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Field experiments assessing companion plants for crop health in horticulture provide actionable knowledge

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Abstract

Fostering plant biodiversity using companion plants (CP) is a promising alternative for the sustainable management of crop health in horticultural systems. To evaluate the contribution to pest and disease control, CPs are tested in field experiments carried in conditions close to those used on commercial farms. Such experiments provide scientific knowledge on the achievement of the targeted function, but also raise many operational issues. We therefore consider that experimenters who design and test systems with CPs support the production of experience-based knowledge. Our objective is to highlight and characterize this knowledge. We interviewed experiment leaders, covering 21 locations in metropolitan France and the West Indies. We defined a "modality of use of companion plants" (MU) as the combination of the CP, its technical management, including spatial and temporal arrangement in the field, and the main expected functional processes assigned to CPs. 46 MUs were investigated. MU scale was relevant for experimenters to report on interactions between practices and CPs, and to properly assess CP success or failure. We showed that experimenters reflect on both anticipated barriers and on barriers they actually faced when implementing CPs in the field. The diverse obstacles encountered were mainly related to CP growth, labour, crop management, or sanitary control difficulties. Experimenters also identified improvements. This knowledge from practical experiments completes scientific knowledge on ecological processes and should be useful to stakeholders intending to adopt CPs. Building on such actionable knowledge would be valuable for the sustainable management of crop health in horticulture.

Keywords: agronomic experiment; multi-species system; vegetable; orchards, ornamental plants; agroecological practices; pest regulation

INTRODUCTION

Designing and implementing horticultural systems with higher plant diversity is a promising way to sustain production and limit crop damage due to pests and diseases (Ratnadass et al., 2021). At field scale, enhancing plant diversity is a strategic practice to combine with other agroecological practices in a systemic approach (Schut et al., 2014). Thus, plant pest and disease regulation services can be delivered in horticultural cropping systems where plant diversity is practised over time and space (Deguine et al., 2021; Gaba et al., 2015). Companion plants (CPs) introduced in the agrosystem are known to stimulate ecological

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processes in order to directly or indirectly regulate pests. A growing body of research focuses on the potential of CPs in crop health management (Ratnadass et al., 2021; Alaphilippe et al., 2022). Considering laboratory results, CPs represent a promising lever for agroecology. Yet their efficient use in the field remains uncertain. More widespread adoption on farms requires a better understanding of how the functional processes expected from CP are actually achieved. However, performing suitable agricultural experiments to assess the processes involved with CPs is a challenge (Alaphilippe et al., 2022). In addition, specific operational knowledge on how to implement these CPs is essential to guarantee effective regulatory functions as well as the compatibility with other practices and practical applicability on farms. The challenge of designing more complex horticultural systems that include CPs makes it more necessary to jointly produce and apply both scientific-based and experience-based knowledge (Girard et Magda, 2020).

Agronomic experiments can meet various complementary objectives, ranging from isolating biological mechanisms in the laboratory, to identifying the conditions for activating mechanisms in the field, and to designing practicable cropping systems compatible with the expected functional processes. Agronomic experiments at field scale ("field experiments", in short) can be performed in a tightly controlled and monitored environment or in agronomic and socio-economic conditions similar to those found on local commercial farms. We focused on the latter type of field experiments carried out in 'almost' commercial conditions, where the common objective was to assess the effect of CPs on pest and disease control for agroecological crop protection in horticultural systems. We assume that these forms of agronomic experiments provide relevant support for generating agroecological actionable knowledge (Cardona et al., 2018; Navarrete et al. 2021). Actionable knowledge refers to context-specific knowledge that assists stakeholders (farmers, agricultural advisors, etc.) in their decision making and their action, for instance to implement innovative cropping systems (Geertsema et al., 2016). It is required to support stakeholders' exploration and adaptation of an agroecological practice tested elsewhere. In this respect, making explicit the agronomic logic, that is, the relationships between the objectives reached, the practices implemented, and the observations made in the field, is a useful resource (Verret et al., 2020; Quinio et al., 2022).

