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RESEARCH ARTICLE

Designing agroecological systems across scales: a new analytical framework

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Abstract

Researchers worldwide are expected to design and develop agroecological systems to address major challenges such as increasing biotic pressure and climate change. But to design effective innovations, researchers should integrate new cropping techniques into wider agricultural systems such as cropping systems, innovative farms, alternative food systems, or multifunctional landscapes. This integration requires a long process of exploration in which the object under design can transform and shift to a different organisational scale. In this article, we wish to introduce a new analytical framework highlighting the systemic mechanisms involved in the scale transformations of design objects along agroecological design processes. We conceptualise an agroecological design process as a non-linear unpredictable process in which four components—a science consortium, non-scientific actors in the field, a problem situation and a design object—interact, and co-evolve through time. The scale transformations of the design objects and their drivers are the results of interactions and knowledge flows between these four components. This analytical framework was tested and further elaborated through ex-post analysis of design processes in three contrasting case studies in the context of tropical horticulture. Data were collected through literature review, interviews, and focus group discussions with the researchers involved in the three design processes. Future design methods should take full account of the lengthy, non-linear, and transformational nature of agroecological design processes and the coexistence of different types of knowledge—holistic vs. reductionist, ecosystem focused vs. human-system focused—which can interconnect and nourish each other.

Keywords Open innovation · Innovative design · Farming system · Food system · Landscape management · Horticulture

1 Introduction

Agriculture worldwide needs to change profoundly and quickly to address unprecedented challenges such as climate change adaptation/mitigation, natural resource conservation, and food provision for a rapidly increasing population (Willett et al. 2019). In that context, it is well established that the mainstream agricultural model promoted since the 1960s does not provide sustainable solutions (Frison, IPES-Food 2016). Conventional farming systems may be productive in the short term, but they are highly vulnerable to pests and climatic hazards in the mid- and long term. As they are heavily dependent on costly exogenous inputs, they have negative impacts on the environment at both local and global scales (Malézieux and Dabbadie 2019). Moreover, farmers are locked into a vicious cycle where systematic use of agrochemicals provokes pest resistance, which in turn obliges the farmers to increase their crop treatments. The resulting

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danger to the health of farmers and ecosystems is particularly high in horticultural systems (De Bon et al. 2014).

Agroecology is recognised as a promising model for transforming agricultural and food systems by addressing the problems facing agriculture in a systemic and integrated way (FAO 2018; Ollivier et al. 2018). It is a holistic approach that simultaneously applies ecological and social concepts and principles to the design and management of food and agriculture systems (Gliessman 2018; Altieri et al. 2015). Agroecology consists in optimising the interactions between plants, animals, humans, and the environment while taking into consideration the social aspects that need to be addressed for a sustainable and fair food system (FAO 2018). By maximising biodiversity at different scales, agroecology seeks to stimulate synergies between different species as part of holistic strategies to build long-term fertility, healthy agro-ecosystems, and secure livelihoods (IPES-Food 2018).

The agroecological transition being at the top of the agenda of public agricultural research organisations and donors (Brunori et al. 2009), scholars are expected to provide knowledge, references, and tools to design innovative agricultural systems that are sustainable from an ecological point of view but also meet economic and social criteria, to ensure their adoption by numerous farmers (Wezel et al. 2009; Doré et al. 2011; Malézieux et al. 2009). Based on literature (Hatchuel et al. 2012; Hatchuel and Weil 2003; Berthet 2013; Salembier et al. 2021), we define design as an active, intentional process to generate concepts and knowledge that lead to new products or technologies.

Over the last few decades, scientific research in agroecology has focused on systems of increasing scale and size, from simple cropping techniques (e.g. pruning and organic fertilisation) to more complex objects such as cropping systems (Debaeke et al. 2009), innovative farms (Bos and Grin 2012; Cerf et al. 2012; Dogliotti et al. 2014), alternative food systems (Wezel et al. 2009), and multifunctional landscapes (Van Berkel and Verburg 2012). This trend has been supported by an expanding range of scientific disciplines involved in designing agroecological systems, e.g. agronomy, entomology, soil science, social science, and geography, with an awareness that solutions designed at a given scale can be rendered obsolete by ecological or social processes that appear at higher scales. Therefore, from a discipline focused on ecological processes and farmers' fields, agroecology has evolved into an interdisciplinary approach aimed at designing food systems in order to achieve environmental, economic and social sustainability (Francis et al. 2003; Gliessman 2015, 2016).

The broadening of the agroecological perspective has also gone hand in hand with an increasing recognition of the role of non-scientific actors in problem assessment and co-design of sustainable solutions (Fischer et al. 2021; Méndez et al. 2013). It is well established that non-scientific actors have a critical role to play in agroecological design processes led by researchers since (i) they express knowledge of site-specific biological regulations and social interactions, and (ii) they produce relevant knowledge by using the object under design (Prost et al. 2017). Therefore, the traditional top-down, linear design approach is not appropriate for the design of complex agroecological systems (Meynard et al. 2017). This calls for new ways of organising the design process by fostering more open, decentralised, contextualised, and participatory approaches (Berthet et al. 2018).

Hence, for the researchers engaged in the design of agroecological systems, the challenge is particularly high since they should embrace multiple scales, disciplines, and actors in their work. For this reason, the design of complex, multi-scaled agroecological systems cannot be achieved overnight. It often involves a long process of exploration in which the system under design can evolve and move from one scale to another (Le Masson et al. 2006; Meynard et al. 2017, Klerkx et al. 2012). Over time, the initial innovations introduced by researchers can be incrementally modified, radically transformed or integrated within wider system innovations. For instance, a particular cropping technique can be progressively introduced into a coherent cropping system (Deffontaines et al. 2020) by combining multiple agronomic levers such as resistant varieties, rotation, cover crops or integrated pest management methods. Similarly, different kinds of cropping or livestock systems can be integrated into innovative farming systems. Eventually, agroecological farming systems can be connected with meta-systems such as alternative supply chains or certification schemes to overcome lock-ins and obstacles to adoption (HLPE 2019; Cerdan et al. 2019).

Past researches on design have developed theories, methods and tools in order to understand and improve design processes. The main theoretical framework, called the C-K theory, is focused on the rationale and reasoning that appear in design (Hatchuel and Weil 2003; Le Masson et al. 2006, 2012). This theory links the definition process of a new object to the activation of new knowledge and conversely (Hatchuel et al. 2012). Agricultural researchers have extensively mobilised this framework (among other theoretical inputs) to develop methods and tools to organise actors' participation and stimulate generativity in a design process (Salembier et al. 2018; Berthet et al. 2018). Although this literature recognises the importance of mobilising multiple scales, disciplines, and non-scientific actors in the design of agroecological systems, it does not show how these elements interact, coevolve, and transform with time during real-life and long-lasting design processes. More specifically, existing methods, tools, and analytical frameworks have limitations with regard to agroecology since (i) they tend to isolate specific moments (e.g. participatory diagnosis, co-construction of new concepts, field experiment, etc.) leading to overlooking the long-term process in which researchers interventions are embedded; (ii) they rarely put the focus on the interactionist and multi-scale nature of agroecological design processes with however few exceptions (Duru et al. 2015); (iii) they often adopt a normative approach of design rooted in management science, which is not based on in-depth observations of how researchers effectively design agroecological systems in their work practice.

In this article, we wish to introduce a new analytical framework which highlights the systemic mechanisms involved in objects' transformations along agroecological design processes. This analytical framework may help answer the three following questions:

(1) How, during design processes, do agroecological systems transform and cross from one organisational scale to another, and what the drivers of these transformations are?
(2) What is the specific role played by researchers from various disciplines and non-scientific actors in the scale transformation of design objects?
(3) What is the role played by object transformation in the agroecological design process?

