Drought field experiments: how to adapt rainout shelters to agroforestry?

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Agroforest Syst
https://doi.org/10.1007/s10457-024-01092-6

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Received: 5 June 2024 / Accepted: 16 October 2024

Abstract Agroforestry could be a major strategy to adapt agriculture to climate change, thanks to the microclimate effects of trees and improved infiltration. However, the experimental validation of these claims is scarce. In this methodological review, we discuss options for the experimental simulation of drought conditions in agroforestry field experiments, comparing it with strategies adopted in natural, agricultural, or forestry ecosystems. We classify rainout shelters used in field experiments according to mobility, completeness of rain interception and height of rainout shelter. We show that specificities of agroforestry systems create constraints and require compromises in the design and operation of rainout shelters. We conclude that large rainout shelters, which induce drought for both the trees and the crops while limiting artifacts and biases, would be most relevant for studying the resistance of agroforestry systems to drought. Unfortunately, the review of rainout shelters already used in agroforestry systems reveals a lack of rainout shelters capable of intercepting rain on both trees and crops, achieving total rain interception, while being relatively low-cost and manageable by a small team. Therefore, we benchmark three novel rainout shelter designs that we tested in a mature agroforestry system under Mediterranean climatic conditions. We discuss their advantages and disadvantages in terms of both scientific and operational aspects. While compromises had to be done between experimental design, risks of artifact/bias, effectiveness, ease of installation, operation and maintenance, and agricultural management, these prototypes are starting points for achieving well-performing rainout shelters and testing the effects of drought in agroforestry experiments.

Keywords Precipitation reduction · Rainfall manipulation · Alley cropping · Experimental design · Rain exclusion

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Introduction

The effects of climate change are directly impacting agriculture in different climatic contexts all around the world (Pachauri et al. 2015). According to the latest IPCC report, the global surface temperature over land has increased by 1.59 °C in 2011–2022 as compared to 1850–1900. Heat extremes have become more frequent and more intense in most regions since the 1950s. Increases in CO_2 and methane since the 1750 are higher than the natural changes between the glacial and interglacial periods over several thousands of years. The intensity and frequency of heavy

Published online: 26 October 2024

precipitation events has also increased. Nonetheless, in several regions of the world, heatwaves have increased since 1950, as well as agricultural and ecological droughts (IPCC 2023). Although there is uncertainty around the net impact of increasing greenhouse gas emissions and climate change on crop yield, it is certain that the effect of climatic hazards will be detrimental to agriculture. For example, heatwaves can damage plant cells, and thus have a negative effect on plant growth and development (Girousse et al. 2021; Girousse 2023). Extreme precipitation events can cause anoxic conditions and plant damage (Fitzgerald 2016). At the same time, in some regions, climate change has contributed to increased agricultural droughts (IPCC 2023). Depending on its occurrence, drought can reduce the vegetative growth period and foliar expansion, or affect the formation of reproductive organs, ultimately impacting the yield (Martin and Jamieson 1996; Tardieu 2012).

Agroforestry is often presented as one of the major adaptation strategies to climate change (Verchot et al. 2007). Thanks to the shadow trees cast over the crops and their windbreak effect, they can limit soil water evaporation and atmospheric evaporative demand (Jackson and Wallace 1999; Kanzler et al. 2019), reduce crop temperature during the hottest hours of the day (Lott et al. 2009; Gosme et al. 2016; Jacobs et al. 2022) and decrease surface runoff (Jacobs et al. 2022). Agroforestry systems have also been shown to strengthen soil biota and microbial biomass, diversity and activity, and improve physical soil quality compared to monocultural controls (Rolo et al. 2023). Moreover, the association of different crops on the same plot can, for some combinations, reduce the overall risk and stabilize yield variability in the face of an increasingly variable climate (Paut et al. 2019, 2020). Thus, the latest IPCC report mentions agroforestry as a high-confidence adaptation option, with good synergies between adaptation and mitigation objectives (IPCC, 2023).