The aim of this article was to highlight how field experiments implemented in agronomic and socio-economic conditions similar to commercial conditions, are also providing actionable knowledge to support the adoption of agroecological practices. We illustrated and characterized knowledge related to decisions and actions that experimenters are able to report back. From these experiences, we identified insights and significant points related to the introduction of companion plants for crop health management in horticultural systems.

MATERIALS AND METHODS

Context of the study, sample and level of data collection

We performed our study on field experiments (FEs) dedicated to assess the effect of CP introduction in horticultural systems to directly or indirectly control pests, diseases or weeds. These FEs were headed by agronomists whose main function was experiment leader (EL). They worked for public or private agricultural institutions involved in research and professional support. We surveyed FEs which had already been implemented in the field. FEs were carried out in experimental stations or farms in conditions close to those of commercial farms, according to the EL interviewed (regarding the cash crop management, environmental conditions, inputs and technical means). We thus surveyed 21 on-going or recently completed

FEs. The study was performed on a diversity of perennial or annual horticultural productions: 38% in open-field market-gardening, 19% in fruit orchards, 19% in protected market-gardening, 14% in off-soil vegetable greenhouses, and 9% in off-soil ornamental plants. We covered diverse French pedoclimatic areas that accounted for 38%, 29% and 9% of the FEs in the Mediterranean, oceanic and continental metropolitan regions, respectively, and 24% in the tropical climate in the West Indies.

The CPs targeted various objectives, such as agroecological management of aerial pests, soil-borne pathogens, and weeds, in respectively 76%, 19% and 5% of the FEs. Each FE could include one or several tested options that were specified according to the functional objectives assigned to the CPs. Options could also vary according to the bioregulation target (Figure 1).

We developed an approach to identify the type of questions related to the 'agronomic logic' inspired by that of Verret et al. (2020), and to specify the level of precision to be described by the interviewed EL. Thus, finding the relevant informative level for data collection was essential to ensure that the EL would be able to precisely reflect on what had been done and learned from this practical experience. We assumed that the CPs' characteristics and their expected functions regarding pests or diseases were closely interrelated with the way a CP was practically integrated into the field plot. As a result, we performed data collection per FE on one or several modalities of use (MU) of agroecological CPs. A MU is defined according to: (i) the selected CP (or a mix of CPs); (ii) the annual or perennial status of CPs that constrains design and practices; (iii) technical management including spatial and temporal arrangements around or within the cash crop (field margin, strip, mixed or rotation), adapting typologies of multi-species systems from Brooker et al. (2015) and Gaba et al. (2015); and (iv) the main expected functional process(es) assigned to CPs to deliver the targeted regulation services. We finally selected and investigated 46 MUs from the 21 FEs, covering a diversity of situations at the MU level (Figure 1).

