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A simulation study of synergies and tradeoffs between multiple ecosystem services in apple orchards

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Abstract

In this study, we analyzed the patterns of relationships between multiple ecosystem services in apple orchards by considering the cascade that links agricultural practices to ecosystem functions and then to ecosystem services. Five major ecosystem services were considered: fruit production, soil nitrogen availability, climate regulation, water cycle maintenance and regulation, including water quality, and pest and disease control. We derived indicators of ecosystem functions and of ecosystem services from model simulations of orchards driven by virtual cropping systems combining various modalities of nitrogen fertilization, irrigation, and pest control. We deciphered the links between practices and ecosystem functions and between those functions and ecosystem services and clustered cropping systems according to their ecosystem service supply. Noticeable synergies were found between yield, fruit mass and sequestrated carbon. The contribution of carbon allocation to fruit in sequestrated carbon was considerable. Nitrogen absorption, impacted by fertilization and irrigation, was a major driver of these relationships. The typology built from these virtual cropping systems clearly followed

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a gradient of provisioning and regulating ecosystem services. Five cropping systems optimized the compromise between provisioning and regulating services and were essentially characterized by organo-mineral fertilization, comfort irrigation, apple scab-resistant cultivars and exclusion nets against codling moth.

Our approach could contribute to the design of cropping systems that would provide an acceptable compromise between multiple ecosystem services in orchards.

1. Introduction

After the seminal works of Costanza et al. (1997) and Daily (1997) and the publication of the Millennium Ecosystem Assessment in 2005 (Reid et al., 2005), the ecosystem service concept has been expanding worldwide. The relationships between ecosystem services have been the subject of a growing number of studies (Cord et al., 2017) because their understanding is essential to the design of public policies and management strategies able to foster the sustainability of ecosystem service provision (Mouchet et al., 2014). There are both positive (synergies) and negative (tradeoffs) relationships between multiple ecosystem services, which arise from underlying ecosystem functions and/or management drivers (Bennett et al., 2009). As shown in the review of Lee and Lautenbach (2016), synergies are dominant between regulating or cultural services, and the relationships between regulating and provisioning services are dominated by tradeoffs. The minimization of tradeoffs is a key challenge of management policies (Rodríguez et al., 2006). As reported by Mouchet et al. (2014) and Cord et al. (2017), the analysis of ecosystem service relationships often includes the identification of ecosystem service bundles that can help link ecosystem management to desirable or undesirable sets of ecosystem services, following the pionneer work of Raudsepp-Hearne et al. (2010).

Landscape and regional scales are the most frequently considered scales in studies of patterns of ecosystem service relationships (Lee and Lautenbach, 2016; Finney et al., 2017), at the expense of smaller scales. In addition, causal relationships are often neglected (Cord et al., 2017) although a few authors have explicitly considered socio-cultural or environmental factors (Martin-Lopez et al., 2012; Renard et al., 2015; Meacham et al., 2016; Lamy et al., 2016; Feng et al., 2017). Ecosystem functions that contribute to services are rarely addressed in those studies (with the exception of Lavorel et al., 2011). Furthermore, ecosystem services are poorly quantified in many cases (Boerema et al., 2017) and there is a lack of use of models to address the issues of quantification and of relationships between services (Seppelt et al., 2011). Several studies of ecosystem service relationships have used

models, but only to quantify the services (Nelson et al., 2009; Bai et al., 2011; Leh et al., 2013; Kragt and Robertson, 2014) rather than to highlight the ecosystem functions that underpin them. The models also have the advantage of making it possible to test a wide range of management scenarios in order to understand the effect of management on ecosystem service patterns, as shown in Kragt and Robertson (2014) and Zanchi et al. (2014).

Agroecosystems, beyond the food production service, may provide multiple non-marketed services such as soil structure and fertility, water quantity and quality, biological pest control, pollination and climate regulation through carbon sequestration and greenhouse gas (GHG) mitigation (Heal and Small, 2002; Swinton et al., 2007; Zhang et al., 2007; Power, 2010). The relationships between agroecosystem services are heavily impacted by agricultural practices as well as by pedoclimatic conditions, as reported by Power (2010) and exemplified by Kragt and Robertson (2014), Schipanski et al. (2014), Syswerda and Robertson (2014) and Finney et al. (2017). This is because, first, every service depends on many ecosystem functions, possibly in opposite ways, and, second, practices and pedoclimatic conditions have a strong influence on these functions, also possibly in opposite ways, as reported in the case of orchards (Demestihas et al., 2017). We are convinced that explicit consideration of the 'cascade' that links agricultural practices and pedoclimatic conditions to ecosystem functions and then to ecosystem services (see Gaba et al., 2015 and Demestihas et al., 2017, following Haines-Young and Potschin, 2009) can help us to understand the patterns of ecosystem service relationships in agroecosystems and to address the challenge of supporting regulating ecosystem services while maintaining or enhancing the provisioning services (Power, 2010).

To this day, there has been little focus on ecosystem services in fruit orchard research. However, orchards appear to be an interesting field of study because of the impact of their perennial character on biogeochemical cycles, their high potential in fruit production, and the importance of pest management practices, among other reasons (Demestihas et al., 2017 ; Simon et al., 2017). In this

study, we analyzed, by means of model simulations, the patterns of relationships between multiple ecosystem services in the case of apple crops and at the orchard scale by considering the cascade that links agricultural practices to ecosystem functions and then to ecosystem services. We fixed the pedoclimatic conditions in order to focus on the role of agricultural practices. We also made a typology of simulated cropping systems according to their ecosystem service delivery, and identified cropping systems that optimize the compromise between provisioning and regulating services. We considered five important ecosystem services: fruit production, soil nitrogen availability, climate regulation, water cycle maintenance and regulation, including water quality, and pest and disease control. Together with these five services, we considered environmental disturbances due to pesticides. According to our cascade approach, we considered, based on the review of Demestihas et al. (2017), major ecosystem functions that underpin the selected ecosystem services, i.e., carbon, nitrogen and water balance processes, as well as pest damage and important agricultural practices that impact these functions, i.e., nitrogen fertilization, irrigation and the control of three main apple pests. Our expectation is that this study contributes to a better understanding of the functional and management bases of the relationships between ecosystem services in orchards, which is a prerequisite for the design of cropping systems that achieve desired profiles of ecosystem services.

2. Materials and methods

2.1 General approach

Figure 1 describes the general approach used in this study. Indicators of ecosystem functions and services (Section 2.2) were simulated on an annual time scale and at the spatial scale of the apple orchard plot based on the association of a crop model, STICS, and a model of crop injuries caused by pests, IPSIM (Section 2.3). Pedoclimatic data (temperature, humidity, radiation, potential evapotranspiration, rainfall and soil characteristics) and agricultural practices were inputs of the models. Model simulations used apple orchard cropping systems, i.e., combinations of agricultural practices, created *in silico* and based on different modalities of five agricultural practices - nitrogen

fertilization, irrigation, and codling moth (*Cydia pomonella*), rosy apple aphid (*Disaphis plantaginae*) and apple scab (*Venturia inaequalis*) controls - in a given pedoclimatic context (Section 2.4). The model outputs, i.e., the indicators of ecosystem functions and services, were then analyzed using two principal component analyses with respect to instrumental variables (PCAIV) in order to formalize, on the one hand, the links between agricultural practices and ecosystem functions and, on the other, the links between ecosystem functions and ecosystem services. A typology of apple orchard cropping systems was then defined using hierarchical clustering and characterized in terms of ecosystem service profiles. This paved the way for an exploration of the optimal compromise between provisioning and regulating services among the cropping systems analyzed (Section 2.5).

Figure 1: Illustration of the general approach used for analyzing ecosystem service tradeoffs and synergies in apple orchards. Agricultural practices, ecosystem functions and ecosystem services are linked together through indicators, models (STICS, a crop model, and IPSIM, a model of crop injuries caused by pests) and data analysis tools.

2.2 Ecosystem service and ecosystem function indicators

Indicators describing ecosystem services are presented in Table 1. Soil nitrogen availability was described by two indicators: organic nitrogen variation, representing the level of organic nitrogen stocked (if positive) or destocked (if negative) within the soil profile every year, and the mean annual NO_3 concentration in the first soil layer (0-30 cm). For climate regulation, we considered the mitigation of nitrous oxide (N_2O) resulting from denitrification, as well as the mitigation of CO_2 emissions from carbon sequestrated in the soil and the annual organs of trees. Sequestrated carbon includes the carbon stored in fruit. As reported in Demestihas et al. (2018), it is tailored to the annual time scale of the study during which fruit growth contributes to lower air CO_2 concentration. It does not claim to represent the ability of the orchard to store carbon over the years, contrary to several studies of carbon budgets in orchards that consider fruit harvest as an export of carbon (e.g.,

Montanaro et al., 2017; Scandellari et al., 2016). The mitigation of nitrous oxide is referred to as "prevention of nitrogen denitrification" in Table 1. It was defined as the opposite of the yearly amount of denitrified nitrogen (i.e. minus this quantity that is intrinsically a disservice; Zhang et al., 2007): this way, a low level of the indicator indicates a low level of service. Water cycle maintenance and regulation, including water quality, was described by the water content in the soil, drainage and nitrate leaching prevention. The calculation of nitrate leaching prevention was similar to that of nitrogen denitrification prevention. Fruit production was described by gross yield and mean fresh fruit mass. Finally, we also considered the mitigation of environmental disturbances due to pesticides, and we used the reduction of the treatment frequency index, calculated in the same way as the prevention of nitrogen denitrification or of nitrate leaching, as a proxy. The pesticide treatments concerned only the three main apple pests, codling moth, rosy apple aphid and apple scab (see Section 2.3). Pest and disease control was not directly described by an indicator. It was implicitly considered through the fruit production indicators (yield and fruit mass) impacted by pest damage.