However, the performance of agroforestry systems is complex and context-dependent, due to the competition for resources (Korwar and Radder 1994; Miller and Pallardy 2001). In the context of shallow soils or soils with water tables that are not accessible to tree roots, intense competition for water between trees and crops may be observed (Smith et al. 1997). However, even in dry environments, the balance between competition and facilitation can swiftly change depending on the soil water conditions (Gao et al. 2018). Furthermore, water competition can also be felt in wet soil conditions (Korwar and Radder 1994; Miller and Pallardy 2001). There is still a debate on whether the benefits of agroforestry outweigh the competition for resources between trees and crops, and whether this balance will change in the future climate. A review by Jacobs et al (2022) showed variable effects on relative humidity, evapotranspiration and especially soil moisture, which many studies report to be dependent on temporal and spatial differences within the system. Moreover, context variables like tree purpose, system design and site characteristics have been reported to have an impact on performance, and are rarely taken into account (Jacobs et al. 2022). More research is needed to understand the behavior of agroforestry systems in the future climate, in order to evaluate their value as an adaptation strategy for farmers (Rolo et al. 2023).

However, experimentation on climate change is difficult, in particular in agroforestry field conditions. First, it is challenging to account for all the climatic factors involved in climate change, as well as all their interactions. Ideally, field experiments aimed at better understanding the impacts of climate change should consider multiple climatic drivers simultaneously, such as atmospheric CO_2, air temperature (mean, minimal, maximal), air humidity, wind and precipitation. For example, when studying the impact of future drought events, one may consider enrichment of atmospheric CO_2 through FACE (free-air carbon enrichment) as it directly affects photosynthesis processes and enhances water-use efficiency (Hatfield and Dold 2019). Recent studies have emphasized the importance of not only reducing water availability in terms of quantity and timing (Jentsch et al. 2007; Beier et al. 2012), but also manipulating the atmospheric demand either by heating air or by reducing relative air humidity (Grossiord et al. 2020; Wright and Collins 2024). However, studying these interactions significantly increases the complexity of the experiment (Kreyling and Beier 2013). It also requires a substantial amount of financial and human resources, and there is still controversy over whether complex approaches are the most relevant for inferring climate change impacts (*e.g.* see the discussion between De Boeck et al. (2020) and Korell et al. (2020)). Therefore, single-factor experiments remain an important step to gather knowledge on the functioning of poorly studied agroecosystems. In the case of agroforestry systems, this difficulty is exacerbated since the advantage of agroforestry is the climate mitigation by trees, and the manipulation of the different components of the climate under the trees by experimentation negates this effect. Furthermore, experimental agroforestry sites are too few to cover the full range of agroforestry systems, due to i) the fact that the focus on agroforestry in temperate agriculture is relatively recent, combined with the long time necessary to set up experimental agroforestry sites, and ii) the diversity of possible agroforestry designs. Another barrier to climate change field experiments in agroforestry is the fact that spatially heterogeneous and slow-developing systems require an even larger amount of financial and human resources to change their environmental conditions. In light of these limits, in this review, we will focus on the simulation of drought conditions. We will also consider only rain exclusion (and not include differential irrigation) because climate change is expected to result in extreme and long agricultural droughts in many regions of the world. Thus we will study rainout shelters, *i.e.* physical devices able to reduce the amount of rainfall entering the system in field conditions. A large diversity of such shelters have already been used in natural, agricultural or forestry ecosystems.

In this paper, we argue that the specificities of agroforestry systems (namely alley cropping) create constraints that require compromises in the design of rainout shelters. We also present possible solutions to manage these compromises to test the effect of drought on the agronomic performance of agroforestry systems in the field. We first present the major types of rainout shelters used in field experiments in agriculture, forestry, and natural ecosystems. Then we highlight the specificities of agroforestry systems that have an impact on rainout shelter design and operation, and describe the rain manipulation experiments already performed in agroforestry. We then present a case study of rain exclusion in a Mediterranean agroforestry system, where three different designs were tested. Finally, we discuss the advantages and limits of the different designs in terms of both scientific and operational terms.