This framework was tested through an in-depth analysis of design processes in three contrasting case studies in tropical horticulture contexts (Fig. 1). These design processes were conducted by the co-authors of this paper, a multidisciplinary research team (the HortSys research unit) from CIRAD (French agricultural research and international cooperation organisation), over a period of two decades (from the 2000s to today).

In the following parts of the paper, we begin by introducing our analytical framework of agroecological design processes (Section 2.1 below) and a data collection method (Section 2.2). We then present our three case studies (Section 3). In the discussion section, we build on our empirical cases and existing literature to discuss and deepen our analytical framework (Section 4.1). We eventually discuss the implication of our study for the methods and tools used by researchers to organize design processes (Section 4.4). The paper concludes with proposals for improving design approaches (Section 5).

Fig. 1 Photographs illustrating the three case studies. (**a**) Weaver ants building their nest in young mango leaves in Senegal. Photograph by R. Belmin/Cirad. (**b**) Trial to test Integrated Pest Management cropping systems, outdoors vs. under nets, in Kenya. Photograph by R. Belmin/Cirad. (**c**) Farmers, extension agents, and catchment managers in Martinique play a game in order to design innovations at catchment scale. Photograph by Cirad.

2 Material and methods

2.1 Building a framework for analysing agroecological design processes

The design theory called C-K theory models the special logic that allows a “new object” to appear. It highlights how previous definitions of objects are revised and new ones can appear, threatening the consistency of past knowledge (Hatchuel et al. 2012). Without questioning that theory, we adopt an interactionist analytical framework which puts the light on the co-evolutionary mechanisms involved in the changes of the design object. Based on the existing literature and our own experience, we conceptualise an agroecological design process as a non-linear, unpredictable process in which four components—a science consortium, actors in the field, a problem situation and a design object—interact, and coevolve through time. The scale transformations of the design objects and their drivers are the results of interactions and knowledge flows between these four components (Fig. 2).

2.1.1 The four components of an agroecological design process

According to the literature, agroecological design processes involve at least four components, which interact extensively:

– The design object is a novelty currently in the process of being designed by researchers with the participation of actors (Hatchuel and Weil 2003). It is the provisional outcome of the design process which may transform with time under the influence of new knowledge (Hatchuel et al. 2012). The design object can take the form of a material prototype (e.g. field experiment, pilot farm, etc.) or a concept (Le Masson et al. 2012). It is characterised by an organisational level (see Section 2.1.2) that may change in the course of the design process.

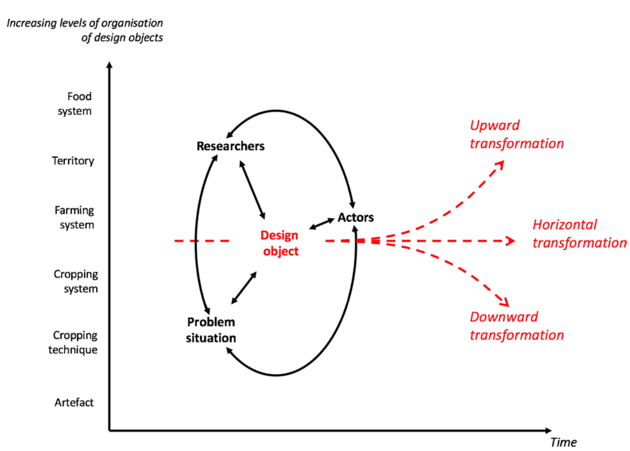


Fig. 2 Overview of the analytical framework for agroecological design processes.

– The problem situation, or “design issue” as defined by Salembier et al. (2018), is a dynamic affecting the actors and/or the natural resources of a given agro-ecosystem (e.g. biodiversity erosion, water pollution, and pest invasion) and which requires corrective intervention. Researchers and non-scientific actors build their own representations of the design issue, which evolve as the problem is being solved and new objects are being designed (Toffolini et al. 2020; Dorst and Cross 2001).

– The researchers are members of science consortia involving several labs and disciplines, who harness scientific and empirical knowledge (learned from actors) to assess the problem situation and design a new object as a solution (Debaeke et al. 2009; Wezel et al., 2009). Researchers often develop adaptive management strategies to organize the design process and stimulate the participation of non-scientific actors (Duru et al. 2015; Fischer et al. 2021).

– The non-scientific actors (we will call them “actors” for practical reasons) are organisations or social groups directly or indirectly affected by the problem situation (e.g. farmers, extension agents or experts on a given crop, or agricultural area), and who are mobilized by researchers for the design of agroecological systems (Kindon et al. 2007; Cuéllar-Padilla and Calle-Collado 2011). Many studies have described the key role played by actors in agroecological design processes, either by taking part in problem assessment, by co-designing new objects with researchers or by testing the new concepts in real situation (Marin et al. 2016; Meynard et al. 2012).

2.1.2 The six levels of organisation of the design objects

The objects under design can be located at various levels of organisation (Gliessman 2015; Prost et al. 2017). We distinguish here six main categories:

– Material artefacts: At the first level, the design objects are various kinds of self-standing artefacts which do not (or do not yet) belong to any agricultural system. Examples would be a new piece of equipment, plant cultivar or animal breed, a specific input or a new bioactive component. As a concrete example, “attract and kill” fruit fly traps have been developed to control populations of fruit flies which are pests of major economic importance (Dias et al. 2018).

– Cropping techniques: Researchers often design particular cropping techniques to improve the performance of existing cropping systems in a given area without calling the system’s overall functioning into question. One example is the replacement of a chemical pesticide by a bio-pesticide (Mossa 2016). Cropping techniques usually put artefacts to practical use.

- Cropping systems: The object designed can also be a cropping system, defined as a coherent set of cropping techniques organised in space and time to achieve a given goal (e.g. achieving a target yield, stimulating an ecological process or enhancing the cropping system's agronomic, economic, and environmental performance). For instance, Colbach et al. (2017) used a specific computer model to design a multi-objective oilseed rape/wheat/barley cropping system with low levels of weed harmfulness and little herbicide use.
- Farming systems: One can design new ways of organising production at a farm scale. This includes developing synergies among and between crops and livestock, along with changes to work organisation or material investments (such as machinery) in order to improve the performance of the farming system as a whole (Berthet et al. 2018). One example is the introduction of diversity into the farm's structure through rotation, crop diversification or agroforestry, or by integrating livestock with crops (Gliessman 2015).
- Territories: Researchers may design spatial arrangements of habitats, resources, and innovative activities to create multifunctional landscapes. Landscape composition and configuration are known to influence ecological, hydrological, and biogeochemical processes (Della Rossa 2020; Prost et al. 2017; Ricci et al. 2009). Research at landscape scale also includes the co-design of collective strategies to improve natural resource management (Etienne 2011). In Senegal, a multidisciplinary team has used satellite imagery (showing the abundance and diversity of trees and vegetation) coupled with molecular tools (characterisation of food web structures) to develop ecologically intensive pest control solutions against the millet head miner *Heliocheilus albipunctella* de Joannis (Lepidoptera, Noctuidae) (Brévault and Clouvel 2019; Soti et al. 2019).
- Food systems: More recently, researchers have attempted to redesign food systems by picturing new ways of organising the relationship between farmers and consumers. One example is the design of sustainable city-region food systems, an approach intended to reshape the flows of food, waste, people, and knowledge between rural, peri-urban, and urban areas (Blay-Palmer et al. 2018). Another example is provided by the Lancet Commission who designed diets that will nurture human health and support the environmental sustainability of global food systems (Willett et al. 2019).