Indicators of ten ecosystem functions were proposed (Table 2). In soil, mineralization and leaching were described by the quantity of organic nitrogen transformed into mineral nitrogen (kg N ha^{-1} $year^{-1}$) and the quantity of nitrogen leached in drained water over the year (kg NO_3- N ha^{-1} $year^{-1}$). Humification corresponded to the carbon sequestrated in the soil organic matter in kg C ha^{-1} $year^{-1}$ (Saffih-Hdadi and Mary, 2008), while carbon sequestration was described by the carbon fixed yearly in the annual organs of the tree (fruits, leaves and stems). The two are related to the climate regulation service. Water use for fruit production was described by the mean value of all daily stomatic sufficiency indices from fruit set to harvest, ranging from 0 to 1, 1 being the maximal comfort value. This index is the equivalent of relative transpiration, i.e., the ratio of actual transpiration to maximal transpiration (Brisson et al., 1998a). Nitrogen stress was described by a nitrogen nutrition index, also ranging from 0 to 1, where 1 is the comfort value (Lemaire and Gastal, 1997). Nitrogen absorption by the tree was defined as the maximal quantity of nitrogen absorbed by

fruits, leaves and stems on a yearly scale. Carbon allocation to fruits, which contributes to the fruit production service, was described by the quantity of carbon accumulated over a year in fruits, using fruit dry biomass at harvest, multiplied by the mean carbon content of fruits. For pest damage functions, fruit and leaf area losses were described by a percentage of fruit lost due to codling moth or apple scab, and a fraction of leaf area index (LAI) removed due to rosy apple aphid infestation, respectively.

2.3 Models

Two models were used to quantify ecosystem functions and service indicators.

The first model was STICS (Simulateur mulTIdisciplinaire pour les Cultures Standards), a soil-plant simulation model (Brisson et al., 2009, 1998b). STICS describes crop growth based on the development of a foliar surface that intercepts light and converts it into biomass that is allocated to roots and three aboveground annual organs: fruits, leaves and annual stems. STICS also describes water and nitrogen balances within the plant and soil compartments. Stress indices are calculated in water and nitrogen balance modules, reducing, if any, leaf growth and biomass accumulation. Inputs concern climate, soil and crop management, as well as nitrogen and water quantities in the soil and above and belowground biomass at the first date of the simulation. The model produces a considerable set of outputs that can be used as indicators of ecosystem functions and services. STICS is a widely used and robust generic model (Coucheney et al., 2015). It was successfully parameterized and evaluated on apple orchards using nine apple orchard systems located in southeastern France (northern and southern ends of this region: 44°58’N, 4°55’E and 43°43’N, 5°10’E, respectively), which presented different climatic conditions, very contrasted soils and different types of agricultural management in terms of nitrogen fertilization, irrigation and planting density (Demestihas et al., 2018). We used the STICS model on an annual time scale.

IPSIM is an aggregative modeling framework that predicts injury profiles as a function of three factors: agricultural practices, abiotic environment – climate, in particular - and biotic environment -

especially pest biological control potential (Aubertot and Robin, 2013). The model is based on a qualitative prioritization of these three factors, structured in a decision tree that enables the simulation of a damage profile on the considered crop for a given pest. IPSIM is implemented in DEXi software, a computer program for multi-attribute decision-making (Bohanec et al., 2004). It was parameterized on apple orchards for the three major apple pests: codling moth, rosy apple aphid and apple scab (Demestihas, 2017). The factors impacting these pest injuries were determined using a bibliographic study and experts' opinions. The model was successfully tested using the nine apple orchard systems used to evaluate the STICS model (see above; Demestihas, 2017). It is valid at least in the geographical region covered by the experts, southeast of France. The outputs of the model corresponded to a series (according to the IPSIM input factors) of mean quantitative values - basically, ordinal values with expert-based quantitative correspondence - of pest injuries on either fruits or shoots. This led to a link with the functioning of the STICS model (Appendix 1). Rosy apple aphid injury was a percentage of daily leaf area loss, corresponding, in the STICS model, to leaf area removal from the peak of rosy apple aphid flight, i.e., in mid-May, to the tree's maximal leaf area establishment (mid-July). Apple scab injury on leaves was not taken into account. Injury levels due to codling moth and apple scab were percentages of marketable fruit loss. These two types of fruit loss, considered as two compatible and independent events, were combined into a general fruit loss percentage, which was simulated at harvest in the STICS model.

Appendix 1

2.4 Designing virtual apple orchard cropping systems

The pedoclimatic conditions were very close to the southernmost orchards used to validate the models (see 2.3). Climate characteristics were those of 2015 in Salon-de-Provence, France (43°36' N, 5°7' E). The climate was Mediterranean, with a mild winter (mean temperature between January and March of 8.5°C), a hot and dry summer (mean maximal temperature in July of 32°C, with 5 mm cumulated rainfall). Annual rainfall was 633 mm. The actual mean daily evapotranspiration minus

rainfall from April 1 to September 30 was 516 mm. The soil was heavy with a clay loam texture (20% clay), no pebbles, a pH of 8.5 and a nitrogen organic content in dry soil of 1 g kg of dry soil^{-1} in the first soil layer. Soil bulk density was 1.3, and the water field capacity was 25% of the soil dry mass, with an available water storage capacity of 98 mm. The initial C/N ratio of soil humus was fixed at 9.5. Soil depth was 60 cm. The Golden Delicious cultivar was used, planted at a density of 2000 trees ha^{-1} without cover crops in the inter-row, the width of which was 4 meters. The maximal tree height was 3 meters. The crop load before fruit loss due to pests was 300 fruits per tree.

In order to create apple orchard cropping systems, we varied an array of five agricultural practices, while all the other management levers were considered to be fixed. We defined different modalities for nitrogen fertilization, irrigation, codling moth control, rosy apple aphid control and apple scab control (Table 3). Nitrogen fertilization was described by the combination of fertilizer type (mineral, organic or both) and quantity (0, 70 and 140 kg N ha^{-1}). Irrigation was triggered each time the stomatal water sufficiency index of the STICS model was under a specific threshold whose values were comfort (1), low water stress (0.7), high water stress (0.4) and no irrigation. For each pest control practice, a set of four to five modalities with different efficacies, plus a 'no protection' modality, were proposed (Beers et al., 2003; Grove et al., 2003; Holb, 2005; Laget et al., 2015). All pesticide applications were considered effective. The combinations of the modalities of the five practices defined the space of the possible virtual orchard cropping systems. Some constraints were imposed on these combinations for the sake of realism and to reduce their number in order to facilitate the interpretation of the results. Thus, it was not possible to have only one pest out of the three with no control (e.g., codling moth with no control and rosy apple aphid with chemical control and apple scab with cultivar resistance). In addition, it was not possible to combine biocontrol and chemical control for codling moth or for rosy apple aphid management. Out of the 1148 possible combinations, 150 cropping systems were randomly selected. The distribution of the different modalities of the agricultural practices in the 150 cropping systems is detailed in Appendix 2.

2.5 Data analyses

We performed n = 150 simulations with the STICS model, corresponding to the 150 sampled cropping systems. Based on the results, we built three data tables, X_{np}, Y_{nq} and Z_{nr}. X_{np} contained p=18 variables that described the agricultural practices of the n simulated systems (Table 3, Appendix 2). Pest control practices were categorical (0/1), whereas the quantitative variables related to both irrigation and fertilizer type were ordinal, i.e., 1 to 4 for irrigation (from no irrigation to hydrological comfort; see Table 3) and 1 to 2 for fertilizer quantities per fertilizer type. A 'No_ferti' categorical variable represented the cases where there was no fertilization (Table 3). Y_{nq} contained q=10 variables that were the indicators of the ecosystem functions of the n simulated systems (Table 2). Z_{nr} contained r=10 variables that were the indicators of the ecosystem services of the n simulated systems (Table 1).

Our analyses had two goals: finding patterns of covariation (i) between agricultural practices and ecosystem functions, and (ii) between ecosystem functions and ecosystem services. To achieve these goals, we used Principal Component Analysis with respect to Instrumental Variables (PCAIV; Sabatier et al., 1989), using the R package Ade4 (Dray and Dufour, 2007). PCAIV, also referred to as redundancy analysis or RDA (Dray et al., 2003), is particularly suitable for analyzing the relationships among response variables conditionally on explanatory ones. In this case, Y_{nq} was analyzed conditionally on X_{np} and Z_{nr} was then analyzed conditionally on Y_{nq}. As reported by Mouchet et al. (2014) and Cord et al. (2017), PCAIV/RDA has been frequently used to identify drivers that shape ecosystem service relationships (e.g., Martin-Lopez et al., 2012; Renard et al., 2015; Lamy et al., 2016; Meacham et al., 2016; Feng et al., 2017). PCAIV first performs multiple regressions of the q variables of Y on the p variables of X. This results in a new data table Ym of 'modeled' response variables. Ym represents the part of response variables linearly explained by the explanatory variables. Ym is then analyzed by a standardized principal component analysis (PCA). The solution of PCAIV is displayed in correlation plots where 'modeled' response variables and explanatory variables are represented by means of vectors whose cosines of angles are equivalent to correlations. The vectors with lengths close to one are the most important for the interpretation of the plane. PCAIVs

were evaluated with the percentage of inertia (variation) of the table of the response variables explained by the table of the explanatory variables. This statistic is computed as 100 times the ratio of the sums of the eigenvalues of the PCAIV and of the PCA of the table of response variables and is referred to as R^2 since it is the multivariate equivalent of the regression coefficient of determination; its significance can be evaluated by randomly permuting the rows of the explanatory table (Thioulouse et al., 2018).