Classification of rainout shelters

While rainout shelters present a wide range of designs, we propose to classify them according to three criteria, namely the amount of intercepted rain, the mobility of the shelter and its position relative to the plant canopy (Table 1). The first criteria distinguishes between shelters that completely intercept a

Table 1 Typology of rain exclusion devices used in field experiments

Completeness of interception	Mobility	Position	System usually used for	Example references
Partial	Fixed	Overstory	Crop natural vegetation	(Yahdjian and Sala 2002; Gherardi and Sala 2013; Furze et al. 2017; Zhu et al. 2022)
		Understory	Crop forest	(Rodríguez-Calcerrada et al. 2011; Martin-StPaul et al. 2013; Dickman et al. 2015; Pangle et al. 2015; Grossiord et al. 2017; Rahman et al. 2018; Limousin et al. 2022; Gagné et al. 2022)
	Mobile	Overstory	Natural vegetation	(Carter et al. 2011; Miranda et al. 2011; West et al. 2012; Báez et al. 2013)
		Understory	Forest	(Pretzsch et al. 2014)
Total	Fixed	Overstory	Crop natural vegetation	(Jentsch and Beierkuhnlein 2010; Walter et al. 2011; Shao et al. 2015)
		Understory	Large woody plants forest	(Jacoby et al. 1988; Nepstad 2002; Wullschleger and Hanson 2006; Fisher et al. 2007; Schwendenmann et al. 2010; Kohler et al. 2010; da Costa et al. 2010; Straaten et al. 2011; Buscardo et al. 2021)
	Mobile	Overstory	Crop	(Bruce and Shuman 1962; Fletcher and Maurer 1966; Day et al. 1978; Upchurch et al. 1983; Foale et al. 1986; Zhu et al. 2010)
		Understory	–	–

rainfall event (i.e. all rain is discharged away from the root system of the target plant) vs. those that intercept rain only partially (i.e. a certain percentage of rain is removed). The mobility criteria indicates whether the shelter can be removed during the dry periods occurring between rain events, or if it is present over the crop during the whole experiment. Finally, the position criteria indicates whether the shelter is placed under or over the plant canopy. All three characteristics have important consequences on the validity of experimental treatments that can be applied, as well as on the operational aspects for the experimenters. Furthermore, the type of shelter is often dependent on the research field (agriculture, forestry, ecology) in which it is used.

The proportion of interception has an effect on the type of drought scenarios that can be experimentally created. Partial interception modifies the mean of a given rainfall distribution and is often used for studying the impact of a smaller but long-term reduction (Yahdjian and Sala 2002), while total interception modifies both the mean and the temporal distribution of rainfall, creating longer periods of extreme drought. In the fields of ecology and forestry, research questions often investigate long-term impacts at the scale of plant communities and trees, respectively. Therefore, partial rainout shelters are often preferred because of their relative simplicity of use and the possibility of distributing them largely (Yahdjian and Sala 2002; Miranda et al. 2011; Báez et al. 2013; Zhu et al. 2022). On the other hand, in the field of agriculture, research questions focus more on the notion of yield or quality, which are both significantly affected by climatic conditions during specific critical periods (Sadras and Dreccer 2015; Slafer et al. 2023). In these conditions, total interception rainout shelters allow the creation of a strong contrast of soil water availability during these sensitive stages between dry and control treatments and therefore an observable impact on yield and other plant variables. Moreover, many scientists, including ones in the field of ecology, have been pointing towards the importance of and a lack of data in field experiments applying changes in precipitation patterns and extreme scenarios (Beier et al. 2012). At the same time, in operational terms, partial exclusion is easier than total interception because there is less water to evacuate during each rain event, and the shelter can be fixed, thus reducing the workload needed to operate it (see below).