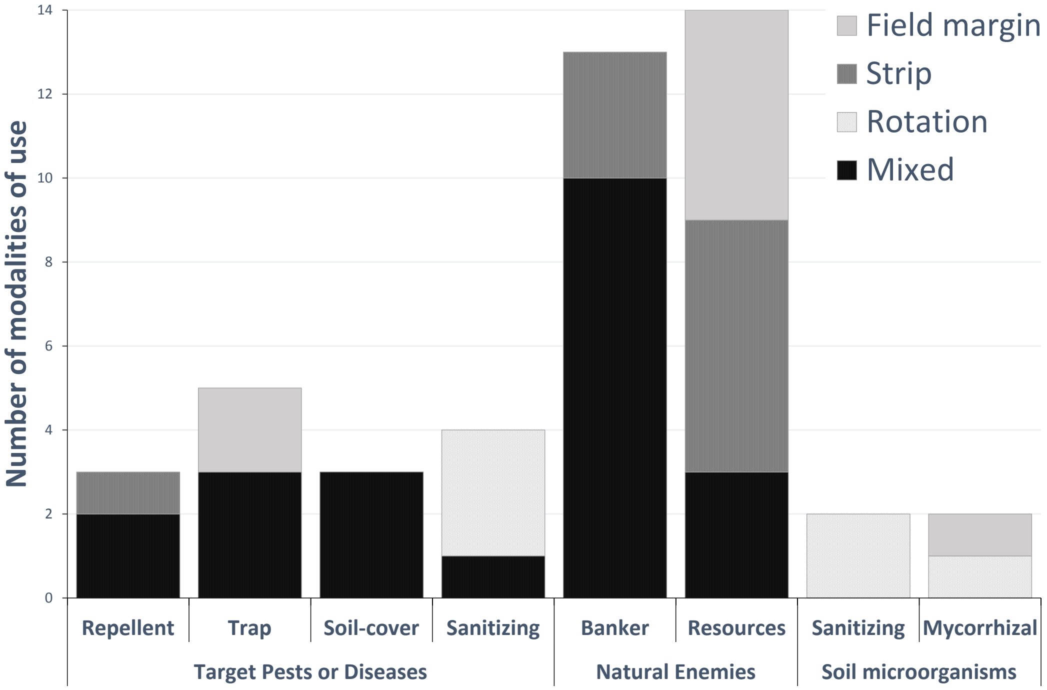

Figure 1. Distribution of the 46 surveyed modalities of use of agroecological companion plants (CP) according to the spatial and temporal arrangement (CP arranged at the edge of the field margin, in strips with the cash crop, in rotation between two cash crops, or mixed with the cash crop) and according to the characteristics of CPs: functions expected in the field (pest repellent, trap, soil-cover to control weeds, soil sanitizing, banker, providing food or habitat resources for natural enemies or mycorrhizal CP) and organisms directly targeted (pests or diseases, including weeds, natural enemies populations or soil microorganisms).

Information collected related to action and data analysis

We collected data from April to July 2021. First, the EL provided all published or internal documents presenting the FE and related project(s). The required data were then identified from documents. We thus prepared the experimenter's interview and were able to preselect from the FE the MUs to be surveyed. Third, a face-to-face meeting at the experimental site with the EL began validating the selection of MUs. A 60- to 90-minute semi-structured interview with the EL was held to complete factual data and explore the remaining points. The answers collected were fully transcribed and then encoded into a set of qualitative and quantitative variables.

The data collected were intended first to identify knowledge that emerged from the stage of agrosystem design and experiment preparation: (i) which CPs were integrated into the cropping system and how, which practices were possibly modified compared to the current system with no CP, and which contrasting options were explored at the design stage; (ii) the functional objective assigned to CPs; and (iii) the types of difficulties that experimenters anticipated before the system was tested. A second group of questions specified knowledge produced during and through evaluation of the experiment: (iv) crop management practices implemented, modifications made during the test stage, and explanations for such adjustments; (v) experimenters' analysis of success and failure of the systems on which experiments were run, regarding targeted functional objectives as well as agrosystem management and the indicators they had used for it; (vi) barriers actually faced; and (vii) solutions identified or tested to improve functional or management dimensions of the agrosystem that integrated CP. We quantified the variables to analyse the 46 MUs regarding anticipated difficulties, barriers actually faced to implement CP, and proposals by ELs for improving solutions.

RESULTS and DISCUSSION

The data collected on FE and related MUs revealed agronomic logics, meaning links between expected functional objectives and the practices implemented, under precisely described and analysed conditions. We illustrate these results by highlighting first the experience-based knowledge from 3 contrasting FEs and secondly, by a transversal synthesis of the 46 MUs.

Actionable knowledge emerged from the modalities of use of CPs: examples from 3 FEs

1. Context and objectives of the design of the system with CP(s)

Three FEs are presented to highlight the type of actionable knowledge revealed by the surveys. The authors of this article are familiar with selected FE2, FE3 and FE14 implemented at INRAE experimental stations, in Pyrénées-Orientales, Drôme and Guadeloupe, respectively.