2.1.3 Three types of scale transformation of the design object

Based on the literature, we consider that objects can be affected by three types of transformation (Fig. 2):

- Horizontal transformation happens when the organisational scale remains unchanged while no radical changes are brought to the object under design. The majority of design studies report cases of horizontal transformation (e.g. Bachinger and Zander 2007; Le Gal et al. 2010; Petit et al. 2021). The iterative design approach proposed by Debaeke et al. (2009) provides a good example: the researchers seek to incrementally improve a given cropping system through "improvement loops" of design and assessment.
- Upward transformation happens when researchers or actors relocate a given object to a wider system. Brun et al. (2021) proposed an approach to couple agricultural innovations with changes at the food system level as a way to promote systemic changes.
- Downward transformation consists in isolating one component of the system under design in order to transform it and to reuse it in a new context. For instance, an essential oil may be extracted from a companion crop in a cropping system and studied to develop a biopesticide as a new artefact (Mossa 2016).

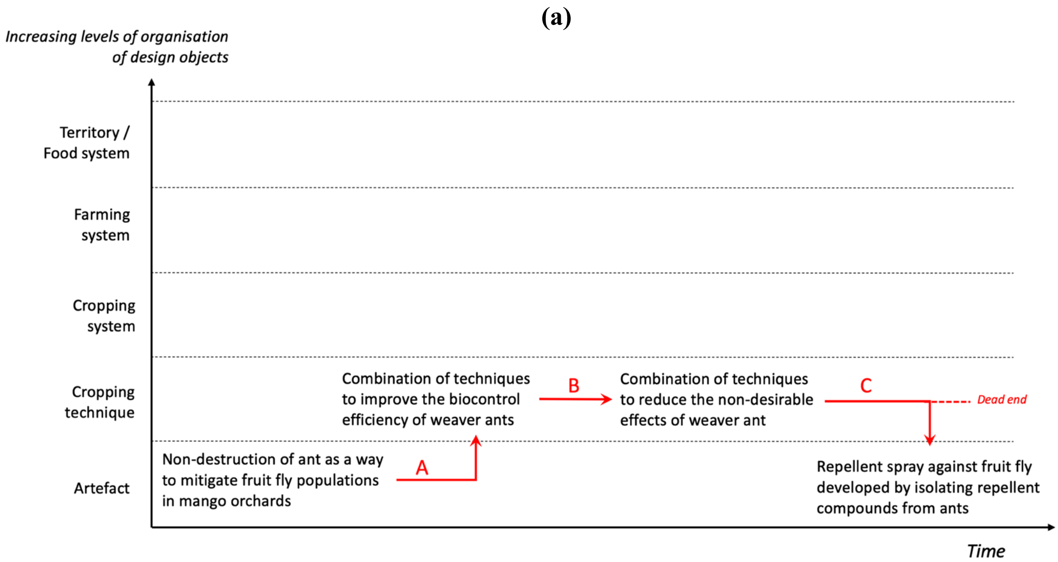
Along an agroecological design process, the design object may transform under the influence of the three other components above mentioned (researchers, actors, and problem situation). In turn, scale transformations of the design object may drive changes in the way actors, researchers, and problem situations act and interact.

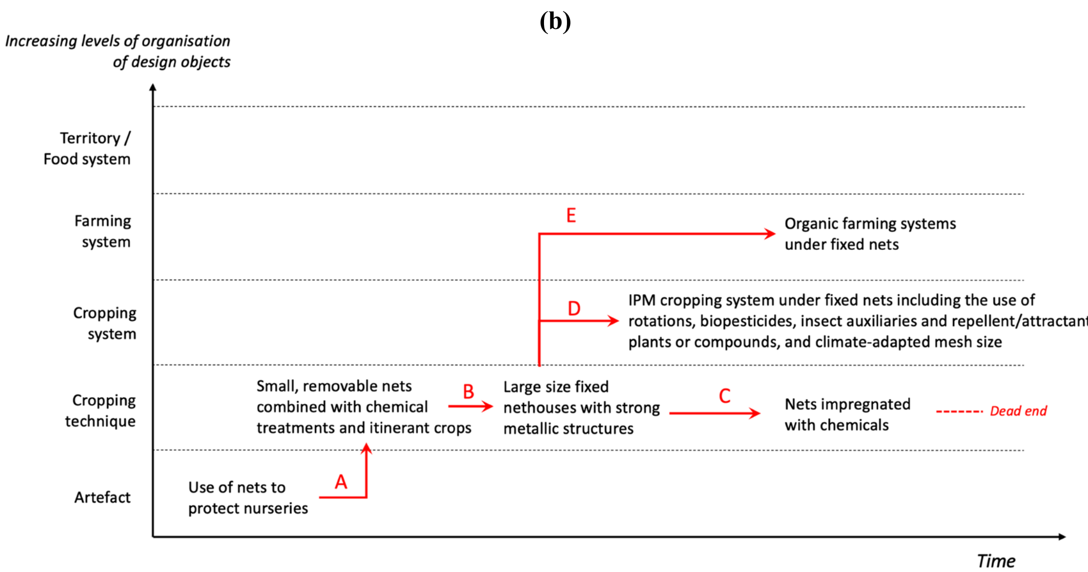
2.2 Case studies

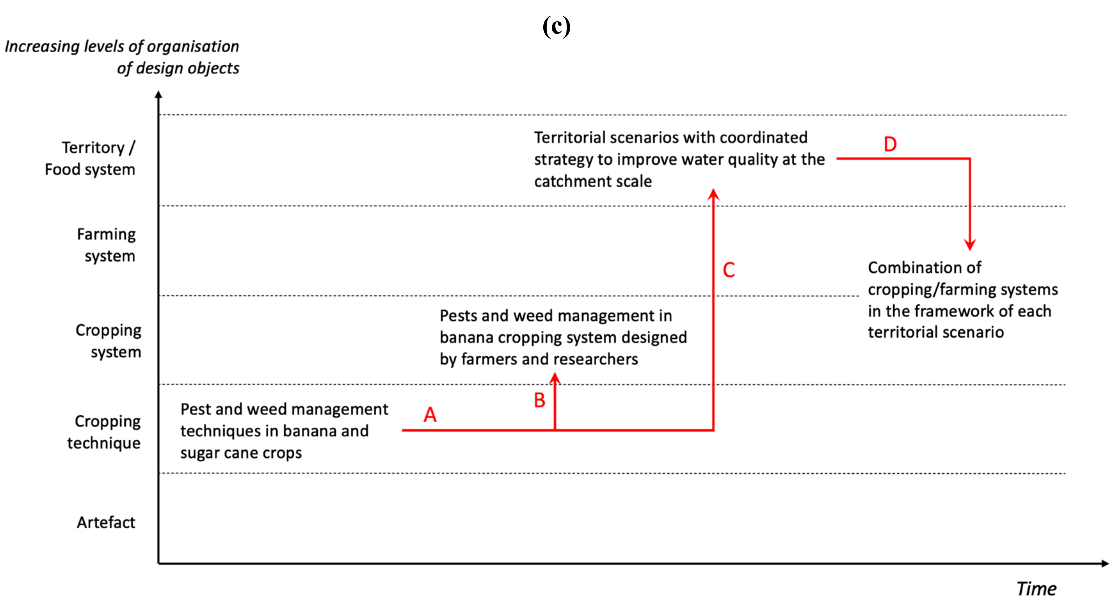
In tropical areas, horticultural systems are at the forefront of agroecological transition challenges: they are expected to contribute to the food security of a growing population while shifting to greener production models (Thomas 2012). However, with climate change and globalisation, they are increasingly subject to biotic stresses such as pests and diseases, leading most smallholders to make heavy use of agrochemicals (De Bon et al. 2014).