Shelter mobility is important in order to i) avoid bias and artifacts and ii) allow the possibility of passage of heavy machinery (in the context of mechanized agricultural systems). When considering microclimate, rainout shelters can create artifacts, *i.e.* unintentional changes in agronomic performances brought about by the shelters themselves. Indeed, even transparent materials only partially covering an area modify light transmission and radiative transfers. For instance, Furze et al (2017) and Yahdjian et al. (2002) found an 8.4% and 10% decrease, respectively, in mean incident Photosynthetically Active Radiation (PAR) under transparent acrylic gutters compared to the control, and a 25% decrease at maximum midday PAR. Polyethylene sheets also block around 10% of PAR (Kreyling et al. 2017). Furthermore, fixed shelters can also modify gas exchange between the plant, soil and atmosphere. Rainout shelters can also create bias, *i.e.* unintentional effects that will systematically increase or decrease the effects of the experimental treatments, *e.g.* by increasing temperature and consequently water demand. Dickman et al (2015) found an increase of 1 °C to 4 °C of maximum soil and ground-level temperatures during the growing season using polycarbonate troughs for partial rain interception. Having mobile shelters allows reducing these unintentional effects to only a few days, during the rain events, in the case of climates with sporadic rains. Mobility has obvious impacts on operational aspects for the management of the experiment: mobile shelters must be moved. Manually mobile shelters require human intervention before and after each rain event, and usually require several persons to be operated. Automatic shelters on the other hand can be triggered by a single person or even by rain detectors on the field (Upchurch et al. 1983; Miranda et al. 2011), but they are more expensive. Finally, the type of system on which the experiment is conducted can also guide the choice of mobility. Mobile shelters, by moving away from the treatment area, allow for easy access of machinery for agricultural practices such as plowing, seeding, application of fertilizers and pesticides. On the contrary, rainout shelters in forests tend to be fixed or only partially mobile, i.e. fixed structures with mobile parts like tilting panels (but see Misson et al. (2011) for an example of total interception mobile overstory shelter in forest). One reason is that large machinery is not used in forests as often as in agriculture, therefore allowing long-term shelters to be placed. Another reason is the fact that forest rain manipulation experiments tend to be long-term, since tree adaptation to external conditions is slow. Rainout shelters in forests also need to be large enough to cover tree roots, and thus would be cumbersome to move, which is another reason to opt for fixed shelters.

The position in relation to the plant canopy has an obvious impact on the ease of installing and operating the rainout shelter, in addition to conducting measurements on the plants: overstory shelters make it possible to access underneath them to observe the plants, but are usually more expensive, and modify the microclimate on the canopy of plants, while understory shelters only modify soil microclimate. In case of mechanization of agricultural practices, fixed shelters must be either over the canopy and high enough (> 3 m) to allow machinery to pass below them, or low and narrow enough to allow tractors to straddle the rainout shelter, while mobile shelters can be lower in height (and so less expensive) than fixed shelters. Therefore, rain manipulation shelters in forests tend to be under-canopy shelters, which are easier to implement knowing the height of trees, while in herbaceous natural or agricultural systems with shorter plants, over-canopy shelters are more practical.

Specificities of agroforestry systems impacting the design and operation of rainout shelters

Agroforestry, as a combination of agriculture and forestry, but also as an intermediate between simple monocultures and complex natural ecosystems, has specificities that constrain the design of a rain interception shelter, compared to experiments in pure agricultural settings, in forests or in natural ecosystems. In the case of mechanized alley cropping systems, the design of rainout shelters is constrained by i) the presence of trees that restrict the movement of machinery and ii) the frequency of technical management imposed by farming practices. Because alley cropping systems conjugate both constraints, the consideration of the passage of machinery is more complicated than in monocultures, while it is not an issue at all in forests (except during the planting and harvesting phases) or natural ecosystems. Mechanization encourages the use of shelters that are either low and narrow enough for machinery to straddle, or high enough for machinery to pass under them, or entirely mobile.

