion of k in the intercropping design. Then, we introduce the coefficient β for the specific effect of intercropping on risk:

$$\sigma_{P(A,B)}^{k} = \sqrt{w_A^2\left(\beta_A LER_A^k \sigma_A\right)^2 + w_B^2\left(\beta_B LER_B^k \sigma_B\right)^2 + 2w_A w_B \beta_A LER_A^k \sigma_A \beta_B LER_B^k \sigma_B \rho_{AB}} \quad (5)$$

β_A and β_B are the partial coefficient of crop A and B respectively, that represent the effect of intercropping on yield variability. Due to the lack of sufficiently accurate data in literature to evaluate β_A and β_B, we will consider β_A and β_B being equal in the present application, but different values of β_i are explored in Appendix A. Beta being strictly positive, we can factorize into Eq. 5bis:

$$\sigma_{P(A,B)}^{k} = \beta\sqrt{w_A^2\left(LER_A^k \sigma_A\right)^2 + w_B^2\left(LER_B^k \sigma_B\right)^2 + 2w_A w_B LER_A^k \sigma_A LER_B^k \sigma_B \rho_{AB}} \quad (5bis)$$

2.3.1 Considering different effects of intercropping on risks: three hypotheses

Yield variability of each crop may be affected by the intercropping design, positively or negatively depending on the choice of intercrops and their interactions. In this study, we will successively consider three contrasted hypotheses representing different effects (β values) of intercropping on yield variability. First, the intercropping design decreases the variability of crops yields (i.e. when $\beta < 1$) compared to a simple diversification strategy (SDS), the portfolio standard deviation σ_P is reduced. This hypothesis integrates an additional risk reduction effect of crop association, compared to SDS. The second hypothesis states that the variability of each crop remains unchanged in intercropping compared to that of SDS. In other words, we assume that there is no biological effect of IC on yield variability of each crop. In this case, the β coefficient is therefore set at 1. Third, the intercropping design has a negative impact on crop yield stability (i.e. when $\beta > 1$), the portfolio standard deviation σ_P would be increased.

2.3.2 Exploration of contrasted scenarios considering our hypotheses

In order to screen different configurations, we developed scenarios that illustrate possible patterns in a contrasting way. Within each scenario, we considered the combination of three effects: (*i*) the effect of crop diversification on risk (ρ_{AB}); (*ii*) the effect of crop association on productivity (LER) and (*iii*) the effect of crop association on risk (β). Depending on how crops interact with each other, the LER can take any positive value, but in most cases, it lies between 0.5 and 1.5. To show contrasting situations, we selected three LER values that represent three distinct biological interactions: competition (LER = 0.5), independence (LER = 1) and complementarities (LER = 1.5). Similarly, the correlation coefficient between crop A and crop B can take any value between -1 and 1. As an extreme situation, if yields are perfectly correlated, ρ_{AB} will be equal to 1. At the other extreme will be a situation where ρ_{AB} is equal to -1, between these two bounds will be a continuum of cases where the yields of the two crops are more or less closely related. In agroforestry systems it may be a common situation where the yields of crops and trees are not correlated (Blandon, 1985), in this case ρ_{AB} will be zero. Finally, considering our working hypotheses (Cf. supra), the association effect on risk (β) was set at 0.5, 1 and 1.5, reflecting a decrease of individual crop variability ($\beta = 0.5$), no effect ($\beta = 1$) or an increase of individual crop variability ($\beta = 1.5$). The combination of these three effects, each taking three distinct values, generated 27 scenarios presented in Fig. 4.