As a research team specialising in the design of horticultural systems in the tropics, we documented design processes we conducted in three contrasting climatic and socioeconomic situations in the tropics. All three design processes were aimed at reducing the use of agrochemicals in horticultural systems. We chose to focus only on design processes led by researchers, although we know there are situations where the design process is led by farmers.

Our three case studies concern the co-design of (1) fruit fly biocontrol strategies based on the conservation and domestication of weaver ants in West African mango orchards, (2) vegetable cropping systems using insect nets to decrease the use of agrochemicals in Benin, Kenya, Tanzania and Côte d'Ivoire, (3) cropping systems deployed across


(a)
Increasing levels of organisation of design objects
Territory / Food system
Farming system
Cropping system
Cropping technique
Artefact
Time
Non-destruction of ant as a way to mitigate fruit fly populations in mango orchards
A
Combination of techniques to improve the biocontrol efficiency of weaver ants
B
Combination of techniques to reduce the non-desirable effects of weaver ant
C
Dead end
Repellent spray against fruit fly developed by isolating repellent compounds from ants


(b)
Increasing levels of organisation of design objects
Territory / Food system
Farming system
Cropping system
Cropping technique
Artefact
Time
Use of nets to protect nurseries
A
Small, removable nets combined with chemical treatments and itinerant crops
B
Large size fixed nethouses with strong metallic structures
C
Nets impregnated with chemicals
Dead end
D
IPM cropping system under fixed nets including the use of rotations, biopesticides, insect auxiliaries and repellent/attractant plants or compounds, and climate-adapted mesh size
E
Organic farming systems under fixed nets


(c)
Increasing levels of organisation of design objects
Territory / Food system
Farming system
Cropping system
Cropping technique
Artefact
Time
Pest and weed management techniques in banana and sugar cane crops
A
B
Pests and weed management in banana cropping system designed by farmers and researchers
C
Territorial scenarios with coordinated strategy to improve water quality at the catchment scale
D
Combination of cropping/farming systems in the framework of each territorial scenario

◀**Fig. 3** Design processes in the cases studied: (**a**) weaver ants (see section 3.1), (**b**) nets (see section 3.2), and (**c**) collective pest and weed management (see section 3.3). The graphs show how the design object evolved over time, producing non-linear trajectories (red lines), branching, and dead ends.

space and time with organisational innovations at water catchment scale in order to reduce water pollution by pesticides in Martinique (French West Indies). The three design processes are based on contrasting innovations: (i) the use of a living organism—the weaver ant—in the first case, (ii) the introduction of an external artefact—the net—in the second case, and (iii) a social innovation—a new cooperation between actors—in the third case. The case studies have all been documented by scientific publications in peer-review journals.

These case studies were chosen based on the following criteria: (i) the organisational scale of the design object should have transformed significantly during the design process; (ii) the design process should have lasted at least 20 years; (iii) the design process should have been led by researchers from the same scientific team; (iv) non-scientific actors should have participated in the design process; (v) the design process should be documented by scientific publications in peer-review journals.

2.3 Data collection

Since the co-authors of this paper took part in these design processes, the present article was constructed using a reflexive approach. The empirical material was gathered through a series of 3 workshops with the researchers involved in each case study and complemented by a literature review covering a period of two decades (2000–2020). During workshops, the lead researchers of each design process were asked to describe the design process freely, with other participants asking questions to clarify grey areas. Supplementary data were collected after the workshops, through individual interviews conducted by the lead author of this article with the lead researcher of each design process.

Data collection and analysis were guided by the analytical framework described in Section 2.1 above. We asked the following questions:

1. What were the nature and organisational levels of the design object (gene, plant, animal, cropping system, farm, etc.)?
2. How did the design object transform over time, and what were the reasons for these transformations?
3. What were the perceptions and specific roles of the researchers and other actors in the design process?
4. How have the four components of the design process—researchers, actors, design object, and problem situation—interacted and coevolved over time?
5. What role object transformations did play in the design process?

The case studies are briefly described below. We provide full descriptions of them in the supplementary materials (SM.1).

3 Results

3.1 Design of fruit fly biocontrol strategies through conservation of weaver ants in African mango orchards

From 2005, the invasion of West African mango orchards by the exotic fly *Bactrocera dorsalis* triggered joint efforts by researchers, donors, and local actors to mitigate fruit losses and safeguard exports. Among various possible solutions, a strong hypothesis was that the ant *Oecophylla longinoda* could be effective in mitigating fruit fly populations in mango orchards. In the first step, researchers based in Benin simply demonstrated and recommended non-destruction of the weaver ant. They subsequently conducted laboratory tests and field experiments to pin down the mechanisms by which the weaver ant regulates fruit flies. This research enabled them to design a combination of techniques to improve the biocontrol efficiency of weaver ants (Fig. 3a, step A). These techniques included preserving the grass cover, avoiding insecticide treatments, increasing ant mobility and boosting early ant colony growth by taking care of nests or introducing multiple queens, and transplanting pupae. This upward transformation of the design object mainly resulted from scientific knowledge of the weaver ant's behavioural and ecological patterns that the researchers had accumulated.

In a second step, researchers designed solutions to reduce the undesirable effects of the weaver ants (Fig. 3a, step B). This second transformation of the design object was prompted by the extensive researcher-actor interactions taking place in eight West African countries, mainly through surveys, training sessions and demonstration plots. These interactions led researchers to understand that many farmers regarded the ants as pests: (i) they bite the farm workers, making the harvesting and the pruning harder and slower; (ii) they decrease the mangoes' market value by encouraging the spread of mutualistic honeydew-producing mealybugs which can damage the skin of the fruit; (iii) they are perceived as reducing yields by damaging flowers and limiting vegetative growth by building their nests in young leaves. Faced with these facts, researchers developed a range of responses to address the criticisms of ant biocontrol. They intensified research on the ant's ecology and demonstrated that ants' nests do not affect the mango trees' vegetative growth and that mealybugs only proliferate if farmers treat their orchards with chemical insecticides. Researchers also screened endogenous knowledge in nine countries in order to capture endogenous knowledge and innovations so as to minimise the disadvantages of the ants' presence (e.g. use of repellent on pickers' hands, harvesting with long picking poles, feeding ants with sugar to reduce their aggressive behaviour).

In the most recent period, researchers have been trying to bypass obstacles to the adoption of the ant method by isolating repellent compounds from ants to produce a repellent spray against fruit flies, so taking advantage of the ants' repellent power without using them in the orchards (Fig. 3a, step C). This third transformation was triggered when chemists joined the research team and proposed an innovative solution—the repellent spray—that was outside the entomologists' scope. Thus in this case study, the object under design was transformed through a four-step process.

3.2 Design of cropping systems with insect nets in Africa

In sub-Saharan Africa, the routine, uncontrolled use of agrochemicals on horticultural crops poses a major threat to human health and the environment. Moreover, repeated broad-spectrum insecticide treatments have triggered resistance in some target fauna, so decreasing the efficacy of the chemicals.

A research team based in Benin, West Africa, observed smallholder farmers using nets to protect their nurseries against birds, insect pests, and stray animals. In fact, the farmers were diverting impregnated mosquito nets from a World Health Organization malaria prevention program. The researchers assumed that nets had the potential to become a credible alternative to agrochemicals since they did not require advanced agronomic skills or knowledge of pest management. The researchers started to investigate the potential for nets to control pests on vegetable seedlings and crops. They first confirmed the farmers' empirical observations: the nets acted as a physical barrier, preventing the diamondback moth (*Plutella xylostella*) from reaching their cabbage seedling beds. The researchers then ran a trial to check the impact of nets on older vegetable crops. They found that although they effectively decreased butterfly populations, nets did not protect against aphids. Worse still, they kept out ladybirds, which are aphids' natural enemies. This led the researchers to combine nets with agrochemical treatments to control aphids (Fig. 3b, step A).