Since agroforestry systems are plurispecific and multi-strata agroecosystems, there is another set of constraints for rainout shelters in agroforestry systems. First, shelter designs in agroforestry ideally should have a size large enough to cover both trees and crops. Furthermore, unlike monocultures or forests, crops in agroforestry systems present a strong spatial heterogeneity of growth related to their location with respect to the surrounding trees. This diversity of species and spatial heterogeneity has been well described by the concept of Ecosystem Service Spatial Unit (ESSU) (Rafflegeau et al. 2023), the smallest spatial unit encompassing all the interacting species and other functional components that together provide a specified set of ecosystem services represented in a farming landscape. Based on this concept, if the research question is related to the analysis of the performance of the entire system, it is necessary to study the whole area of the ESSU. Second, if the performance is measured in terms of Land Equivalent Ratio (LER) (Mead and Willey 1980), it is necessary to establish and follow monoculture and forestry control plots, with rainout shelters of their own. The addition of extra shelters in different settings might not only require different designs, but also increases the human and financial costs of installation and maintenance of a larger number of shelters. Third, since trees provide a microclimate for the crops grown adjacent to them, it is all the more important for rainout shelters not to cause any confounding effects on temperature and radiation to avoid biases regarding the effect of the presence of trees. Biases could be caused by any processes that might alter the effect of temperature buffering or shade provided by the trees on the crop. For example, the greenhouse effect caused by fixed tunnel-shaped rainout shelters, which is an artifact in pure crop experiments, becomes a bias in agroforestry experiments: the greenhouse effect is stronger in the agricultural control than in the agroforestry treatment, due to reduced radiation under the trees. Fourth, unlike monocultures and forests, agroforestry, especially alley cropping, includes both perennial and annual plants. The former may present a delayed impact of drought stress in the long-term, after the season of occurrence of the stress (Limousin et al. 2022). Annual plants on the other hand will be affected during the same cropping season. Therefore, if the research question aims at studying the effect of drought on the entire agroforestry system, the duration of use of a rainout shelter needs to extend over several cropping seasons, which requires longer-term experiments with continuous or recurring funding. Thus, the fact that agroforestry systems are plurispecific and combine annual as well as perennial plants urges for the use of large rainout shelters, used over several seasons, and allowing targeted drought during key physiological stages of the annual crop.

Yet another constraint stems from the fact that, compared to trees in forests, agroforestry trees are usually planted at a lower density, thus making the ESSU comparatively larger. The presence of widely-spaced trees in the system requires a larger shelter than in a forestry setting, to ensure the interception of rain on the whole tree root system that may be spread over larger areas. This will avoid a bias due to the "split-root effect", which happens when a part of the roots of a tree are in a drier part of the soil (such as under a shelter) while another part is in a wet volume of soil: the tree will extract unproportionately more water and invest more carbon for root growth in the wet compartment, thus decreasing the apparent competition for water that trees exert on plants, as well as decreasing the effect of drought on tree growth (Simonneau and Habib 1994). In terms of experimental design and measurements, compared to forest experiments, most researchers examining the growth of crops in agroforestry systems need access to these crops more regularly. This translates into rainout shelter designs that are either i) fixed and high enough for humans to access and for crops to reach their maximal height, ii) or placed on the ground in between crop rows, iii) or mobile (completely or partially).

So it seems that rainout shelters that are the most adapted to study the effect of drought on the performance of agroforestry systems as a whole, monitored at a high frequency over a long period of time, need to be large, mobile, and placed above the crops in the alleys. It is difficult to design rainout shelters that satisfy all these constraints perfectly: increasing the size of shelters increases the amount of resources needed to construct and maintain them, either in terms of human resources (availability of manpower for construction and maintenance) or financial resources (availability of funds for professional construction and automation for maintenance). Adding mobility and height to a shelter also increases the needed resources, as well as the risk of damage (and thus cost of maintenance). Following the system at a high frequency over a long period of time also requires a large amount of recurrent funding. In the following sections, we will present the compromises that have been made in the design and operation of rainout shelters in agroforestry systems, and present three further proposals of rainout shelters that represent different compromises.