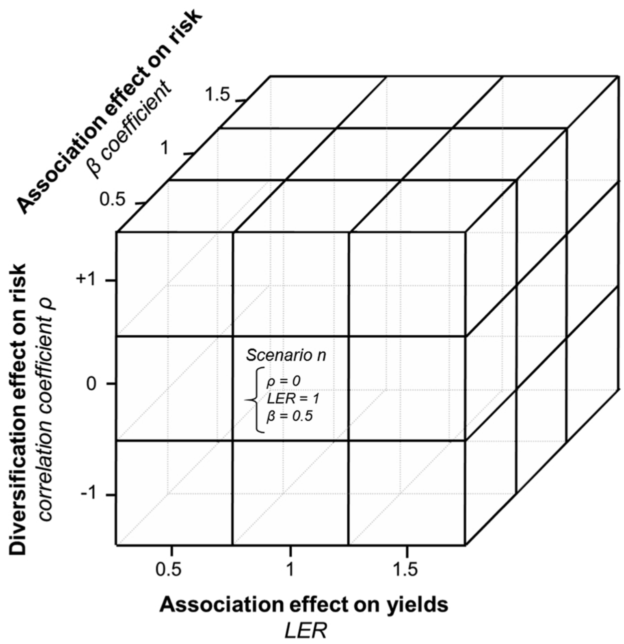

Fig. 4. Parameter values for the development of the 27 contrasted scenarios.

2.4 Mini review on intercropping systems based on fruits and/or vegetables to identify promising intercropping systems for the design of mixed horticultural systems

2.4.1 Data collection

In order to illustrate our approach, we applied our framework to real situations of intercropping. A literature review was carried out on horticultural intercropping systems. Studies were identified from a search in the Institute for Scientific Information Web of Knowledge and Google Scholar databases. We searched for the following terms: *(intercrop* OR agroforestry OR mixed crop*) AND (fruit* OR orchard OR vegetable* OR market gardening).* Among the 1,387 publications that came out of this query, we selected 74 studies that provided the data necessary to compute LER values. The reviewed papers involved vegetables and/or fruits in intercropping or agroforestry designs. It resulted in 534 experiments (an experiment is defined by a unique crop combination in site and year) from which 449 were complete, meaning that both crop yield as sole crops and intercrops were available. From each experiment, we also extracted and coded crop species, relative crop density, LER, location and other useful information from each treatment. The list of reviewed papers is provided in Appendix B.

2.4.2 Simulations

Among the 74 studies reviewed for LER values, our model combining MPT and LER approaches was applied to all studies for which there were inter-annual repetitions of yield measurements. This resulted in 41 studies for which sufficient data were available: the yield of each crop $E(Y_i)$ is the mean yield of inter-annual repetitions; the standard deviation of each crop σ_i is calculated as the inter-annual variability of yields; the Land Equivalent Ratio LER_i^k is the LER of crop i at the proportion k; the weight of each crop in the portfolio w_k is the proportion of crops in the intercropping design and the correlation coefficient ρ_{AB} is the correlation between crop yields through time.

Once $E(Y_i)$ and σ_i were computed for each intercropping design, we simulated the yield and risk combinations for 100 proportions of crop A and crop B (from $w_A = 0$ to $w_A = 1$) considering our two hypotheses.

First, assuming intercropping had no effect on risk, Eqs. (4) and (5) were applied to calculate yield and risk respectively. Second, assuming intercropping had an effect on risk, we used raw data from the paper to obtain the coefficient β by solving Eq. (5bis). Finally, intercropping systems were clustered using a k-means clustering on the three model output parameters (LER, β, ρ). Clusters were projected on the three dimensions and a Tukey's HSD was used to identify differences in cluster parameters. The model was implemented and graphical outputs were realized with R software 3.5.0 (https://cran.r-project.org).

3 Results

3.1 Yield and risk trade-offs: comparing SDS and IC

For the 27 possible combinations of Land Equivalent Ratio (LER), beta coefficient (β) and correlation coefficient (ρ), the yield-risk relationship curves were plotted, based on Eqs. (4) and (6). Points named Crop A and Crop B represent the yield and risk of sole crops ($w_A = 1$ and $w_B = 1$ respectively). The transition from Crop A to Crop B corresponds to the consideration of systems with an increasing area of crop B.