In 2012, net tunnels were distributed to groups of volunteer farmers in Benin and Kenya. Based on results from the first trial, researchers advised the farmers to remove the nets during the day to give access to pests' natural predators. Farmers were also advised to use agrochemicals in the event of severe aphid infestation. These were low net tunnels which could be handled and removed as required. The results of this multi-site experiment were encouraging, but farmers pointed out the amount of work required to install and remove the nets every day. Researchers, therefore, developed a new model of tall, fixed net tunnels on strong metal frames (Fig. 3b, step B). However, the use of fixed nets increased biotic and abiotic pressure (accumulation of biting pests under the closed nets), which prompted the researchers to explore further. At first, they tried to reduce biotic stresses by impregnating the net with chemicals. This attempt failed and led to controversy owing to the risk of rain flushing pesticides from the net onto the crop (Fig. 3b, step C). The researchers then changed their approach, combining physical protection with cropping systems based on Integrated Pest Management principles (Fig. 3b, step D): (i) they diversified the cropping systems, using rotations to mitigate telluric pests and diseases (e.g. nematodes); (ii) they tested a range of biocontrol strategies to limit the populations of biting insects (aphid, etc.) that accumulated under the closed nets. Methods tested included biopesticides, beneficial insects, and repellent/attractant plants or compounds. The researchers found that these methods were more effective inside the nets than in open field conditions; (iii) to mitigate the extreme temperatures that could affect the netted crops during the day, researchers started looking for the appropriate mesh size for each country's climate conditions. Mesh size should strike a balance between the natural aeration it provides and the insect species it lets through. Introducing IPM required a broadening of the research consortium, bringing in agronomists, entomologists, chemists, and private companies working to develop biocontrol tools. Finally, in a new multi-site experiment conducted in Kenya, Tanzania, and Côte d'Ivoire, some farmers spontaneously shifted to organic farming systems under the nets (Fig. 3b, step E). Thus the net house case study exemplifies a progressive increase in the complexity of the object under design, from the use of a simple artefact to cover the crops to complex cropping systems combining physical protection, biocontrol and rotations.

3.3 Design of innovations to reduce water pollution in Martinique (French West Indies)

Martinique is an island in the French West Indies where agriculture mainly consists of mono-cropping plantations of banana and sugar cane, and mixed cropping systems with fruit, vegetables, roots, tubers, and flowers. In the tropical climate of the West Indies, abundant rainfall, warm temperature all year long result in high weed, and pest pressures. This situation has led most farmers to apply large amounts of pesticides. Between 1972 and 1993, banana farmers have massively used a toxic and highly persistent organochlorine pesticide chlordecone to control a borer pest called banana weevil (*Cosmopolites sordidus*). Due to its persistency in soil and erosion, this highly toxic molecule has contaminated large tracts of farmland and natural areas for centuries.

This problem situation prompted actors and researchers to incrementally introduce innovations for weed and pest management. The research was conducted separately for the banana, sugar cane and mixed cropping systems (Fig. 3c, step A). Innovations in banana crops included pheromone traps, crop rotation, and improved fallow plants as a way to mitigate insect pests and nematodes. Researchers and actors also designed a bundle of sustainable weed management practices to decrease herbicide use. These included cover crops, crop associations, the use of animals such as poultry and small ruminants, and mechanical weeding (tillage, mowing, and crushing). Further research led them to combine these cropping techniques into coherent cropping systems. For their part, some farmers redesigned their entire cropping systems by gradually adding simple changes or by a direct change of system (Fig. 3c, step B). Despite these efforts, the problem of herbicide pollution in the watersheds remained unsolved. In 2013, a study explored the impact of agrochemicals on the quality of streams throughout a river catchment. The resulting spatio-temporal modelling revealed that the contamination of rivers by pesticides was due to the accumulation of farmers' practices at the catchment scale. Thus, only a collective approach of pesticide reduction by farmers could help to reduce pollution. A second study exploring the socio-technical drivers of herbicide use revealed that it was difficult to foster effective herbicide reduction strategies because the catchment was not a management entity: it included three types of specialised farms (banana plantations, sugar cane plantations, and small-mixed farms) that did not interact with each other, each being encouraged to use chemicals by specific sectoral drivers. This situation had led to a lock-in, limiting the exploration of innovative solutions so that researchers did not think to challenge the basic monocrop-based model.

In the light of these two studies, the researchers were able to overcome single-sector thinking and widen the scope of the design process. Actors from the banana, sugar cane, and mixed horticulture subsectors were brought together and asked to co-design territorial scenarios to improve water quality at the catchment scale (Fig. 3c, step C). This upward transformation of the design object was made possible by the models, co-design approaches (KCP method, role-playing) and other boundary objects used by researchers to organize the process of innovative design. These tools played a critical role in stimulating inventiveness and structuring collective learning. For each territorial scenario, participants eventually designed a combination of cropping, farming, and organisational systems to improve weed management at the farm level (orchard conversion, forming groups to hire brush cutter operators, etc.) (Fig. 3c, step D). So in this case study, the object under design evolved from simple cropping techniques to improve monocropping systems incrementally to a combination of cropping systems deployed across space and time, with organisational innovations introduced at catchment scale.

4 Discussion

4.1 How did the different components of the design processes interact and contribute to object transformation?

Based on our three case studies, we discuss how the four components—researchers, non-scientific actors, design object, and problem situation—have interacted and coevolved over time along with design processes (Fig. 4).

In each of the three cases, the problem situation influenced the design pathways by guiding the design agenda and providing legitimacy for the design work and for getting actors involved (Fig. 4, right). Initially, problem construction was often driven by the researchers' scientific knowledge and positioning (e.g. crop damage by fruit flies preventing the export of mangoes in Senegal, the appearance of resistance to agrochemicals among pests in West and East Africa, and large-scale pesticide pollution in the French West Indies). In each case, various forms of collaboration with actors (bilateral consultations, co-design methods and tools, and on-farm trials) led to significant changes in the way problem was understood. The change of perception encouraged researchers and actors to bring new knowledge into the design process and to transform the object under design. For example, when surveys and multi-site experiments made it clear that farmers perceived ants as pests, researchers tried to mitigate their undesirable effects by looking into endogenous knowledge and innovations. Similarly, in the French West Indies, researchers implemented the design of a coordinated catchment-wide strategy to reduce water pollution once they understood the distributed nature of the problem. As past studies have shown, problem situations are designated via a constructionist process in which both actors and researchers qualify and requalify the societal problems (Hay and Barab 2001). Perceptions of the problem situation also differ among and between actor groups, as well as between actors and researchers (ElSawah et al. 2013).