Compromises chosen in previous agroforestry rain exclusion experiments

Rain exclusion shelters used in agroforestry systems are limited in number (Table 2). Most shelters only exclude rain from the crop area and not the trees. The most common shelters are fixed shelters partially excluding rain from crops only and not the trees, which allows them to be easily adapted from experiments in monocultures. Of these, the majority are overstory shelters inspired by Yahdjian and Sala's design (Yahdjian and Sala 2002). This design consists of transparent gutters placed on a slanted metal frame and directed towards a perpendicular gutter. The advantage of this design is the decrease of the greenhouse effect induced by total interception fixed shelters that are used for crop monocultures. However, this fixed shelter does not intercept rain for trees if a significant proportion of the rooting area is not covered. It is also too low to allow the passage of machinery. The only other type of partial fixed shelter used in agroforestry is the understory shelter of Gagné et al (2022): a series of gutters placed 10 cm above the ground between the rows of crops, slightly sloped towards drainage ditches. It allows the passage of machinery and is easy to handle. However, it possibly creates a confounding factor as it covers the soil and interferes with the soil-level microclimate by buffering temperature and humidity changes, but does not create greenhouse effect for the crop.

To achieve total rain interception, there are two examples of shelters used in agroforestry. One is a fixed understory shelter using slanted clear panels on bamboo frames placed under agroforestry cocoa trees, directed towards gutters (Schwendenmann et al. 2010). It is understory in relation to the trees as it was applied in an agroforestry system consisting only of trees (the crop is cocoa trees).

Table 2 Classification of existing rain exclusion devices used in agroforestry according to the typology presented in Table 1, and synthesis of their performance. + and − signs indicate advantages and disadvantages, respectively. ± indicates the presence of positive and negative aspects of performance

Completeness of interception	Mobility	Position	Tree exclusion	Crop exclusion	Artifacts/bias	Access of agric. machines	References
Partial	Fixed	Overstory	−	+	±	−	(February et al. 2013; Nasielski et al. 2015; Furze et al. 2017; Renwick et al. 2020; Zhao et al. 2022a, b; Hidalgo-Galvez et al. 2022; Rodriguez-Calcerrada et al. 2022)
		Understory	−	+	±	+	(Gagné et al. 2022)
Total	Fixed	Understory	+	n/a	±	−	(Schwendenmann et al. 2010; Moser et al. 2010; Kohler et al. 2010)
	Mobile	Overstory	−	+	+	−	(Kerr 2012)

Therefore, this specific shelter is not applicable to alley cropping systems. Furthermore, it creates an artifact (decrease of CO_2 concentration under the shelter), but no effect on air temperature, radiation nor relative humidity. The only example of total interception shelter applicable to alley cropping is Kerr's partially mobile overstory shelter (Kerr 2012). It is made of a light wooden frame on which a rollable greenhouse sheeting was fixed using nails. The removability of the plastic cover eliminates the greenhouse effect bias. However it was only used for rain interception on crops and not the trees. Moreover, in reality the mobility did not pan out well as it was too time-consuming to remove the nails, and the plastic cover was rarely removed. The structure might also be too light to withstand strong wind.

This literature review of rainout shelters in agroforestry systems shows the absence of total interception mobile shelters capable of withstanding strong winds. This is related to the large size required from rainout shelters in agroforestry systems, while at the same time the difficulty of installing and handling such large structures, both financially and physically (Svejcar et al. 1999). The literature survey also shows a general lack of rain interception shelters capable of intercepting rain on both trees and crops, achieving total rain interception, while being able to be built on a limited budget and handled by a small team.