Fig. 5 shows the possible scenarios for 27 alternative cropping systems. Moving from scenario 1 to 3 corresponds to an increasing association effect on yield, whereas moving from A to C corresponds to taking the different hypotheses of intercropping effect on risk into account. Notice that the line joining crop A to crop B in the scenario B2 also represents the weighted average of crop yields and risks. It can serve as a basis for the assessment of land-use alternatives on yield and risk dimensions. In confronting the different diversification alternatives, we can observe that some options perform better than sole crops on both dimensions (A3, B3). Some other options are only of interest in one of the two dimensions (A1, A2, B2, C2 and C3), which illustrate that intercropping can lead to a trade-off between the different expected benefits. Finally, some combinations perform poorly compared to the weighted average on both dimensions (B1 and C1). These portfolios, in addition to being in a competitive situation, exhibit greater variability than their pure crop equivalents.

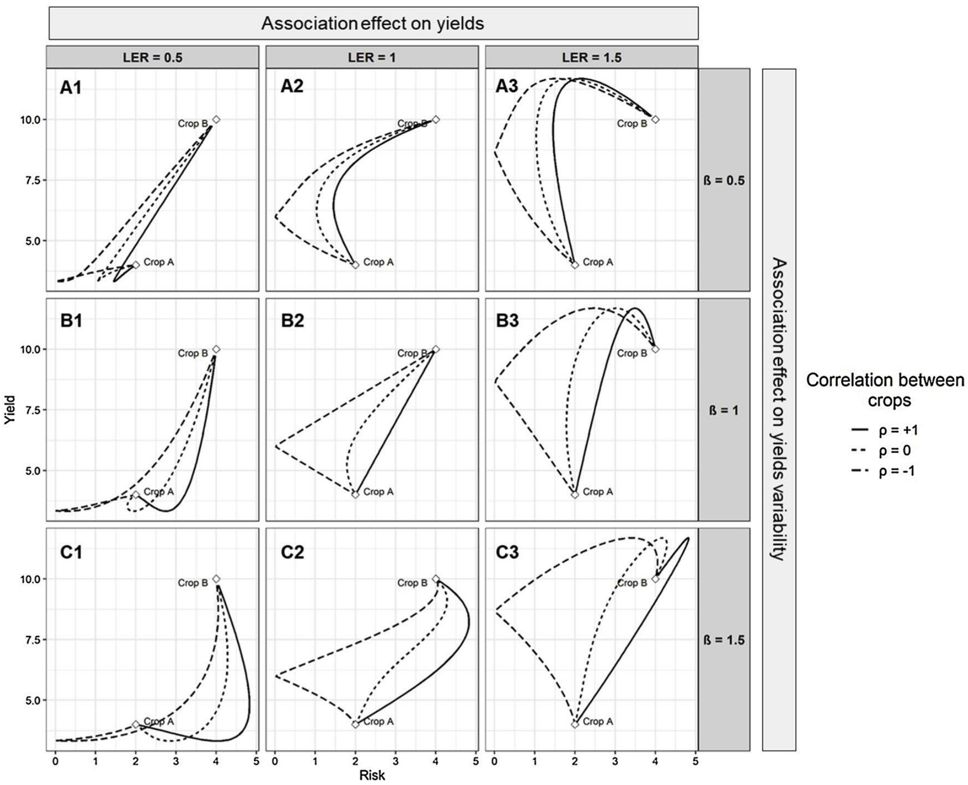

Fig. 5. Yield and risk trade-offs among 27 contrasting scenarios of land-use options. Each curve represents a unique combination of LER, β and ρ coefficients. Moving from crop A to crop B corresponds to the consideration of systems with an increasing area allocated to crop B.

In addition, the combination of crops are presented considering a low risk – low yield crop combined with a high yield – high risk crop. This type of combination is very common in agriculture. However, other functional forms may be obtained when a high yield – low risk crop is combined with a low yield – high risk crop as shown by Paut et al. (2019). Interestingly, this functional form adding a high-risk crop to a low-risk monoculture is still beneficial in terms of risk reduction. We do not detail these situations in this result section but we observed the same diversity of patterns. The reader may find them in Appendix C.