In our three cases, the researchers strongly influenced the design pathway since they were the main architects of the object under design and lynchpins of the process (Fig. 4, top). The work of diagnosis, design, and bringing actors into the process were often guided by knowledge and rules related to the researchers' disciplines and the social organisation of science (e.g. agenda and rules imposed by donors,

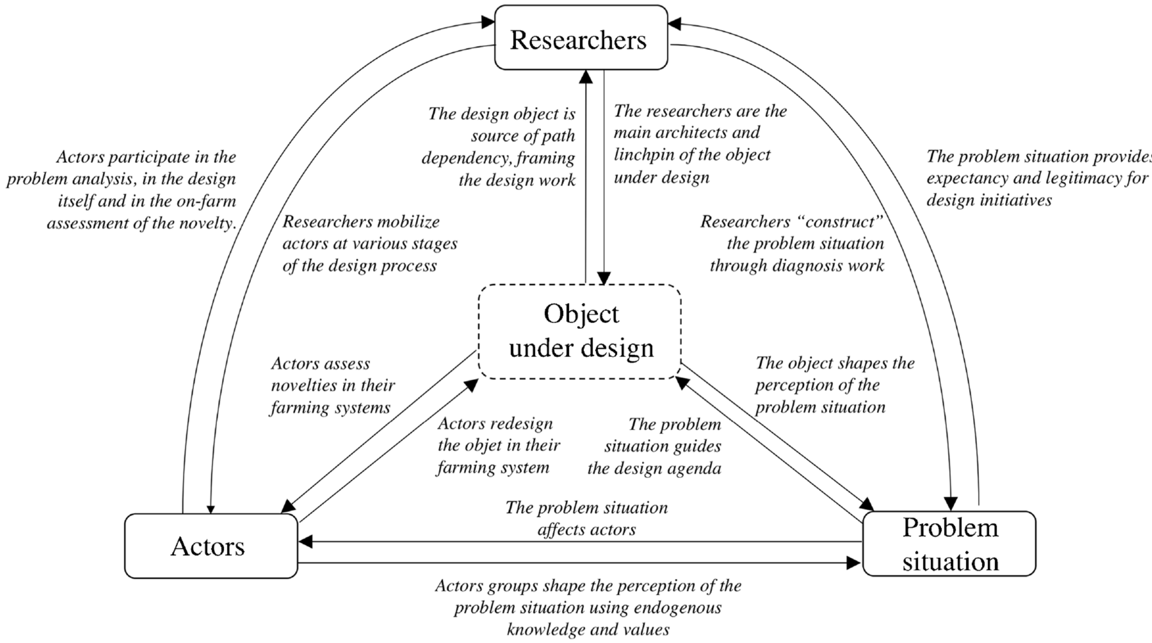


Fig. 4 The four components of agroecological design processes led by researchers and their interactions.

publish or perish, career interests, theoretical frameworks, the vision of societal progress in the light of a specific discipline). In all three cases, a change in the membership of the research team contributed to a transformation of the design object, by allowing new types of knowledge to be harnessed and by altering the way the problem situation was assessed, the way in which the actors were involved, and the design agenda itself. For instance, in the net-house case study, broadening the consortium to include agronomists, entomologists, and chemists enabled the team to develop complex cropping systems to mitigate biotic and abiotic pressures on crops. In Martinique, agrohydrologists opened up new perspectives for pesticide pollution management at the watershed scale. In Senegal, an entomologist focused on using a natural predator (ants) for pest control while a chemist suggested getting rid of the ants by using their repellent compounds.

Transformations of the design objects also resulted from interactions between scientific and non-scientific actors (Fig. 4, left). Farmers influenced design processes by taking part in problem (re)assessment, in the design itself or by testing on their farms the innovations proposed by researchers. In doing so, they pointed out economic constraints (e.g. initial choice of nets as a pro-poor technology), ergonomic problems (e.g. from low net tunnels to tall ones) or incompatibilities with their own strategies, knowledge bases, constraints, values, and visions of desirable change (e.g. ants seen as pests by African farmers). Actors also initiated or nourished the design process through their grassroots innovations. As we have shown, the researchers made active use of endogenous/expert knowledge, such as using nets to protect nurseries in Benin. Interactions between researchers and actors occurred in a variety of contexts, including surveys, multi-stakeholder workshops, on-farm trials, and catchment-scale experiments. In workshops, for instance, actors were invited to co-design or assess innovations proposed by researchers. Multi-site on-farm trials were used for testing the agronomic and economic performance of innovations in different sociotechnical and pedoclimatic contexts. In this kind of experiment, farmers could arrange and adapt the innovations provided by researchers to fit their own strategies and constraints (e.g. using net houses for new crops or in a shift to organics). This enabled researchers to enrich or transform the design object based on observation of the farmers involved. This happened in Benin, where researchers designed techniques to reduce the undesirable effects of the weaver ants based on observation of local farmers' solutions. Membership of the actor-network was not fixed; it often evolved, enabling changes in perceptions of the problem and transformations of the design object. Although very challenging, co-production of knowledge between academic and non-academic communities is an essential prerequisite for research aiming at more sustainable development (Pohl et al. 2010). Past research has shown that it is possible to foster coordination across scales by developing a more networked approach to design and innovation (Elzen et al. 2012; Hermans et al. 2016).

The objects under design transformed over time, either incrementally or by moving (up or down) to another organisational level, as the group of researchers and actors evolved, interacted, and learned about the problem situation and the object itself (Fig. 4, centre). The object's transformation resulted from co-evolutionary mechanisms among the four components of the design processes. In our three case studies, the scale transformations of design objects resulted from: (i) a change in the membership of the research consortium, allowing new types of knowledge to contribute to the design process; (ii) the involvement of non-scientific actors, who highlighted obstacles to adoption; (iii) a change in the perception of the problem situation, leading researchers and actors to re-assess initial prototypes in a new light.

4.2 How to have object transformations influence agroecological design processes?

Based on our analytical framework, we identified three types of transformation of the design object, each provoked by a specific set of drivers (Table 1), and each playing a specific role in the design processes (Fig. 5):

(i) When the object under design evolved without changing organisational scales (**horizontal transformation**), it became a source of path dependency, framing the design process, and limiting generativity. In our case studies, it did so (i) by shaping the researchers' perception of the problem situation, the definition of the problem to be solved being guided by a preconceived idea of the object to be designed (e.g. designing weed management techniques within the framework of monocropping); (ii) by constraining innovation possibilities by the material nature of the object (e.g. fixed net houses generating biotic and abiotic constraints); (iii) by generating a cognitive fixation that constrains the perception of what can be done or not; (iv) by orienting the knowledge production process, since the researchers in a design routine gradually accumulate knowledge, always of the same kind, in order to build and refine objects that are rarely called into question.

(ii) **Upward transformation** happened when researchers or actors coupled a given object with an innovation structured at a wider scale. In our cases studies, upward transformation contributed to cognitive defixation by encouraging new actors, new researchers and new types of knowledge to feed the design process. It led researchers and actors to broaden their assessment of problems by mobilising more holistic knowledge. In some cases, it also allowed design teams to overpass adoption breaks. In Martinique, for instance, the design object shifted from mono-cropping systems to a coordinated catchment-wide strategy to reduce water pollution. This change encouraged researchers (i) to mobilise jointly actors from the three subsectors of banana, sugar cane and diversified vegetable; (ii) to mobilise knowledge of sociotechnical systems and spatio-temporal dynamics of contamination of rivers by pesticides; (iii) to design sustainable and acceptable solutions to address the issue of herbicide pollution.

(iii) **Downward transformation** consisted in de-coupling the object under design in order to reuse one of its components in a new context. In our case studies, downward transformation led researchers to use reductionist approaches to focus the design on a sub-component of the object in order to bypass adoption breaks. In the ant case, chemists proposed an innovative solution—the repellent spray—to take advantage of the ants' repellent power without using them in the orchards. Hence, contrary to a well-established idea in agroecological literature, there are some cases where de-coupling objects through reductionist approaches of science could address problems that holistic ones could not solve. Many other cases of downward transformation were documented in the literature, although authors did not conceptualise it in our way. For instance, an essential oil may be extracted from a companion crop in a cropping system and studied to develop a biopesticide as a new artefact (Mossa 2016).