FE2 studied the potential of *Calendula officinalis* L. as a banker plant for a mirid predatory bug *Macrolophus pygmaeus* R. (Homoptera: Miridae) on protected vegetable system (Perrin et al., 2019). The objective assigned to this CP was to provide alternative food, refuge and shelter to generalist natural enemies able to control the most prevalent pests on tomato. *C. officinalis* was expected to provide trophic resources and habitat to keep *M. pygmaeus* populations high in the winter period so that they could colonize cash crops early the next year from this local rearing. Within FE2, four MUs were studied. MUs differed in their spatial arrangement within the tomato crop – whether they were arranged in strips or mixed intercropping –, and in the way *C. officinalis* was introduced (sown, planted or in pots). MUs were designed to consider farms' diversity of production constraints, such as whether they practised soil solarization or not, and were selected depending on whether the CP remained in the field at the end of the tomato cycle or was removed. Prior to the trials, the EL feared the MUs would come with excessive costs, difficulties in work organization, and additional sanitary risks, and would display uncertainty as regards pest management efficiency.

FE3 studied the potential of rosemary *Rosmarinus officinalis* L. as a perennial CP in an apple orchard. The objectives assigned to this CP were to repel and disrupt the apple rosy aphid *Dysaphis plantaginea* Passerini (Homoptera: Aphididae) (Dardouri et al, 2019) as well as providing food resources for natural enemies of pests. *R. officinalis* was expected to release volatile organic compounds (VOCs) likely to directly affect the development of and the tree colonization by *D. plantaginea* in spring and autumn, respectively. Within FE3, two MUs were studied. MUs differed in their spatial arrangement within the orchard plots (strip or mixed arrangement). Interviewees pointed out that *R. officinalis* was a relevant choice of CP in the orchard as a perennial plant and emphasized its hardiness and low water requirements due to its Mediterranean origin. MUs were designed to explore the potential to maximize VOC emissions while being a practicable system for machinery. The original orchard was modified for the MU with mixed cropping since a few apple trees were removed to densify the CPs in the orchard. Prior to the trials, EL feared MUs would induce difficulties in pest management efficiency, labour organization and intensity, and that they would be an obstacle to regular orchard practices. They also feared a lack of knowledge about CP management and regulatory bottlenecks such as the prohibition of organic pesticide applications when flowers are present in the orchard.

FE14 studied the potential of *Crotalaria juncea* as a sanitizing and mycorrhizal plant in diversified open-field market-gardening systems under tropical conditions (Deberdt et al. 2015; Chave et al. 2017). The objectives assigned to CPs were to reduce the incidence of two soil-borne pests, bacterial wilt and root-knot nematodes, and to increase tomato mycorrhization. *C. juncea* used as a cover crop was also expected to contribute to weed control and to nitrogen provision. Interviewees highlighted the multiple services provided by crotalaria, based on scientific knowledge and interest in this rustic, indigenous and short life-cycle plant whose low-cost seeds are easily available. Within FE14, two MUs were studied. MUs differed in spatial and temporal arrangements: in rotation as a previous crop whose aerial parts are then left as a mulch and as a field margin. Experimenters paid attention to the design step to select other agroecological practices compatible with the mycorrhization process. They feared that MUs would involve excessive costs, difficulties in work organization and a lack of suitable equipment.

2. Experience-based knowledge produced from the experiments and its evaluation

The experimenters cited a set of indicators to assess the functional processes involved and additional indicators to assess the system being tested in the field. In Table 1, we illustrate how the experimenters analysed their experience to identify not only points of satisfaction about each MU but also barriers faced in many dimensions. In addition, they pointed out improvements.

The 3 FEs detailed illustrate that the experimenter who designs and tests agroecological systems under conditions close to those of production produces experience-based knowledge. These 3 FEs emphasized that the functional objectives and the modalities of use of CPs must be considered together in order to properly assess CPs.

Table 1. Success or failures from experimenters' analysis, barriers faced, solutions identified from 3 field experiments.