3.2 Application of our framework to selected cases from the literature

3.2.1 Characteristics of fruits and/or vegetables intercropping systems in the literature

The analysis of LER values among these observations found an average 38% increase in yield in intercropping designs compared to their monoculture components (*t*-test, $p < 0.001$). Overall, intercropping was more efficient than monocropping, since 405 out of the 449 calculated LER values were larger than 1 (Fig. 6a) but still 44 situations showed a LER < 1 corresponding to a lower yield in association than in sole crops. Moreover, the standard deviation on LER was 0.36, suggesting a high variability in LERs depending on crop species, treatments and experimental designs.

3.2.2 Modelling diversification and association effect on selected cases from the literature

Our model combining MPT and LER approaches was run on 41 studies for which sufficient data was available. From the reviewed papers, we could also extract the β value, which gives an indication of the relevance of the intercropping (in a given pedoclimatic context) with regard to yield variability. For illustrative purposes, two contrasting case studies have been selected among a large variety of cases, but the full set of intercropping systems is described in Appendix D.

In the first example given here (lettuce-radish intercropping, Fig. 7a, Cecílio Filho et al., 2007), diversification led to a strong reduction in risk and association made it possible to reach the lowest level of risk for a yield similar to the one obtained with lettuce only. In this case, there is a supplementary risk reduction effect due to the intercropping design (β < 1). Thus, in addition to having a positive effect on yield (LER = 1.48), the intercropping has an additional risk-related advantage over a simple diversification.

Another interesting example of agroforestry system for which we found sufficient data in the literature is Apricot-Peanut intercropping (Fig. 7b, Bai et al., 2016) and it corresponds to the C3 functional form (Cf. Fig. 7). In this particular example, crop yields are strongly positively correlated, meaning that there is little effect on risk due to diversification. The yield improvement is important (LER = 1.35) but we can observe a strong increasing effect of intercropping on yields variability (β = 1.67). In this example, there is no effect of diversification on risk, but additionally, the intercropping increases yield variability.

From the reviewed papers, we observed an average positive correlation between crop yields; the average correlation coefficient was 0.25. The findings also indicate a strong positive effect of intercropping on yields, the average Land Equivalent Ratio was 1.40. We also extracted the β value, which gives an indication of the relevance of the intercropping with regard to yield variability. This coefficient provides information on whether the intercropping is profitable in terms of risk reduction, compared to a simple diversification strategy (in a given pedoclimatic context). The average value of β was 0.79. The statistical analysis (*t*-test) of β showed that it was significantly below 1 ($p < 0.001$) meaning that on average intercropping reduced individual crop variability.