As reported by Cord et al. (2017), cluster analysis is widely used in the studies of ecosystem service relationships to identify types of service bundles. Examples can be found in Turner et al. (2014), Queiroz et al. (2015), Renard et al. (2015) and Lamy et al. (2016). In particular, agglomerative hierarchical clustering (AHC) has been successfully used in a study of service bundles in relation to socio-cultural factors (Martin Lopez et al., 2012). We used AHC to define a typology of cropping systems according to their ecosystem service delivery. AHC was performed on the 150 orchard cropping systems described by ten indicators of ecosystem services (Table Z_{nr} mentioned above), with Ward's method and squared Euclidian distances (Everitt et al., 2011; Murtagh and Legendre, 2014). The average silhouette method (Rousseeuw, 1987) was used to determine the optimal number of clusters. The mean values of the ecosystem service indicators were calculated for each group defined from the AHC results, and normalized following Bradford and D'Amato (2012) and numerous studies of service bundles (e.g., Lu et al., 2014; Schipanski et al., 2014; Feng et al., 2017) as:

$$\frac{es - es_{\min}}{es_{\max} - es_{\min}} \qquad \text{Eq. 1}$$

where *es* is the mean value of the service in the group and es_{min} and es_{max} are the minimal and maximal values of *es* over the groups defined from the AHC results. That way, a normalized value ranged from zero, the lowest level of *es* in the groups, to 1, the highest level. Ecosystem service profiles were represented by means of radar plots using these normalized values. Radar plots are very commonly used to illustrate ecosystem service bundles (Cord et al., 2017).

In order to identify the cropping systems that optimized the compromise between provisioning and regulating services, the 150 cropping systems were plotted in a decision space represented by two criteria: the mean normalized value of provisioning ecosystem service indicators (i.e., yield and mean fruit mass) on the y-axis, and the mean normalized value of regulating ecosystem service indicators (i.e., all the other indicators) on the x-axis. The normalization of each service followed the general principle of Eq. 1, where *es* was the value of the service for a cropping system and es_{min} and es_{max} the minimal and maximal values of this service over the 150 cropping systems. To evaluate the tradeoffs between these two criteria, we used the concept of Pareto-dominance that is commonly used in ecosystem service research (Groot and Rossing, 2011; Lafond et al., 2017; Sanon et al., 2012; Seppelt et al., 2013). For the cropping systems investigated, the set of 'non-dominated' tradeoffs, known as Pareto-optimal solutions, represented the best series of compromises across all criteria since no other cropping system is more effective when all of the services are considered. These tradeoffs can be quantified by their distance to the theoretical ideal solution (in which both criteria attain the maximal value).

3. Results

3.1 Agricultural practices heterogeneously impact ecosystem functions

The first PCAIV, applied on the 150 cropping systems, indicated that agricultural practices accounted for a large part of the variation of ecosystem function indicators (R^2=83.7%, P<0.01). The first two principal components of the PCAIV explained 81.6% of the total variation (Figs. 2A and B). Agricultural practices and ecosystem functions were well distributed on the PCAIV projection plane.

3.1.1 Nitrogen- and water-related functions

The first PCAIV factor was related to the intensity of irrigation and to the type of fertilization (Figs. 2A and B). The irrigation intensity (IRRI) ranged from 0 for no irrigation, to 500 mm $year^{-1}$ for water comfort in the case of intensive orchard management. It had a considerable effect on water comfort

(Appendix 3.A). The irrigation intensity was related to an increase in nitrogen mineralization (Appendix 3.C) as well as a decrease in carbon sequestrated in the soil. These effects are due to the fact that the biological activity supporting soil nitrogen mineralization depends on soil moisture and that carbon sequestration in soil is antagonistic to nitrogen mineralization. The close proximity of carbon allocated to fruit and carbon sequestrated in the annual organs of the trees on the PCAIV plane was indicative of the large contribution of fruit to carbon sequestration in the tree. Nitrate leaching, carbon sequestration in annual organs, nitrogen absorption and the nitrogen nutrition index were all positively correlated to irrigation intensity and nitrogen fertilization gradients (Figs. 2A and B). However, the impact of irrigation on carbon sequestrated in the annual organs of trees (Appendix 3.B) seemed weaker than that of fertilization (Appendix 4.C). Fertilization impacted carbon sequestration in the annual organs, the nitrogen absorbed and the nitrogen nutrition index in a discontinuous way, with a jump between mineral and organo-mineral modalities that yielded higher values, and organic and 'no fertilization' modalities that yielded lower values (Appendices 4.A, B and C), but it increased nitrate leaching in a continuous way (Appendix 4.D). For intensively fertilized cropping systems (Min140), we observed a high variability of nitrate leaching quantities due to the combined effect of water and nitrogen inputs. In the Min140 cropping systems, low nitrate leaching values corresponded to the use of rain-proof covers for scab control, which prevented rainfall.

3.1.2 Pest control-related functions

The second component of the PCAIV plan was determined by pest control practices for the three pests (codling moth, rosy apple aphid and apple scab; Fig. 2). Chemical pest control and exclusion nets were negatively correlated with fruit and leaf area loss, whereas systems without pest protection showed high losses. Biological control lay between these two extreme situations. Codling moth and apple scab control modalities (except rain-proof cover against apple scab: SCcov) only affected fruit loss. It is interesting to note that SCcov was positively correlated on the first

component of the PCA with the sequestration of carbon in the soil, probably because rain-proof covers prevent the supply of rainwater and decrease the soil water content.

The control of rosy apple aphid had an impact not only on leaf area loss but also on carbon sequestrated in annual organs. The effect is not visible when all cropping systems are considered, but it is clear that chemical control increased carbon sequestration on intensively fertilized and irrigated cropping systems, compared to oil or clay application and no control (Appendix 5).

Figure 2: Correlation plots of explanatory variables, i.e., agricultural practices (A), and of response variables, i.e., ecosystem functions (B) with respect to the first two PCAIV components, PC1 (x-axis, 57.8%) and PC2 (y-axis, 23.8%). Abbreviations are defined in Tables 2 and 3.

3.2 Ecosystem service patterns of correlations are explained by ecosystem functions

In the second PCAIV, ecosystem functions accounted for a major part of the ecosystem service variation (R^2=88.1%, P<0.01) (Fig. 3). Components 1, 2 and 3 explained 92% of the total variation. Ecosystem functions and ecosystem services were, like in the first PCAIV, well distributed on the PCAIV projection plane.

3.2.1 Synergies

Sequestrated carbon, yield and fruit mass were positively correlated (Fig. 3B). According to the PCAIV, these services were linked to carbon sequestration in the annual organs of the trees, most of which was allocated to fruits, the nitrogen nutrition index and nitrogen absorption (Fig. 3A). More specifically, yield and carbon sequestrated were multiplied by more than five when nitrogen absorption increased from 20 to 120 kg N ha^{-1} $year^{-1}$ (Fig. 4). Water comfort was not linked to yield or fresh fruit mass.

According to the PCAIV results, drainage and mean soil humidity were positively correlated, probably due to their strong link to the water comfort function (Fig. 3 and Appendix 6). Water-related services have a specific status because they can impact other ecosystem functions. Water in soil impacts nitrogen mineralization by stimulating microbial activity, while it also contributes to the increase in the tree's water comfort level.

The service indicators SoilNO_3 and VarNorg were positively correlated, without any clear explanation in terms of underlying functions, and the correlation was probably due instead to the type of soil.

3.2.2 Tradeoffs

Sequestrated carbon, yield and fruit mass were in conflict with the prevention of nitrogen denitrification and of nitrate leaching due to two positively correlated ecosystem functions: nitrogen absorption and nitrate leaching (Fig. 3 and Appendix 6).

The service indicators for the prevention of nitrate leaching and soil nitrate concentration were logically negatively correlated (Fig. 3). More interestingly, organic nitrogen variation was negatively correlated to water-related services (mean soil humidity and drainage; Fig. 3B). This negative correlation can be explained by a key function: nitrogen mineralization (Fig. 3A). Water increases nitrogen mineralization values, and more mineralization implies less organic nitrogen variation. Furthermore, since carbon and nitrogen sequestration go hand-in-hand, carbon sequestration in the soil was at the exact opposite of nitrogen mineralization on the PCAIV plane (Fig. 3A).

Pest-related variables (i.e., fruit and foliar surface loss for ecosystem functions, TFI reduction for response variables) were accounted for on the third component (Appendix 6). Yield was negatively correlated to TFI reduction. Fruit and leaf area losses were positively correlated to TFI reduction, suggesting that in the conditions of the simulations, a reduction of pesticide use was not actually compatible with efficient pest control.

Figure 3: Correlation plots of explanatory variables, i.e., ecosystem functions (A), and of response variables, i.e., ecosystem services (B) with respect to the first two PCAIV components, PC1 (x-axis, 51.5%) and PC2 (y-axis, 32.4%). Abbreviations are defined in Tables 1 and 2.

Figure 4: Relationships between nitrogen absorbed (function indicator) and yield, fruit mass and sequestrated carbon (service indicators). Lines represent linear regressions.

3.3. Typology of apple orchard cropping systems: a tradeoff between provisioning and regulating ecosystem services

Five groups were defined based on the AHC of the 150 cropping systems described by the indicators of ten ecosystem services and the use of the average silhouette approach. The five groups were well distributed on the first plane of the second PCAIV (i.e., linking ecosystem functions to services), mostly on the first component corresponding to the conflict between yield, fruit mass and sequestrated carbon, on the one hand, and the prevention of nitrogen denitrification on the other (Fig. 5). However, group 4 had higher scores than the other groups on the second component because of lower values of organic nitrogen variation and of soil nitrate concentration, and of higher values of prevention of nitrate leaching (Fig. 5). A detailed description of the agricultural practices in each group is given in Table 4. The ecosystem service profiles of the five groups are described in Table 5 and on the radar plots of Fig. 6. Globally, the average of normalized values of all ecosystem services taken together was the highest for group 1 (0.611) and the lowest for group 5 (0.392), groups 2, 3 and 4 being intermediate (0.532, 0.545 and 0.476, respectively).

The first group included 14 cropping systems. Yield, fruit mass and sequestrated carbon reached very high values in this group. Intensive leaching reduced the ability to maintain water quality. Irrigation was conducted in water comfort mode, creating higher mineralization and, consequently, a higher level of destocked organic nitrogen. Chemical pesticides were used to control codling moth and rosy apple aphid, which explained the low value of TFIreduc.