FE/MU	**Assessment**[a]	**Barriers**	**Examples of solutions or problems to solve**	
FE2/1 Strip CP planted	FO: + M: ++	CP growth, CP management, Work organization, Lack of technical knowledge.	To prevent from weeds development where the plastic mulch was removed to plant CPs with no excessive costs or labour: adapt irrigation in the planted area, increase CP density. CP could be planted earlier.	
FE2/2 Strip CP sown	FO: 0 M: 0	CP growth (*seeds germination failure*)	To succeed in CP germination and growth: perform a specific soil preparation before sowing CP, increase water supply and CP sowing density.	
FE2/3 Strip CP in pots	FO: ++ M: +	CP growth, CP management, Labour intensity, Complexify the system management.	To limit its dryness and provide sufficient substrate for the CP along the cash crop cycle: use bigger pots. Pay attention to the climatic conditions that can be lethal for mirids at the time of transfer from tomato plants to CP	
FE2/4 Mixed CP in pots	FO: ++ M: +			
FE3/1 Mixed within row Between apple trees	FO: + M: -	CP growth, Cash crop management inconvenience, Lack of locally adapted CP plants or seeds	Use annual CP between the trees within the row and a perennial CP in alleyways OR use a CP variety with a better soil-cover capacity OR re-design future orchards to optimise the arrangement of trees, CPs and drips.	
FE3/2 Strip Between trees rows	FO: + M: ++	Cash crop management inconvenience, Equipment circulation	To control weeds between tree rows: test tools already mobilized by the producers of aromatic plants. Get inspiration from agroforestry designs with wider CP strips between tree rows.	
FE14/1 Rotation and then as a mulch	FO: + M: +	Excessive costs, Uncertain pest and disease control, Work organization, Lack of adapted equipment, Equipment circulation, Other: CP mowing	Increase CP density and replace dead CP. Sow and low CP earlier. Use a relevant sowing drill for crotalaria seeds. Use several species of CP.	Let CP intercropped in the tomato field. Facilitating mechanization.
FE14/2 Field margin	FO: - M: ++	Excessive costs, Uncertain pest and disease control, Work organization, Other: weed control		Bring CP closer to tomato. Specific irrigation on field margin

[a] Experimenter's assessment for FO: Functional objectives; M: practicability and crop management; '0' unsatisfied, '-' hardly satisfied, '+' satisfied, '++' highly satisfied. FE: Field experiment; MU: Modality of use; CP: Companion plant.

Transversal analysis from the 46 modalities of use for companion plants

Experimenters anticipated in average more potential difficulties than were actually faced. An average of 4.8 potential barriers per MU was anticipated, whereas 3.7 types of barriers faced per MU were reported. The main barriers feared at the system design stage related to sanitary problems: "sanitary risks" from the CP and "uncertain control of pests and diseases" using CP were associated respectively with 70% and 52% of the MUs (Figure 2). Moreover, "Work organization" complexity, "CP growth" difficulties and lack of "Technical knowledge or references" were feared for 50%, 48% and 46% of the MUs (Figure 2). The main obstacles actually faced during the implementation in field conditions related to "CP growth" (in 54% of the MUs). Work was also affected since "work organization" and "system management or monitoring" were considered as highly complex in respectively 50% and 33% of the MUs (Figure 2). Pest and disease control was not considered efficient in 35% of the MUs (Figure 2). Moreover, during the face-to-face discussion, ELs were able to cite and specify solutions to test or already tested (as illustrated in Table 1). These solutions were expected to improve the achievement of functional objectives and the management of the agrosystem in 54% and 61% of the MUs, respectively.