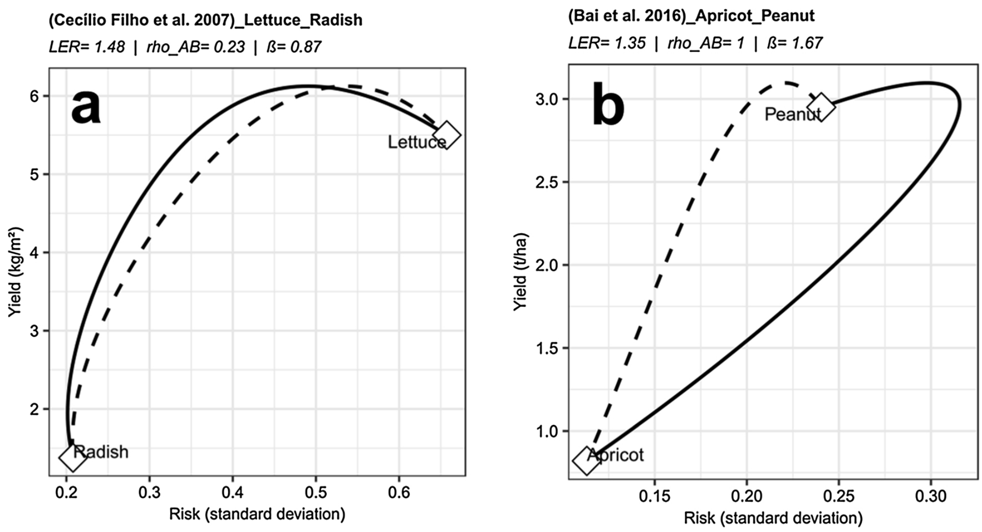

Fig. 7. Risk-yields combinations considering our two hypotheses for two crop couples: (a) Lettuce-Radish and (b) Apricot-Peanut. The dashed curve represents the baseline hypothesis (H1) in the case where intercropping is assumed to have no effect on risk (beta = 1). The solid curve represents the alternative hypothesis (H2) in the case where intercropping effect on risk is considered (β = 0.87 Fig. 7a; β = 1.67 Fig. 7b). Moving from crop A to crop B implies an increasing proportion of crop B in the intercropping design.

3.2.2 Distinction in intercropping types

On the basis of a cluster analysis (k-means) the 41 selected experimentations were categorized into four clusters with different patterns in the dimensions LER, β and ρ (Fig. 8). The different intercropping clusters showed important variations in their structural parameters, except from the Land Equivalent Ratio, which remained relatively similar between clusters. Cluster 1 is characterized by a low correlation coefficient (-1) and a low β (0.63). Cluster 2 shows a similar β but can be distinguished from the first cluster by a correlation coefficient equal to 1. Clusters 3 and 4 differ from the two first ones on parameter β, which is close to one (0.94 and 1.06 respectively). They differ from each other on the parameter ρ (0.18 and 1.00 respectively). Overall, the clusters are characterized by different combinations of β and ρ values. This reflects a variety of diversification and association effects on yield variability. The details of the cluster analysis and further statistical analysis are presented in Appendix E.

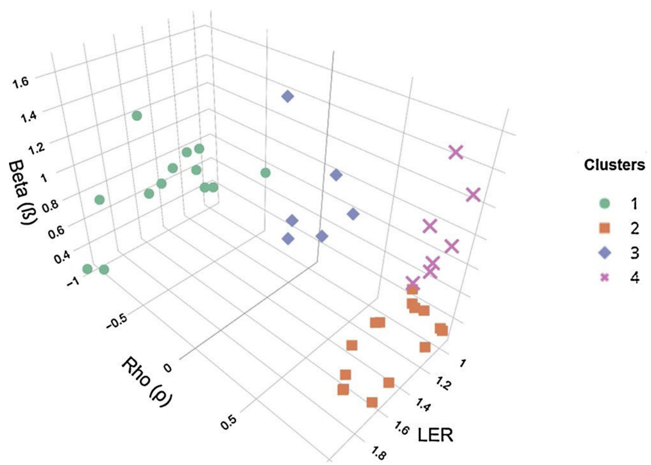

Fig. 8. Representation of the studies reviewed as a function of the three dimensions (LER, β, ρ) considered in our model. K-means clustering on the three dimensions distinguished four types of intercropping systems.

4. Discussion

4.1 A framework to comparre simple diversification strategy and intercropping

The two perspectives examined here were Modern Portfolio Theory and Land Equivalent Ratio. The former quantifies the effect of diversification on risk, the latter measures the effect of association on production. This research has merged both approaches in a combined framework in order to assess intercropping and agroforestry system performances. By applying this framework to real cases from the literature, our work contributes to a better understanding of the possible impacts of diversification strategies on the trade-offs between productivity and risk. The present model is not straightforward for deciders, but it requires some minor adaptations to serve as a decision-making tool. By formalizing the model to make it accessible and to facilitate the interpretation of its results for application purposes, it may therefore facilitate the choice of farm portfolios that results in the best agronomic performances associated with the lowest variability. The advantage of a bi-dimensional assessment (yield-risk) of portfolios is that it does not offer a unique better option, but rather provides a wide range of choices among which each option results in a combination of association and diversification effects.