Group 2 included 28 cropping systems. A part of the cropping systems used 140 kg ha^{-1} $year^{-1}$ of mineral fertilizers and water comfort for irrigation. This created high mean nitrate concentrations in the soil. However, since some of the group's cropping systems used organo-mineral fertilization and had low water stress, organic nitrogen and the prevention of nitrogen denitrification increased compared to group 1, whereas yield, carbon sequestrated and fruit mass decreased. TFIreduc was

low in group 2 despite the use of exclusion nets against the codling moth and biocontrol against the rosy apple aphid because of a chemical control of apple scab.

Group 3 included 37 cropping systems that were close to the center of the PCAIV projection plane, thus corresponding to the minimal conflict between all ecosystem services. Fertilization was mineral or organo-mineral in this group, with a balanced distribution between the four modalities. This may be an explanation for increased prevention of nitrogen denitrification compared to the previous groups. The soil nitrate concentration was surprisingly high in these cropping systems, which could be explained by the reduced production of annual organs and a resulting decrease in nitrogen absorption. That could be the reason why nitrate leaching was maintained relatively high (39.6 mg NO_3 l^{-1} drained water). Most of these cropping systems were either not irrigated or submitted to conditions of high water stress. Compared to the previous groups, this could have contributed to decreased nitrogen denitrification as well as yield, fruit mass and sequestrated carbon. Yield was also impacted by the predominant 'No control' modality for codling moth and rosy apple aphid control, which also increased TFIreduc compared to groups 1 and 2.

Group 4 included 48 more unconventional cropping systems that globally increased nitrogen denitrification and nitrate leaching prevention services, whereas soil nitrate concentration, yield, fruit mass and sequestrated carbon were low. The major reason is that fertilization was absent or organic with low bioavailabilty in these systems. TFIreduc was high in this group where the use of exclusion nets against the codling moth was dominant and the distribution of the other control modalities was fairly balanced for all three pests.

Group 5 included 23 unconventional cropping systems. Yield, fruit mass and sequestrated carbon were the lowest of all groups. Fertilization was mainly organic or absent and, accordingly, the prevention of nitrogen denitrification was similar to that in Group 4. Most importantly, water stress prevailed in these cropping systems, either with low or no irrigation inputs or due to cover nets for apple scab control (which prevented rainfall), or with the combination of both of these practices

(represented in the lower right part of Fig. 5). Thus, the levels of the water-related services, mean soil humidity and drainage were the lowest of all the groups, and organic nitrogen variation, in conflict with these services (Section 3.2.2), was high. TFIreduc was high in this group where the use of rain-proof covers against apple scab was predominant and the distribution of the control modalities regarding codling moth and rosy apple was fairly balanced.

Five cropping systems optimized the compromise between provisioning and regulating services (Fig. 7). The shortest distance from a theoretical ideal solution was attributed to one cropping system that used mineral fertilization with 70 kg N ha^{-1} $year^{-1}$, comfort irrigation, chemical control for codling moth and rosy apple aphid, and an apple scab-resistant cultivar. The four other cropping systems used organo-mineral fertilization with 140 kg N ha^{-1} $year^{-1}$ (3) or mineral fertilization with 70 kg N ha^{-1} $year^{-1}$ (1), comfort irrigation, exclusion nets (3) or chemical control (1) against codling moth, and an apple scab-resistant cultivar. All cropping systems belonged to group 1. Their ecosystem profiles are shown in Appendix 7.

Figure 5: Five groups of apple orchard cropping systems projected on the two first components of the PCAIV of ecosystem functions and services.

Figure 6: Profiles of ecosystem services of the five groups of apple orchard cropping systems on radar plots. Abbreviations are defined in Table 1.

Figure 7: Tradeoffs between provisioning ecosystem services, i.e., yield and fruit mass, and regulating services, i.e., soil nitrogen availability, climate regulation, hydrological cycle maintenance and regulation and reduction of environmental disturbances due to pesticides. Each point or number represents a cropping system. The double-arrowed cropping systems represent the highest performances for provisioning services and for regulating services, respectively. Cropping systems

represented by numbers are those that optimize the compromise between provisioning and regulating services. Dotted lines are the distances from a theoretical ideal solution.

4. Discussion and conclusions

4.1. Main achievements and limits

Our simulation study demonstrated the strength of the links between agricultural practices, ecosystem functions and the resulting patterns of relationships between ecosystem services in apple orchards. It seemed that nitrogen fertilization, often interacting with irrigation, was the agricultural practice with the greatest impact since most of the ecosystem services considered were linked to nitrogen. Nitrogen fertilization has also been identified as one of the most important determinants of the delivery of multiple agroecosystem services in a study conducted along a gradient of cropping systems (Syswerda and Robertson, 2014). In the range of studied cropping systems, observable synergies were found between yield, fruit mass and sequestrated carbon. The contribution of carbon allocation to fruit in sequestrated carbon at the annual scale was considerable, and this is clearly a specificity of orchards compared to other ecosystems. These services were in conflict with the prevention of nitrogen denitrification and leaching, also reported by Syswerda and Robertson (2014). Nitrogen absorption, which is impacted by fertilization and irrigation, was a major driver of these relationships. Water supply appeared to impact ecosystem functions such as nitrogen mineralization (De Neve and Hofman, 2002), and the resulting services such as organic nitrogen variation. The functions related to pest and disease control only contributed to yield. Consequently, they were poorly represented on the first plane of the second PCAIV (linking ecosystem functions to ecosystem services). It can be observed that practices that impact many functions are more likely to reveal tradeoffs or synergies between services. For example, irrigation influences a wide range of services by its actions on ecosystem functions of the nitrogen cycle (nitrogen mineralization, denitrification, nitrate leaching) and of the water cycle (runoff, infiltration, evapotranspiration, water allocation to

tree organs), as shown here and reported by Demestihas et al. (2017). It also influences pest regulation through the modification of the physical or chemical dimension of the ecological niche of pests (e.g., Gibert et al., 2007; Gibert et al., 2009; Rousselin et al., 2018). Other practices investigated in studies of bundles of agroecosystem services have similar multiple actions on ecosystem functions and positive effects on a large range of services, such as the use of cover crops in annual crops (Schipanski et al., 2014) or that of shade trees in coffee agroecosystems (Meylan et al., 2017).

With the exception of a synergy between sequestrated carbon and yield or fruit mass characteristic of orchards (see above), our study showed tradeoffs between provisioning and regulating ecosystem services. The five groups of apple orchard cropping systems described by ten ecosystem services were distributed on a gradient expressing this tradeoff. This confirms a general trend, observed at large scales (see Introduction) and at the scale of plots in agroecosystems (Syswerda and Robertson, 2014; Kragt and Robertson, 2014; Rapidel et al., 2015).

However, we found five non-dominated cropping systems that optimized both provisioning and regulating services. Management options can be found that correspond to acceptable compromises between agroecosystem services (Power, 2010; Kragt and Robertson, 2014; Finney et al., 2017). In our study, the five non-dominated cropping systems were obtained using two very simple criteria. However, these criteria were calculated considering the same weight for each service, whereas each service weight should be discussed with experts in order to more clearly differentiate between different types of criteria that enable multiple ecosystem service optimization.

The simulations were based on two models adapted to apple orchards, STICS and IPSIM. For STICS, this adaptation relied on the estimation of some parameters using data from apple orchards located in southeastern France. Even though more experimental data would be necessary to consolidate this adaptation, we are confident in the fact that its domain of validity exceeds this area, as discussed in depth in Demestihas et al. (2018). On the one hand, STICS was proven to be accurate and robust in a wide range of agropedoclimatic conditions (Coucheney et al., 2015). This robustness of the STICS

model has enabled it to be used under very diverse conditions, sometimes on a very large scale, as in the study of the impact of climate change on viticulture on a European scale (Fraga et al., 2016). On the other hand, a thorough comparison of the simulated values of ecosystem functions and services to literature values, e.g. LAI, nitrate concentration and humidity in soil, emissions of N_2O, allowed us to be confident in the capacity of the model to support ecosystem services analysis (Demestihas et al., 2018). Important limits concerning the time scale of the study can be emphasized. Since we simulated crop functioning over a single year, no organic matter was returned to the soil, which explains why the organic nitrogen variation remained negative. On a long-term perspective, fresh organic matter returned to the soil from cover crops or crop residues could significantly increase the soil organic nitrogen stock from one year to another (Strullu et al., 2014). The relationship between water regulation and organic nitrogen variation should therefore change when operating multi-year simulations. Moreover, since simulations took place on bare soil conditions, this may have increased nitrogen denitrification and leaching values. Further research is needed on the functioning of apple orchard cover crops in order to adapt the intercropping module of STICS used for annual crops to this case (Brisson et al., 2004). In addition, nitrogen reserve remobilization from the structural parts of the tree was not considered, increasing the dependence of fruit production and of carbon sequestration in the annual organs of the trees on nitrogen absorption.

Regarding IPSIM, the adaptation of the modelling framework to apple orchards was valid at least in the geographical region of the experts and of the dataset used for the test, southeast of France. The simulations studied here used the climatic conditions of the southernmost orchards of this dataset. A larger database outside this region would be necessary to evaluate the predictive quality of the model. If the results were not satisfactory, a further adaptation would be necessary, knowing that the modelling framework is generic *per se*. In addition, coupling the crop-soil functions described in STICS and the pest damage described in IPSIM has been one of the main difficulties of this study since IPSIM is not a dynamic and mechanistic model, contrary to STICS. Thus, the pest damage was considered globally (e.g., fruit loss due to apple scab or codling moth was considered at harvest and

not during the growing season), as was the effect of pest control practices. Moreover, the IPSIM model is based on a weighting system of factor effects on pest damage. Given the present state of knowledge and the high pest pressure used in the simulations, chemical and integrated pest control had a much greater effect on pest and disease control in the broad sense than biological control, i.e., that provided by the planned and/or spontaneous biodiversity.