4.3 How did various scientific disciplines contribute to the design processes?

Our findings call for a more nuanced view of the contributions different types of research can make to agroecological design processes. Scholars generally build an ontological opposition between two distinct approaches of agroecological design, based respectively on ecosystems and on human systems, and each connected with a specific field of knowledge (Méndez et al. 2013; Willett et al. 2019). Scholars involved in natural science disciplines (e.g. entomology and ecology) design agricultural systems based on in-depth knowledge of the functioning of agroecosystems. Based on the ecology of agricultural systems, their approach takes inspiration from natural or anthropized ecosystems to develop new objects at various scales (plot, farm, landscape) (Malézieux 2012). Participatory approaches are not excluded, but they are generally restricted to validating prototypes that have already been the subject of extensive research. So when knowledge of social systems is called on, it is already late in the design process. Examples of such approaches include using the functional traits of a species, containing pests via complex trophic chains or using plant properties or other biological methods to control them (Malézieux 2012). The second approach to agroecological design considers, first and foremost, the broader forces—market, agricultural extension, or

Table 1 Drivers associated with each type of object transformation.

Object transformation	Definition	Transformation drivers		
		Problem situation	Actors	Researchers
Horizontal transformation	The object under design evolves incrementally without changing organisational scales.	No change in the structuration level of the problem.	No major adoption breaks revealed by actors.	Researchers intend to fill knowledge gaps on existing design objects in order to refine them, without considering other possible knowledge production pathways.
Upward transformation	The object is relocated to a system innovation structured at a wider scale.	Broadening of the problem assessment leads researchers and actors to understand that solutions designed at a given scale are rendered inoperable by ecological or social processes taking place at a higher scale.	Obstacles to adoption revealed by actors.	Researchers detach from the "know-it-all" objective to move towards wider agroecological systems; Intervention by new researchers using holistic approaches to overcome adoption obstacles; Use of methods and tools to stimulate innovative thinking among researchers and actors.
Downward transformation	Sub-components of the design object are isolated and reused in a new context.	No change in the structuration level of the problem.	Obstacles to adoption revealed by actors.	Researchers focus the knowledge production process on a subsystem. Intervention by new researchers using a reductionist approach to bypass adoption obstacles.

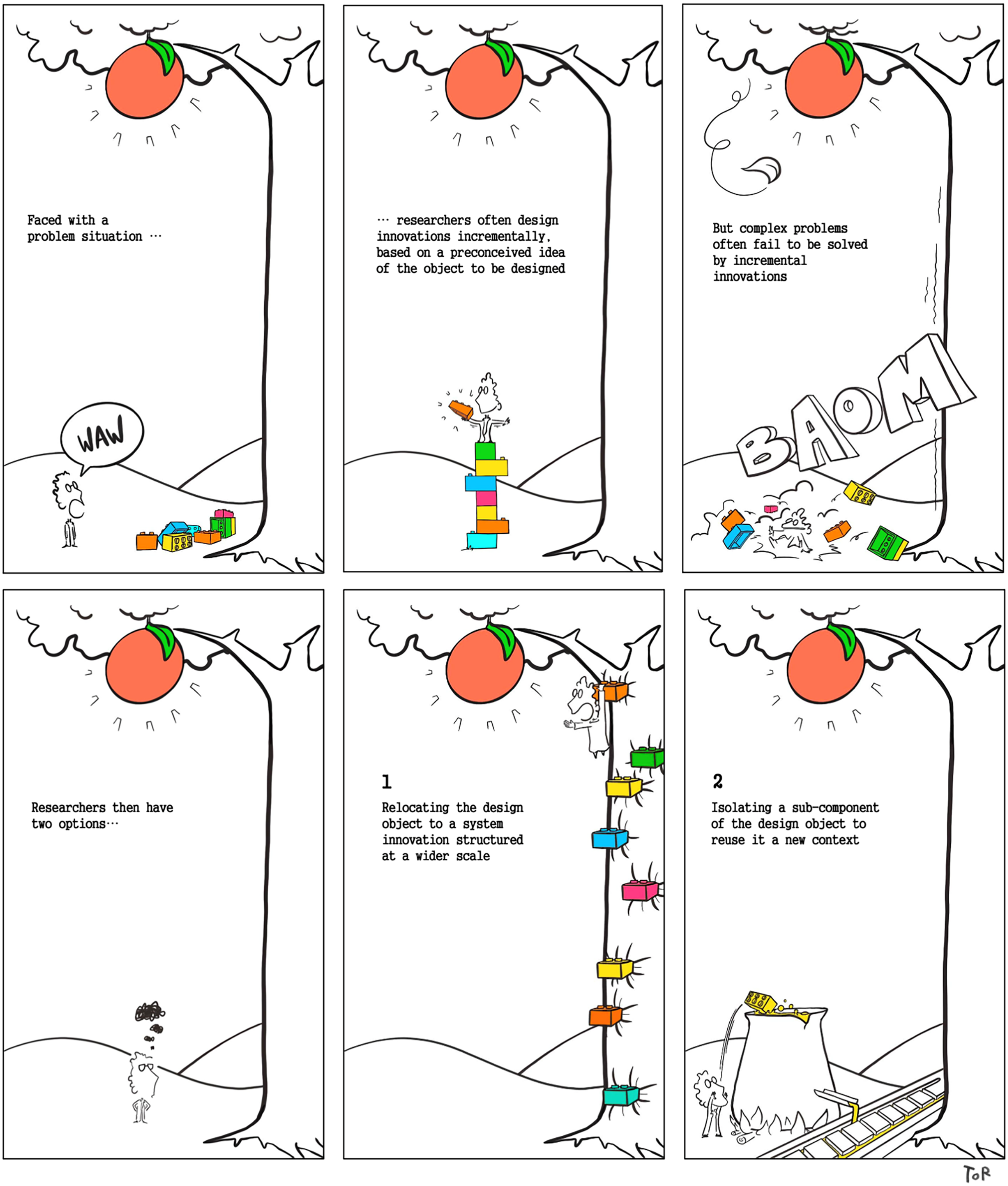


Fig. 5 Cartoon illustration depicting the three possible types of transformation of a design object. Cartoon courtesy of Victor Pied (Tor).

public regulations—that undermine farming practices, livelihood systems, and their ecological resource base (Francis et al. 2003; Willett et al. 2019). This approach is grounded in the belief that smallholder farmers and other players have an active role to play in the experimental design of complex objects since they have deep knowledge of place, content, and practices. So this approach promotes transdisciplinary, participatory, action-oriented research as a way to develop innovations that are problem oriented and that fit well into food systems and socio-cultural contexts (Méndez et al. 2013). In these approaches, knowledge of real-world performance and natural regulation is not the research teams' core preoccupations: they enter into the process at a late stage, when trialling an ideotype that has been co-designed in workshops. A good example of this is Participatory Action Research (PAR), which offers a practical approach for bringing forward the expertise of non-researchers through iterative cycles of research, reflection, and action (Méndez et al. 2017).

We argue that these two approaches should not be seen in opposition to each other or as differing in importance, since in real life they are rarely implemented alone (Méndez et al. 2013). As our findings show, researchers of various disciplines and taking different approaches intervene either simultaneously or at different stages of an agroecological design process. In West Indies, for instance, the co-design of a greener catchment scale was fed by three types of scientific inputs: a sociotechnical diagnosis, a spatio-temporal modelling of the river contamination, and a set of agronomical innovations to improve weed management at the farm level. Hence, during design processes, nature-oriented and actor-oriented approaches interact extensively and depend on each other. They provide mutually complementary knowledge on agricultural systems at various organisational levels. On the one hand, the natural sciences provide a good understanding of the biotic and abiotic processes to be activated, but this can only contribute to operational prototypes when connected with knowledge about human systems. One the other hand, design approaches based on knowledge of human systems provide a good understanding of the socio-technical drivers to be taken into account, but they fall flat in the end if not fuelled by agronomic innovation and accurate biophysical and ecological knowledge.