4.2 Segregate or associate crops? Necessary trade-offs

Some authors reported that mixed cropping (Kiær et al., 2009; Reiss and Drinkwater, 2018) or intercropping (Raseduzzaman and Jensen, 2017) might be sustainable strategies for increasing agroecosystems performances, by enhancing mean yield and yield stability, associated with a lower environmental impact. Our findings seem to indicate that this is indeed the case in horticulture. By comparing different diversification alternatives (Cf. Fig. 5) we can observe that some intercropping options give better results than sole crops in both dimensions (A3 and B3, Fig. 5). Those are the intercropping designs that might be encouraged without requiring compromises. Some other options are only of interest in one of the two dimensions. They will have to be the subject of trade-offs according to the production objectives of each farmer and his/her risk aversion. From the application of our framework to existing literature, we could quantify these trade-offs for a range of crop couples. First, the high average LER (1.40) indicates that intercropping is advisable in terms of yield improvements as compared to monocultures. Second, we observed a positive correlation between crop yields (average $\rho = 0.25$; median = 0.83). This might be due to the low number of inter-annual repetitions that tend to result in extreme correlation values. Nevertheless, this indicates that in intercropping, diversification has a minor effect on reducing yield variability in the reviewed papers. Finally, the mean β was 0.79, suggesting that in our sample, intercropping has overall an additional risk reducing effect as compared to Simple Diversification Systems.

By disentangling the effect of diversification and association on yield variability, our findings indicate that beyond the well-known effect of intercropping on yield, intercropping is also likely to be beneficial in terms of yield variability (or stability) and this beyond the simple diversification effect. However, the scarcity of long-term data leads us to be cautious about the numerical conclusions provided here. Moreover, our cluster analysis shows that risk reduction from intercropping is highly reliant on crop combinations. Rao and Singh (1990) highlighted this specific issue and pointed out that intercropping stability also depends a lot on crop cultivars and agronomic management. In a wider sense, it is interesting to note that a shift toward more agroecological practices can in some cases lead to increased variability in yields. Knapp and van der Heijden (2018) showed that organic agriculture has, per yield unit, a higher variability compared to conventional agriculture. Similar results were reported in horticulture by Lesur-Dumoulin et al. (2017). More generally, although agroecological systems (such as intercropping or organic agriculture) may be more environmentally friendly, further attention should be paid to reducing the variability of their yields.

Finally, trade-offs also occur in practice. Whether to integrate or segregate crops is still debated (Sida et al., 2018; van Noordwijk et al., 2012) and it is often a matter of balancing the benefits expected from the association with the complexity generated. A farmer intercropping multiple crops has to integrate other types of knowledge than that required by monocropping practices (e.g. coordinate plant growth, water requirements, pests and diseases management, harvest, etc.). This increased management complexity is even more critical when intercropping is integrated into highly mechanized agricultural systems (Bybee-Finley and Ryan, 2018). Nevertheless, in temperate areas, this is part of an ongoing 'path dependency' rather than an insurmountable challenge, as shown by research on mechanized agroforestry in Europe (Dupraz et al., 2005; Eichhorn et al., 2006).

4.3 Perspectives for the model improvement

In the present study, risk was assessed by the standard deviation of yields. It is the definition of risk which is brought by the portfolio theory. Standard deviation (or variance) is also a widespread metric for risk assessment in agricultural sciences (Ben-Ari and Makowski, 2014; Zhong et al., 2016). However, other useful approaches of risk were suggested and assumed to be suitable for intercropping systems. Rao and Willey (1980) suggested evaluating risk by calculating the probability of crop 'failure' to produce a specific income in comparison with single crops. The estimate of the probability of crop 'failure' can be meaningful because it provides a more consistent reflection of farmers' attitudes towards stability. It would also allow any tradeoff between mean increase and variance reduction to be assessed quantitatively (Van Noordwijk et al., 1994). Integrating this alternative notion of risk in our model would make it clearer whether SDS or IC can be chosen over pure crops.