4.2. Advantages of our approach

In our study, three innovative key features stand out, partially addressing the criticisms made by Seppelt et al. (2011) of the current research in ecosystem service analysis.

The first feature was to analyze synergies and tradeoffs in multiple ecosystem services, which is common in general studies at regional or landscape scales but less common in agroecosystem studies on smaller scales. In particular, as shown in the review of Rapidel et al. (2015), most studies on perennial crops have focused on two-way service relationships, considering a provisioning service and a regulating service: for example, grapevine yield and fungal disease regulation (Guilpart et al., 2017), grapevine yield and runoff mitigation (Ripoche et al., 2011) or fruit production and biodiversity conservation (Baumgärtner and Bieri, 2006). Small-scale modeling or experimental studies of relationships among multiple agroecosystem services, including provisioning services and a whole array of regulating services, are still scarce (Kragt and Robertson, 2014; Robertson et al., 2009; Syswerda and Robertson, 2014, Finney et al., 2017). Unlike some of them that include different agroecosystems, our study focused on a particular agroecosystem - the apple orchard – thus placing greater emphasis on the comparison of specific types of apple orchard management.

The second feature was to link ecosystem functions to ecosystem service indicators using models. Models make it possible to describe and quantify the relationships between functions and between functions and services. In this study, they provided a clear picture of ecosystem service

interdependency based on feedback loops and interactions between ecosystem functions, as already demonstrated with the APSIM model by Kragt and Robertson (2014).

The third and last feature was the use of a wide range of cropping system situations. This enabled us to connect types of cropping systems and profiles of ecosystem services, as well as to identify cropping systems that provide a good compromise between provisioning and regulating ecosystem services. Rapidel et al. (2015) stressed the importance of making farmers aware of the possibilities of combining the best sets of practices to provide the desired combinations of ecosystem services. The space of possibilities in terms of cropping systems could be expanded and its exploration could be facilitated by using multi-objective optimization procedures (Grechi et al., 2012; Ould-Sidi and Lescourret, 2011).

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Appendices

Appendix 1 (Table)

Appendix 2 (Table)

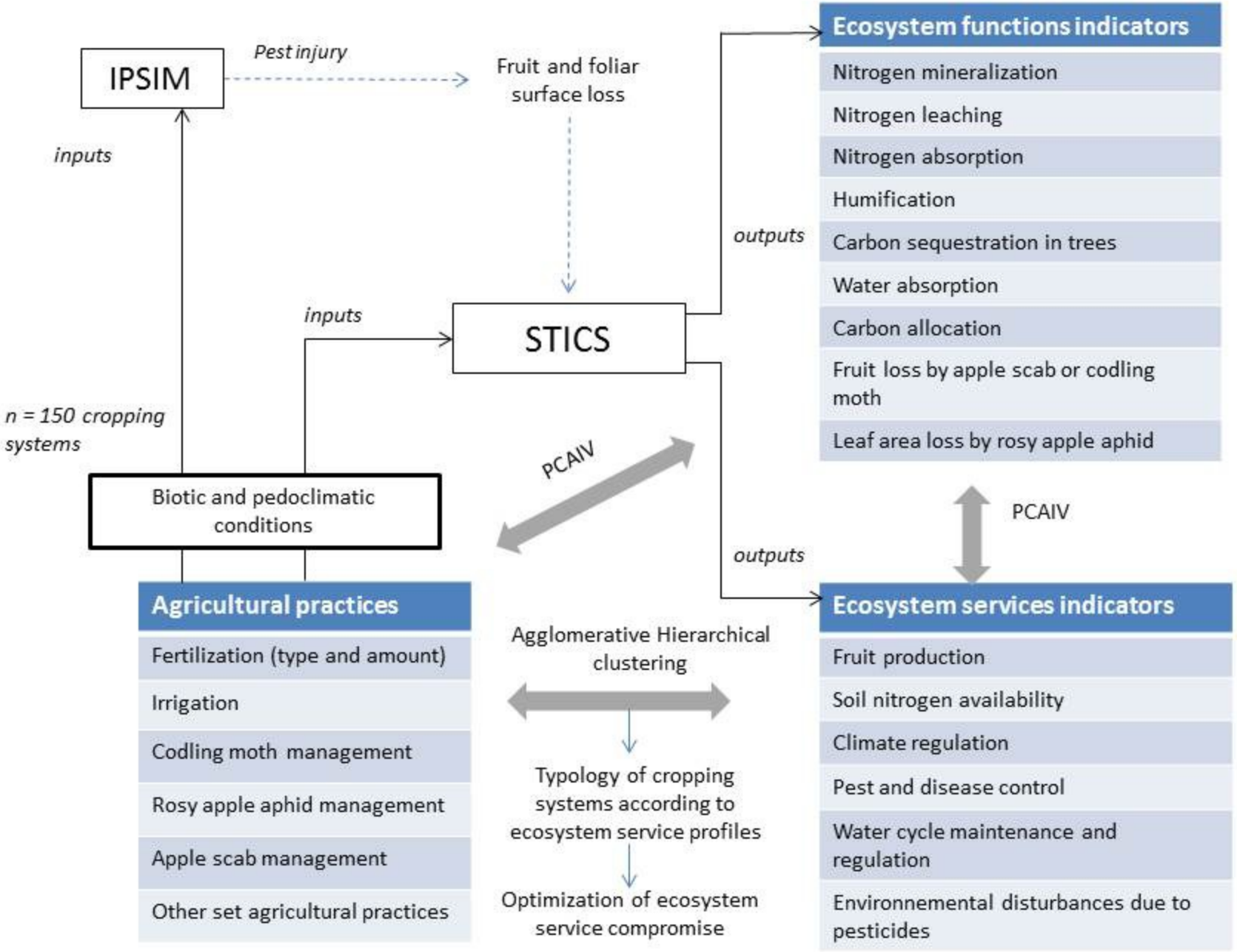
Appendix 3: Boxplots of the impact of irrigation modalities on water comfort (A), carbon sequestrated in the annual organs of trees (B), and N mineralized (C). Abbreviations are defined in Tables 2 and 3.

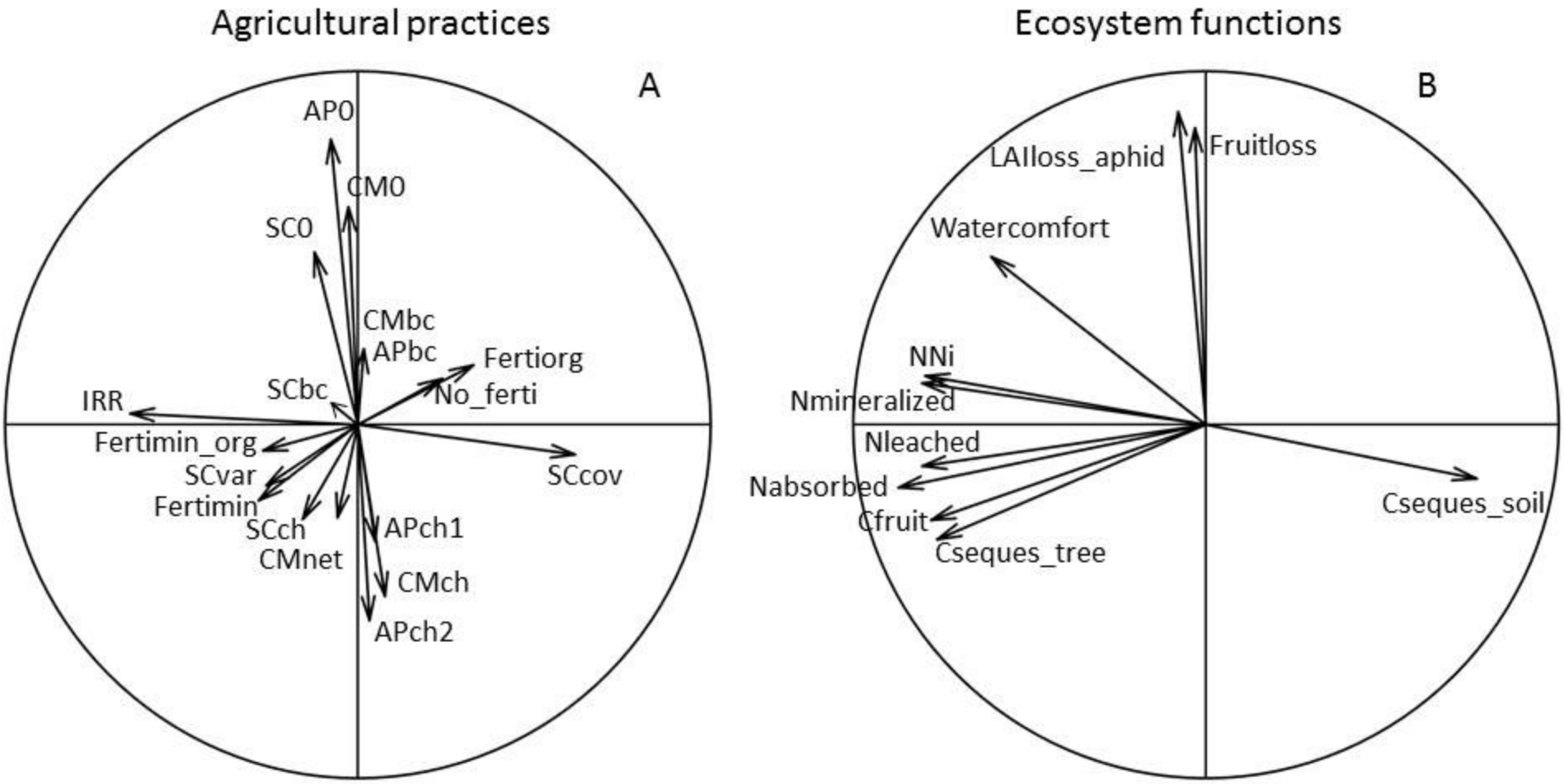
Appendix 4: Boxplots of the impact of fertilizer type and quantity on the nitrogen absorbed (A), the nitrogen nutrition index (B), the carbon sequestrated in the annual organs of trees (C), and the nitrate leached (D). Abbreviations are defined in Tables 2 and 3.