4.4 Towards methods and tools adapted to agroecological design processes

The specific characteristics of agroecological design processes—lengthy, non-linear, and multi-scaled challenge the methods and tools used by researchers in their work of co-design. Existing studies of design in agriculture often describe the advantages and limitations of design methods and tools to be used by practitioners. Methods generally propose a series of steps for organising the design process (e.g. diagnosis, participatory modelling, field experiments, and iterative loops for assessing and refining the system under design) (Salembier et al. 2018; Le Bellec et al. 2012). Tools may range from simple artefacts (cross-tabulation, map, and blackboard) to complex models (Le Gal et al. 2011; Jones et al. 2003) or role-playing games (Gourmelon et al. 2013). They are used as boundary objects to structure mutual exchange between actors and researchers, to stimulate innovative thinking among participants (Duru 2013; Jakku and Thorburn 2010) and to facilitate knowledge flows between diverse actors (Berthet et al. 2018). We argue that these studies are of obvious value, but they show some important limitations with regard to agroecology.

On the one hand, most design methods and tools tend to overlook the issue of scales. Yet, the existence of three types of transformations and their specific role in agroecological design processes should question the researchers' design practices. It is well established that to address complex sustainability problems, design work taking place at different scales should not be carried out separately: researchers should bring together knowledge and innovations from various organisational levels into systemic, multi-scaled innovations authors (Berthet et al. 2016; Bland and Bell 2007; Meynard et al. 2017; Pigford et al. 2018). However, in agriculture, most existing design methods and tools provide resources to organise horizontal transformations, either at the level of cropping systems (Bachinger and Zander 2007), farming systems (Le Gal et al. 2010), or territories (Petit et al. 2021). Recent studies have developed multi-scaled agroecological design frameworks. Brun et al. (2021) proposed an approach to couple agroecological farming systems with innovations located in other components of a food system (product, varieties, harvest, postharvest, processing, and marketing) so as to promote upward transformations and unlock opportunities. For their part, Duru et al. (2015) introduced a participatory methodology for designing the agroecological transition in a given territory. The method includes co-design activities in the three management domains of farming systems, supply chains and natural resources.

Other methodological frameworks offer possibilities for a deep transformation of design objects, although they do not clearly set the issue of scale. These frameworks propose system-wide approaches such as the “transdisciplinary, participatory, and action-oriented approach” (Mendez et al. 2013), the “Innovation Ecosystems thinking” (Pigford et al. 2018), “redesign” (Meynard et al. 2012), the “de novo” design (Meynard and Casabianca 2012), and the “innovative design” (Hatchuel and Weil 2003; Le Masson et al. 2006). This type of approach is often presented as an alternative way to broaden the field of possibilities and to prototype agricultural systems that break away from the existing ones. Applying such approaches involves detaching from the “know-it-all” objective (e.g. understanding every ecological regulation factor in a given system) and accepting knowledge gaps as a necessary condition for anyone to move towards complex agroecological systems without self-imposed restrictions. For instance, with the innovative design method, designer teams can free themselves from cognitive fixations to identify missing fields of knowledge and explore a wider range of concepts. This way, they save time and avoid going deeper and deeper into a subject without knowing if it will actually be relevant in the end. Although originally not specific to agriculture, the innovative design approach has been shown to be appropriate for fostering a genuine agroecological transition for agricultural and food systems (Salembier et al. 2018; Berthet et al. 2016).

Existing methods and tools also tend to isolate specific moments in the design process, leading them to overlook the long term, a non-linear process in which researchers interventions are embedded. In our three cases studies, the development of agroecological systems was a long and unpredictable process. Researchers and actors went through a step-by-step process of exploration in which the identity and organisation level of the object ultimately designed was not known in advance. The design object evolved over time, owing to a range of drivers. This resulted in non-linear trajectories through various types of transformation, branching, and dead ends (Fig. 3). The design processes were also characterised by repeated changes in the fields of knowledge mobilized as well as in the research teams and groups of actors involved. The objectives of the design process itself evolved over time owing to changes in the perception of the problem to be solved. Moreover, a significant proportion of the researchers involved in designing agroecological systems did not use formalised methods and tools in their work. Design processes were generally not planned, and not all researchers organised a participatory process using well-established steps. Researchers navigated by sight, adapting in real time to the contingencies and opportunities thrown up by projects, funders or partners. Participatory methods and tools were used at particular moments in the development of an innovative system, but they did not constitute the core of the design process. For instance, in the West Indies, researchers associated the K and C phases of the KCP method with socio-technical analysis and a role-playing game to picture a new catchment-wide way to organise pollution control. This initiative occurred after decades of incremental innovations within monocropping systems. Hence, articles that spotlight crucial moments in a design process (e.g. multi-stakeholder workshops followed by participatory experiments) often do not tell the overall story in which these organised methods are embedded.

Accordingly, we argue that there is an urgent need to develop design methods and approaches that take full account of the lengthy, non-linear and multi-scale nature of design processes. Such tools could help researchers and practitioners to conduct reflexive and adaptive management of design across scales.

5 Conclusion

In this article, we introduced a new analytical framework of agroecological design processes in order to understand how agroecological systems transform and move to new complexity levels over time, and what are the drivers and consequences of these transformations. We conceptualised an agroecological design process as a non-linear, unpredictable process in which four components—a science consortium, non-scientific actors in the field, a problem situation and a design object—interact and coevolve through time. The scale transformations of the design objects and their drivers are the results of interactions and knowledge flows between these four components.

This analytical framework was tested and further elaborated through ex-post analysis of three design processes which had been conducted over a period of two decades by the co-authors of the paper, a multidisciplinary research team focused on tropical horticulture.

In our three cases studies, the development of agroecological systems were long, unpredictable processes in which the identity and organisation level of the object ultimately designed were not known in advance. In each case, the researchers and actors went through a step-by-step process of exploration in which the object under design transformed as the groups of researchers and actors evolved and interacted, their perceptions of the problem to be addressed shifting in the process. The problem situations influenced the design processes by guiding the design agendas and providing legitimacy for the design work and the mobilisation of the actors. While the researchers were the main architects of the object under design and lynchpins of the process, the actors influenced the process by participating in problem analysis or in the design itself, or by assessing on their farms the innovations proposed by the researchers.

The objects under design evolved over time, either incrementally (horizontal transformation) or through upward/downward transformation. The scale transformations of the design object were driven by (i) a change in the membership of the research consortium; (ii) the involvement of non-scientific actors, who highlighted obstacles to adoption; (iii) a change in the perception of the problem situation, leading researchers and actors to re-assess initial prototypes in a new light. In turn, the objects' transformations played a driving role in the design processes: while horizontal transformations strengthened incremental design approaches and cognitive fixation, scale transformations encouraged new types of knowledge to feed the design process, allowing to overpass (in cases of upward transformations), or to bypass (in cases of downward transformations) adoption breaks.

Future design methods should take full account of the systemic mechanisms involved in the transformation of design objects. They should also take into account the lengthy, non-linear, and multi-scale nature of design processes as well as the coexistence of different types of knowledge—holistic vs. reductionist, focused on ecosystems vs. on human systems—which interlink and nourish each other.

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Availability of data and material All data generated or analysed during this study are included in this published article or in the supplementary material.

Declarations

Ethics approval The study was conducted according to the guidelines laid down in the 1964 Helsinki Declaration and its later amendments.

Consent to participate All study participants gave their informed consent to participate in the study.

Consent for publication The authors affirm that the human research participants provided informed consent for this publication. All the persons recognisable on the photographs in this article have been informed of their publication and have given their consent for their publication.

Conflict of interest The authors declare no competing interests.

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