Besides the issue of measuring risk, a further limitation of our application is that we limited our analysis to crop production, which does not directly reflect profitability *stricto sensu*. The issue of economic efficiency of agroforestry systems in a context of uncertainty has already been discussed (Blandon, 2004, 1985; Ramírez et al., 2001; Reeves and Lilieholm, 1993) but the lack of knowledge on biological interactions between crops and economics of such systems has made it difficult to develop a systemic model for the comparison of diversification schemes (SDS vs. IC) in relation to risk (Paul et al., 2017). Thus to refine our model, more information on production costs and returns (especially in the context of intercropping systems) for a wide variety of crops would be necessary (Pande et al., 2018). The issue of incorporating economic valuation in the model also lies in knowing the relationship between crop yields and prices. However, while the introduction of economic data can affect crop profitability, it would not generate new relationship typologies (as presented in Fig. 5). It also would have an equal impact on SDS and IC, then would not modify the relative performance of both strategies (Paul et al., 2017). In line with the issue of profitability being a suitable indicator for the assessment of such systems, we assume that alternative indicators could be integrated in the comparison between diversification strategies (Convertino and Valverde, 2013). Following Groot et al. (2012), multi-criteria approaches may be useful for the further development of our model taking into account the multiples agriculture ecosystems services. Each service can be treated separately or as proposed by van Noordwijk et al. (2018), as a whole multifunctionnalty indicator.

The illustrative applications of our framework to real situations were limited due to the scarcity of literature data. Further evaluations of yield and associated standard deviations in a wide range of systems are now needed to determine the conditions in which SDS or IC would be more efficient. In depth understanding of the biological interactions between crops, between trees and crops, pests and environmental conditions is still lacking, while it is often presented as a basis for farmers to design new mixtures and new ways to organize compatible crops in the field space (Francis, 1989). Understanding ecological functioning is indeed important and often highlighted in studies dealing with intercropping, but our data driven approach offers a complementary point of view that makes it possible to overcome the lack of knowledge on ecological processes.

Finally, the diversification approaches in this study were limited to portfolios composed of two species. Yet, considering the growing interest of farmers in combining a large number of species within complex rotations (Galluzzi et al., 2010; Hoang et al., 2014; Morel et al., 2017), it would be especially interesting to extend our approach to more diversified systems. From the theoretical point of view, extension of the framework to situations with more than two crops is straightforward and does not present any mathematical difficulty (Paut et al., 2018; Van Noordwijk et al., 1994). The issue once again lies in the availability of data, since data requirement increases rapidly with the number of crops. To our knowledge, very little research has evaluated yield and standard deviations of more than two crops in associations compared to monocultures.

5. Conclusion

Taking risk into account in decision-making for the definition of sustainable crop rotation strategies has become essential. Our approach provides an analytical framework that can help farmers or land-use planners in the comparison of simple diversification strategies with more integrated ones such as intercropping or agroforestry. By disentangling the effects of association and diversification on risk and production, we propose an approach that makes it possible to decompose the interests and limits of each of these strategies. We show that there are trade-offs between the increase in yield generated by intercropping, the reduction of risk resulting from diversification, but also the specific effect of intercropping on risk. Taking into account the resultant of these three elements is therefore crucial for the definition of diversification strategies. Long-term field experiments will be needed to better understand biological processes that underlie these interrelationships. The example applications presented in this study illustrate the particular case of horticultural systems. Nevertheless, the approach developed here remains applicable to most agricultural systems. Indeed, our model only requires farm components (crops or animal products) yield and variance, which are commonly available data, relevant for most farming systems. In this perspective, our method and findings may have wider implications for other farming systems such as field crops or mixed crop-livestock farming systems.

Declaration of Competing Interest

None.

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Appendix A, B, C, D and E

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