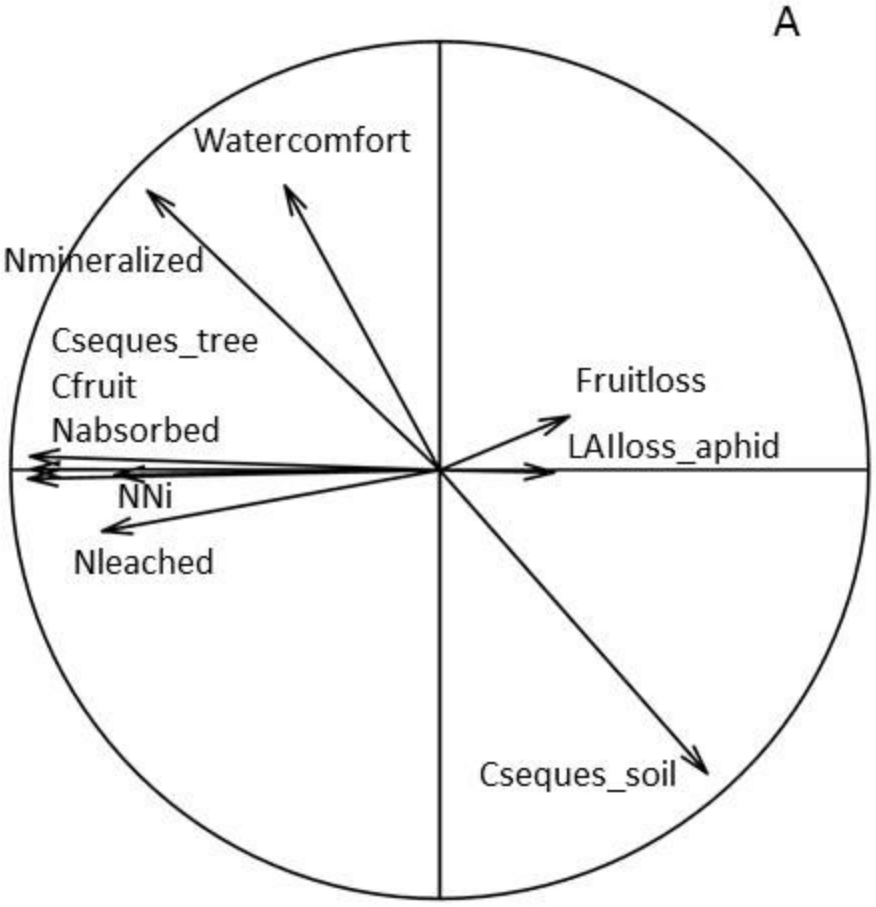
Appendix 5: Boxplots of the impact of rosy apple aphid control on carbon sequestrated in the annual organs of trees for all cropping systems (A), and for intensively fertilized (i.e., Min140 or Min70) and irrigated (i.e., Com) cropping systems (B). Abbreviations are defined in Tables 2 and 3.

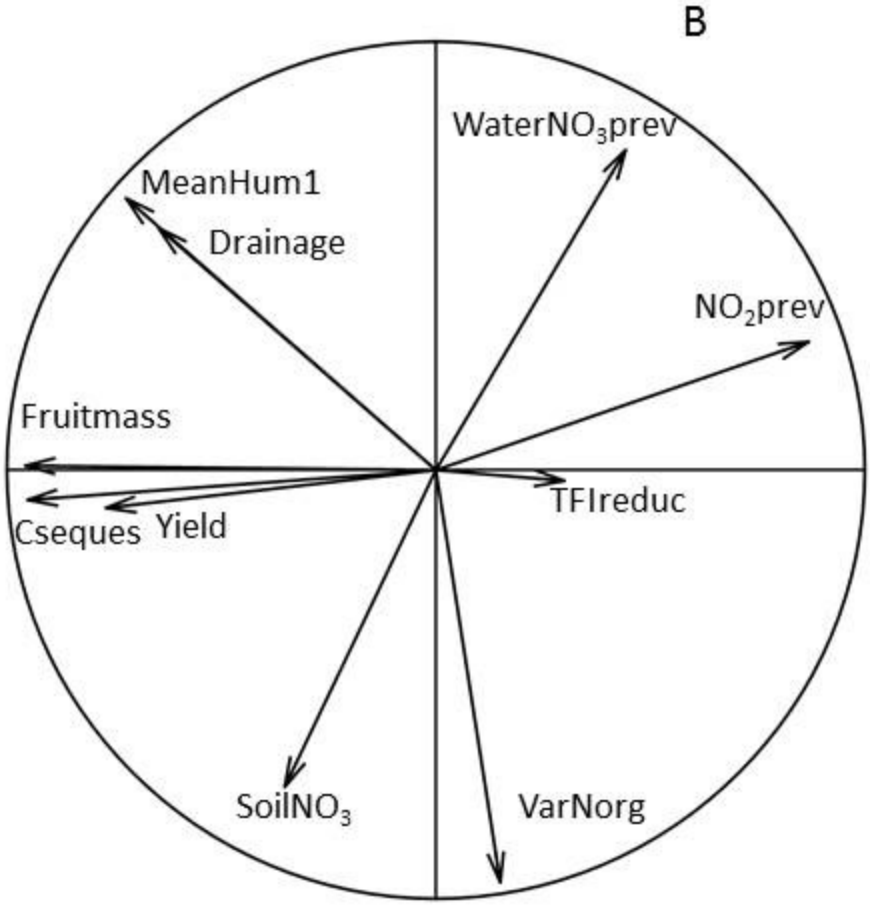
Appendix 6: Correlation plots of explanatory variables, i.e., ecosystem functions (A), and of response variables, i.e., ecosystem services (B), with respect to the first and third PCAIV components, PC1 (x-axis, 51.5%) and PC3 (y-axis, 8.2%). Abbreviations are defined in Tables 1 and 2.

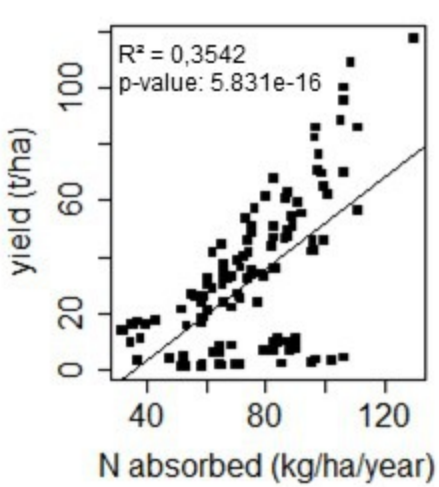
Appendix 7: Ecosystem service profiles of the five identified non-dominant cropping systems (CS) on radar plots. CS1 and CS3 have the same profile. CS1 presents the shortest distance to the ideal tradeoff solution.

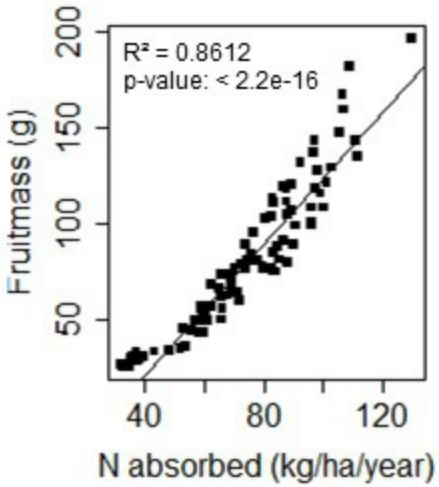

IPSIM
Pest injury
Fruit and foliar surface loss
inputs
inputs
STICS
outputs
outputs
n = 150 cropping systems
Biotic and pedoclimatic conditions
PCAIV
PCAIV
Ecosystem functions indicators
Nitrogen mineralization
Nitrogen leaching
Nitrogen absorption
Humification
Carbon sequestration in trees
Water absorption
Carbon allocation
Fruit loss by apple scab or codling moth
Leaf area loss by rosy apple aphid
Agricultural practices
Fertilization (type and amount)
Irrigation
Codling moth management
Rosy apple aphid management
Apple scab management
Other set agricultural practices
Agglomerative Hierarchical clustering
Typology of cropping systems according to ecosystem service profiles
Optimization of ecosystem service compromise
Ecosystem services indicators
Fruit production
Soil nitrogen availability
Climate regulation
Pest and disease control
Water cycle maintenance and regulation
Environnemental disturbances due to pesticides

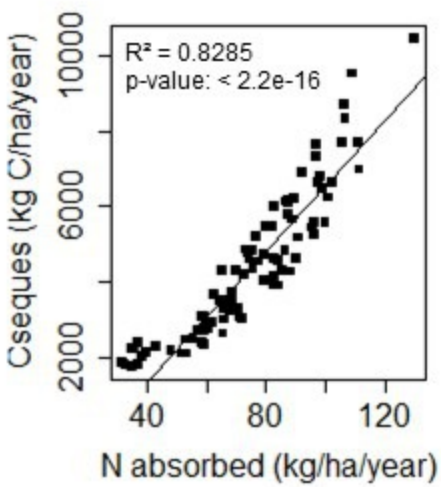

Agricultural practices
A
AP0
CM0
SC0
CMbc
APbc
Fertiorg
No_ferti
SCbc
IRR
Fertimin_org
SCvar
Fertimin
SCch
CMnet
APch1
CMch
APch2
SCcov
Ecosystem functions
B
LAIloss_aphid
Fruitloss
Watercomfort
NNi
Nmineralized
Nleached
Nabsorbed
Cfruit
Cseques_tree
Cseques_soil