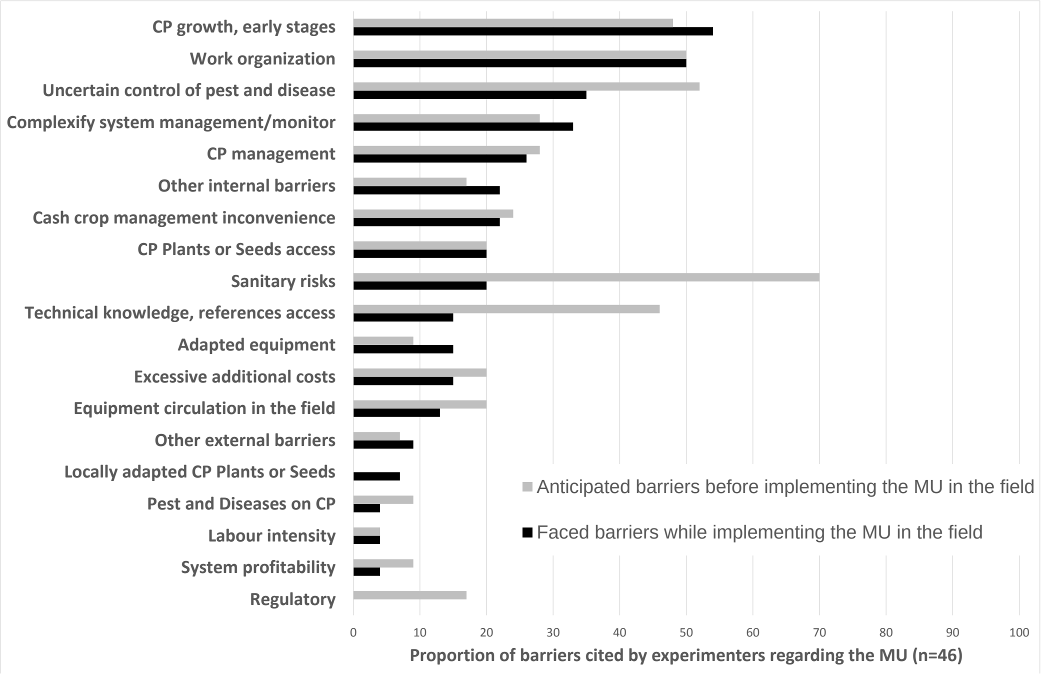

Figure 2. Proportion of barriers anticipated before and actually faced during the experiment with each of the 46 modalities of use of companion plants (CP). MU: Modality of use of agroecological companion plants.

Based on a wide range of situations we show that field experiments are supporting the production of actionable knowledge in a strategic agroecological practice. Experimenters were able to anticipate a wide range of problems, relating not only to technical aspects. The main barriers encountered during the experiment focused less on technical and sanitary problems than anticipated. This indicates that experimenters are already facing part of the real-life conditions in such FEs, including barriers at the scale of innovative agroecological systems as a whole (Cardona et al., 2018). Like innovative farmers, the leaders of this type of FE are designers who are continuously adjusting to find a compromise between realization of the function and operational feasibility, taking into account broader issues than those of the trial or of the field scale (Navarrete et al., 2021).

The first obstacle identified is the growth of the companion plant, a prerequisite for the function to be fulfilled. Particular attention must be paid to this stage by seeking a trade-off between CP management and its final added value. Labour is also one of the main obstacles identified. Additionally, agrosystems that include CPs become more complex and need to be managed differently (Alaphilippe et al., 2022). Multi-species systems must be redesigned, at least to some extent, to ensure that the functional as well as the productive and labour processes are compatible (Schut et al., 2014). A larger sample of horticultural field experiments should be surveyed to detect whether specific productions or CPs faced particular barriers. Taking these barriers into account in research projects on CPs is essential if CPs are to be adopted on the farm. Moreover, building relevant cognitive resources to give visibility to this knowledge is as strategic as presenting scientific results (Girard and Magda, 2020; Quinio et al., 2022). Such resources could present the modalities of use as options to explore, where experimenters have already gained useful experience.

CONCLUSION

In this study, we documented how field experiments carried out in conditions similar to those found on local commercial farms can provide useful actionable knowledge for managing CPs for crop health in horticultural systems. This illustrated the value of these experiments for agroecological transition, as they both support scientific knowledge on CPs, and reveal barriers and solutions in many respects. Research projects on CPs should take into consideration the barriers thus revealed in the practice, as this actionable knowledge is necessary for the adoption of CPs by stakeholders. Thus, dissemination of field experiment results should include and put forward this knowledge. Scientific- and action-based knowledge is produced jointly in agroecological field experiments and should both be applied.

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