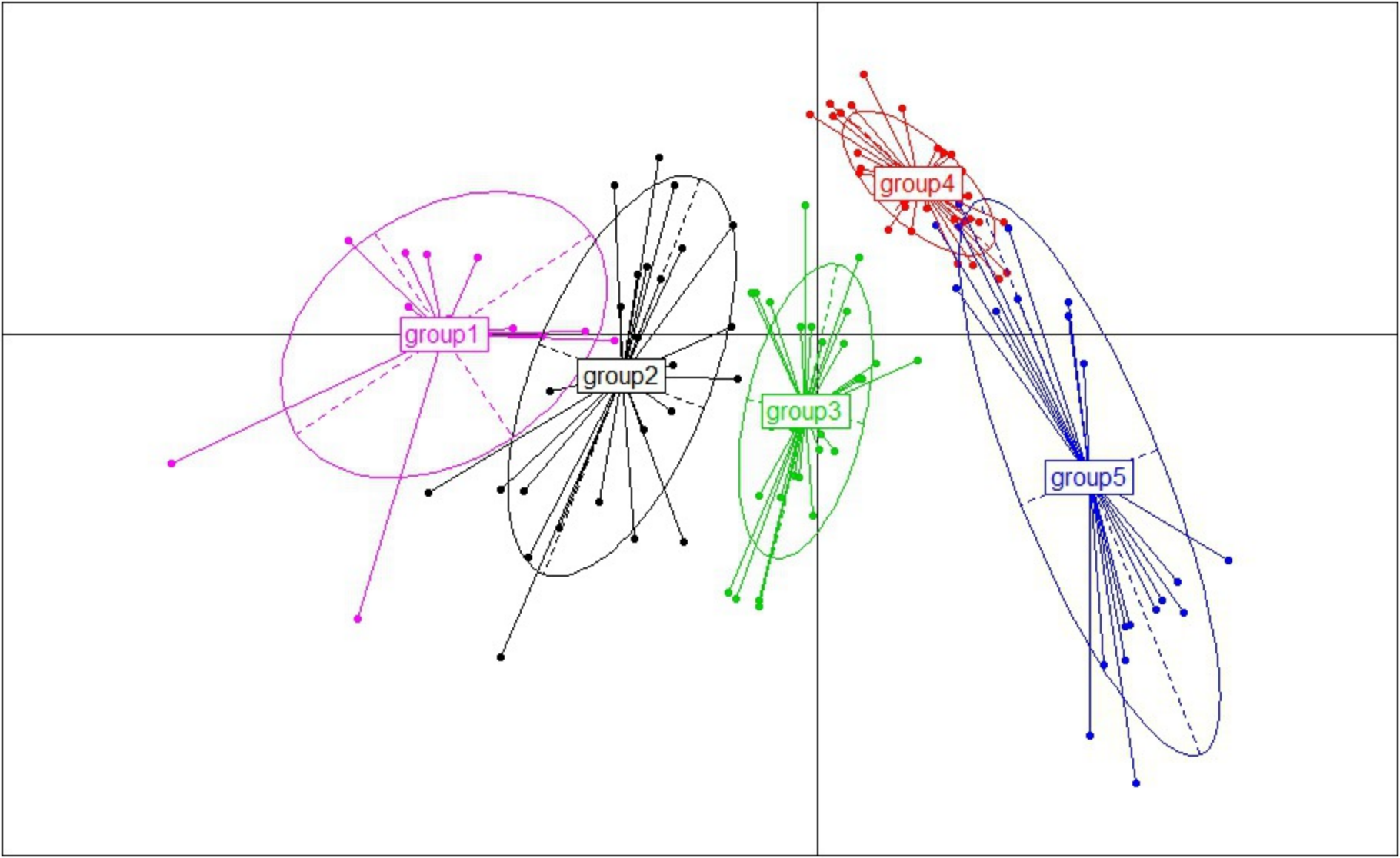

Ecosystem functions
A
Watercomfort
Nmineralized
Cseques_tree
Cfruit
Nabsorbed
NNi
Nleached
Fruitloss
LAIloss_aphid
Cseques_soil

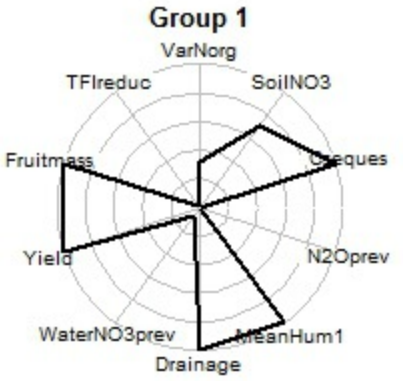

Ecosystem services
B
WaterNO3prev
MeanHum1
Drainage
NO2prev
Fruitmass
TFIreduc
Cseques
Yield
SoilNO3
VarNorg

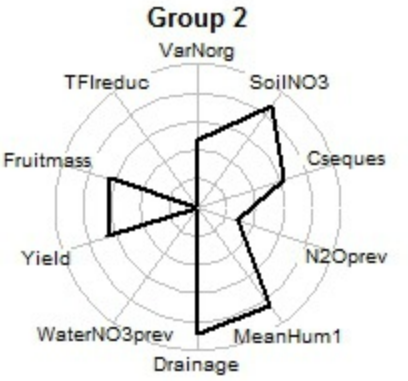

R² = 0,3542
p-value: 5.831e-16
yield (t/ha)
0
20
60
100
40
80
120
N absorbed (kg/ha/year)

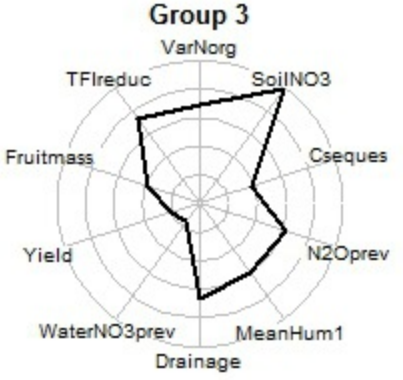

R² = 0.8612
p-value: < 2.2e-16
Fruitmass (g)
50
100
150
200
40
80
120
N absorbed (kg/ha/year)

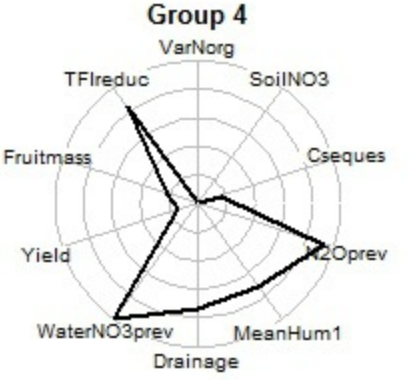

R² = 0.8285
p-value: < 2.2e-16
Cseques (kg C/ha/year)
2000
6000
10000
40
80
120
N absorbed (kg/ha/year)

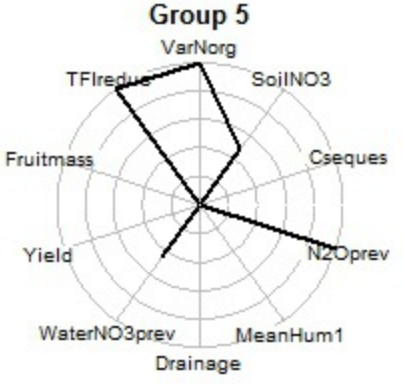

group1
group2
group3
group4
group5


Group 1
VarNorg
SoilNO3
Cseques
N2Oprev
MeanHum1
Drainage
WaterNO3prev
Yield
Fruitmass
TFIreduc


Group 2
VarNorg
SoilNO3
Cseques
N2Oprev
MeanHum1
Drainage
WaterNO3prev
Yield
Fruitmass
TFIreduc


Group 3
VarNorg
SoilNO3
Cseques
N2Oprev
MeanHum1
Drainage
WaterNO3prev
Yield
Fruitmass
TFIreduc


Group 4
VarNorg
SoilNO3
Cseques
N2Oprev
MeanHum1
Drainage
WaterNO3prev
Yield
Fruitmass
TFIreduc


Group 5
VarNorg
SoilNO3
Cseques
N2Oprev
MeanHum1
Drainage
WaterNO3prev
Yield
Fruitmass
TFIreduc

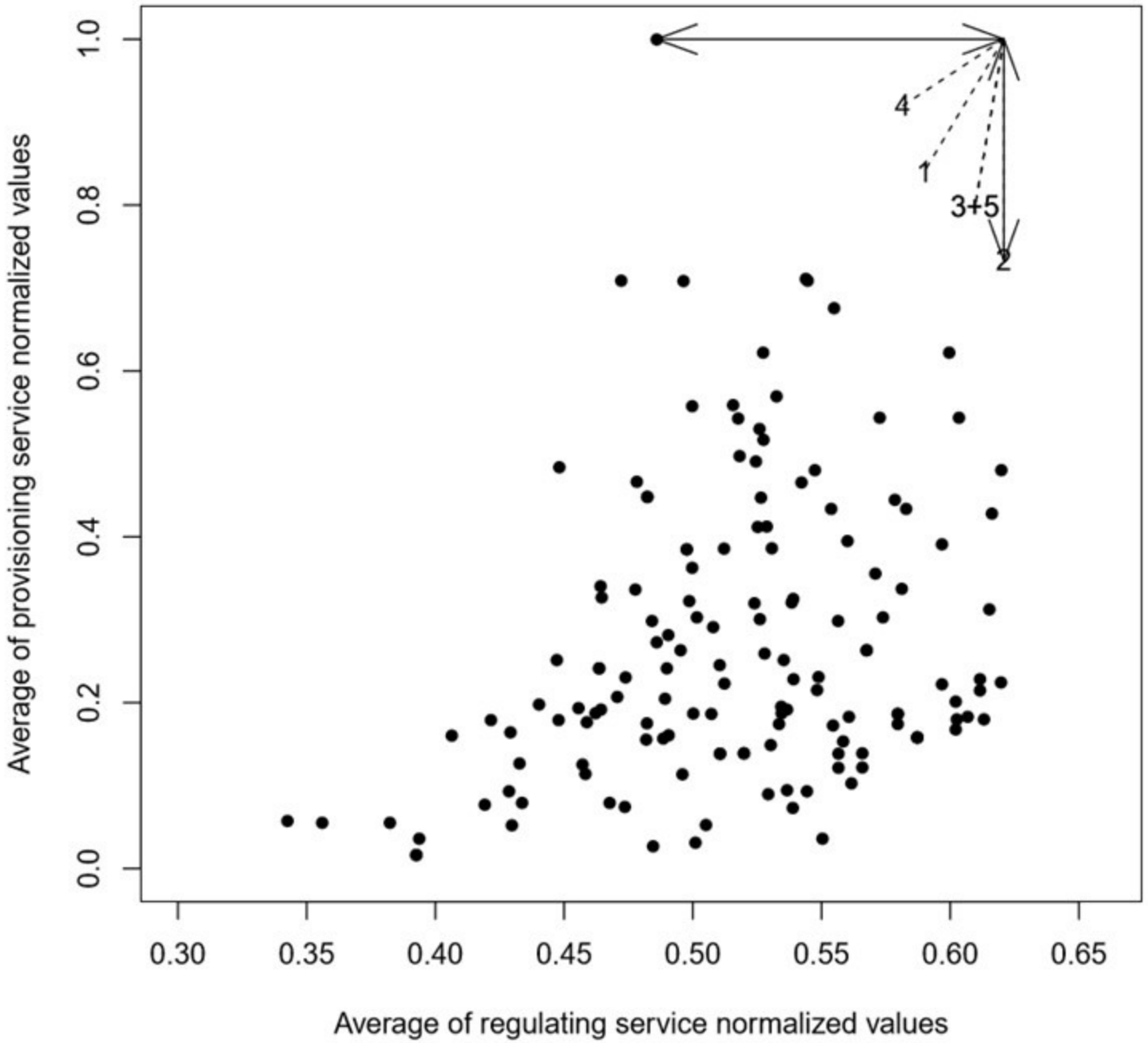

Average of provisioning service normalized values
0.0
0.2
0.4
0.6
0.8
1.0
0.30
0.35
0.40
0.45
0.50
0.55
0.60
0.65
Average of regulating service normalized values
4
1
3+5
2

Table 1: Ecosystem service indicators, abbreviated names and units.

Service	Indicator	Abbreviated name	Unit
Soil nitrogen availability	Yearly variation of organic nitrogen	VarNorg	kg N $ha^{-1}year^{-1}$
	Mean nitrate concentration in 0-30 cm soil layer	SoilNO_3	mg N-NO_3 kg of dry $soil^{-1}$
Climate regulation	Prevention of nitrogen denitrification	N_2Oprev	kg N-N_2O ha^{-1} $year^{-1}$
	Quantities of carbon fixed in the soil and in the annual organs of the tree	Cseques	kg C ha^{-1} $year^{-1}$
Water cycle maintenance and regulation	Mean soil humidity in 0-30 cm soil layer	MeanHum1	% soil dry mass
	Water drainage	Drainage	mm $year^{-1}$
	Nitrate leaching prevention	WaterNO_3prev	mg NO_3 l of drained $water^{-1}$
Fruit production	Yield	Yield	t ha^{-1}
	Mean fresh fruit mass (quality criterion for the market)	Fruitmass	g

Mitigation of environmental disturbances due to pesticides	Reduction of the treatment frequency index (treatments concern codling moth, rosy apple aphid and apple scab)	TFIreduc	dimensionless

Table 2: Ecosystem function indicators, abbreviated names and units.

Function	Indicator	Abbreviated name	Unit
Mineralization	Quantity of nitrogen mineralized	Nmineralized	kg N ha^{-1} $year^{-1}$
Leaching	Quantity of nitrate leached in water drainage	Nleached	kg NO_3-N ha^{-1} $year^{-1}$
Humification	Carbon sequestrated in soil	Cseques_soil	kg C ha^{-1} $year^{-1}$
Carbon sequestration	Carbon sequestrated in the tree's annual organs (fruits, leaves, stems)	Cseques_tree	kg C ha^{-1} $year^{-1}$
Water use for fruit production	Mean stomatic water sufficiency (index varying between 0 – high water stress - and 1 – no stress)	Watercomfort	Dimensionless
Nitrogen nutrition	Nitrogen nutrition index (index varying between 0 – high nitrogen stress – and 1 – no stress)	NNi	Dimensionless
Nitrogen absorption	Maximal quantity of nitrogen absorbed by the annual organs	Nabsorbed	kg N ha^{-1}
Carbon allocation	Carbon quantity in fruits at harvest	Cfruit	kg C ha^{-1}
Fruit loss due to codling moth or apple scab	Percentage of fruit loss	Fruitloss	Dimensionless

Foliar surface loss due to rosy apple aphid	Fraction of daily leaf area loss	LAIloss_aphid	Dimensionless

Table 3 : Agricultural practices and their modalities. Each practice or modality is described by an abbreviated name. Regarding pest control, 'bc' means biocontrol and 'ch' means chemical.

	Agricultural practice	Abbreviated names for agricultural practices	Agricultural practices modalities	Abbreviated names for agricultural practice modalities
Cultural practices	Nitrogen fertilization: type x quantity (kg ha^{-1}) of fertilizers	FERTImin	Mineral 140	Min140
			Mineral 70	Min70
		FERTImin_org	Mineral + organic 140	Min_org140
			Mineral + organic 70	Min_org70
		FERTIorg	Organic 140	Org140
			Organic 70	Org70
		No_ferti	No fertilization	No_ferti

Pest control practices	Irrigation: water input level	IRRI	Comfort	Com
			Low water stress	LWS
			High water stress	HWS
			No irrigation	No_irrig
	Codling moth control	CM	Exclusion nets	CMnet
			Granulovirus + mating disruption	CMbc
			Chemical pesticides + mating disruption	CMch
			No control	CM0
	Rosy apple aphid control	AP	Oil and/or clay applications	APbc
			Oil + chemical pesticides	APch1
			Chemical pesticides	APch2
			No control	AP0
		SC	Chemical fungicides	SCch

Apple scab control	Sulfur and copper (products authorized in organic agriculture)	SCbc
	Resistant variety	SCvar
	Rain-proof cover	SCcov
	No control	SC0

Table 4: Absolute frequencies of the modalities of the agricultural practices within the five groups of virtual orchard cropping systems. Values in bold indicate the dominant practice used in each group. Abbreviations are defined in Table 3.

		Group 1	Group 2	Group 3	Group4	Group5
Fertilization	Min140	0.14	**0.32**	**0.24**	0.00	0.13
	Min70	**0.43**	0.18	**0.27**	0.00	0.04
	Min_org140	**0.43**	0.18	**0.27**	0.00	0.09
	Min_org70	0.00	**0.32**	**0.22**	0.00	0.04
	Org140	0.00	0.00	0.00	0.23	**0.22**
	Org70	0.00	0.00	0.00	0.33	**0.26**
	No_ferti	0.00	0.00	0.00	**0.44**	**0.22**
Irrigation	Com	**0.57**	**0.36**	0.14	**0.29**	0.00
	LWS	0.43	**0.36**	0.14	**0.31**	0.04
	HWS	0.00	0.29	0.24	**0.23**	**0.39**
	No_irri	0.00	0.00	**0.49**	0.16	**0.57**
Codling moth control	CMnet	0.29	**0.50**	**0.35**	**0.41**	**0.22**
	CMch	**0.50**	0.25	0.16	0.19	**0.39**
	CMbc	0.00	0.18	0.14	0.19	0.09
	CM0	0.21	0.07	**0.35**	**0.21**	**0.30**
Rosy apple aphid control	APch1	0.43	0.32	0.14	**0.27**	**0.31**
	APch2	**0.57**	0.21	0.11	**0.21**	**0.35**
	APbc	0.00	**0.46**	**0.30**	**0.25**	0.17
	AP0	0.00	0.00	**0.46**	**0.27**	0.17

Apple scab control	SCch	0.21	**0.32**	**0.27**	0.17	0.09
	SCbc	0.07	0.29	**0.27**	**0.27**	0.13
	SC0	0.21	0.07	0.08	**0.23**	0.13
	SCvar	**0.50**	0.21	0.19	0.14	0.04
	SCcov	0.00	0.11	0.19	0.19	**0.61**

Table 5: Mean values (non-normalized) and standard errors of ecosystem service indicators for each of the five groups of cropping systems. The definitions and units of the abbreviations are given in Table 1.

	Group 1	Group 2	Group 3	Group 4	Group 5
Number of cropping systems	14	28	37	48	23
VarNorg	-83.72 ±1.88	-78.66±2.27	-71.40±2.13	-94.35±0.81	-61.39±4.80
SoilNO3	13.09 ±0.66	14.54±0.93	15.51 ±0.85	7.23±0.03	11.18±1.56
Cseques	8263±241	5993±103	4444±46	3201±45	2148±50
N_2Oprev	-0.87±0.03	-0.67±0.04	-0.44±0.03	-0.25±0.17	-0.20±0.02
MeanHum1	20.77±0.09	20.26±0.08	19.45±0.09	19.85±0.08	17.45±0.33
Drainage	145±2.47	138±3.17	125±2.98	129±2.70	86.69±5.95
WaterNO_3prev	-40.70±1.73	-41.49±2.03	-39.64±1.03	-29.68±0.15	-36.27±1.00
Yield	73.46±10.6	52.58±3.27	24.64±2.90	21.04±1.84	12.41±1.64
Fruitmass	157±4.72	113±2.04	81±0.77	60.89±0.95	34.64±1.68
TFIreduc	-8.00±1.62	-8.04±1.08	-6.11±0.94	-5.85±0.76	-5.43±1.24