Case study: drought experiments in an alley cropping system

To study the effects of drought on field crops grown in a mature alley cropping system, we tested three different rainout shelter designs at the Restinclières farm estate (Prades-le-Lez, south of France), a historic agroforestry research site (Dufour et al. 2013). The selected plot had been planted with walnut trees in 1995 and was cultivated with arable crops. We deliberately performed total rainfall interception in order to significantly reduce soil water availability during specific periods within the crop growth cycle. This allowed us to study the effects of long and intense dry spells as predicted by regional climate change projections (IPCC, 2023). The designs tested were also mobile (completely or partially) in order to minimize the possible interference with the microclimate created by the trees. Finally, another common goal between these three shelters was for them to be realized and managed with a limited budget and limited availability of manpower.

The initial design aimed to fully exclude rainfall events at the scale of both trees and crops (Fig. 1A). To achieve this, a cable structure fixed on the tree trunks supported a foldable tarpaulin that covered two alleys (2×13 m) over 35 m (*ca.* 900 m^2).The cable structure consisted, in each alley, of (i) a central top cable strung along the alley and kept under tension by transversal cables crossing the alley between opposite

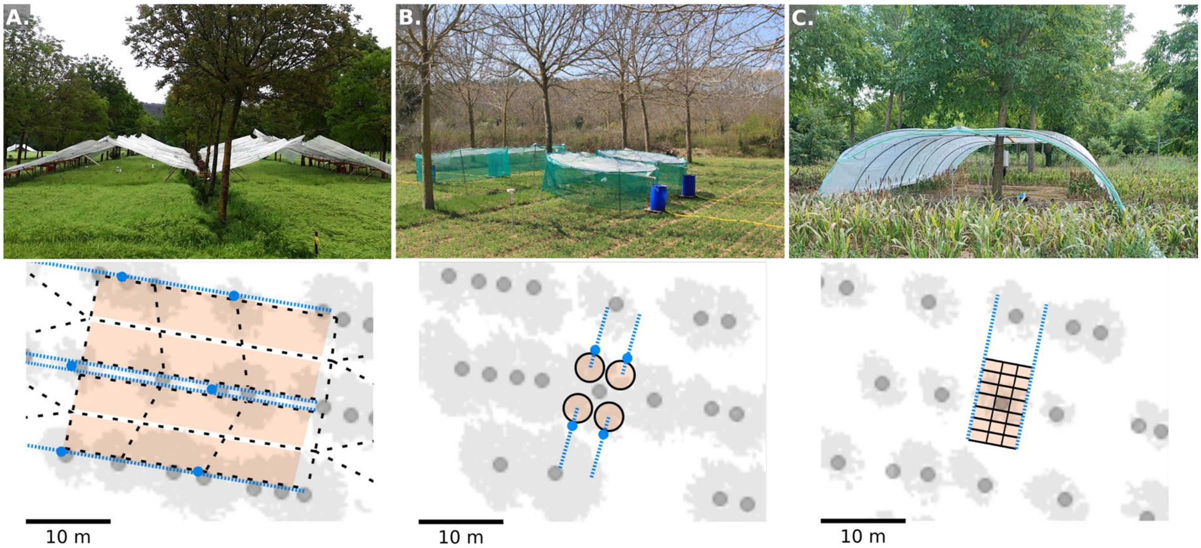

Fig. 1 Designs of rainout shelters tested in a well-developed temperate alley-cropping parcel (Restinclières Farm Estate, France). **A** Rainout shelter 1 **B** Rainout shelter 2 **C** Rainout shelter 3. The trees and their canopy are represented by gray dots and adjacent light gray surfaces, while the orange-colored areas indicate the area covered by the rain-intercepting structures when installed. Black lines represent structural elements, either tubes (solid line) or cables (dashed line). Blue lines show rain collectors and pipe elements to discharge water out of the area of interest

trees, (ii) bottom cables attached lower and lower on five successive trees on each side of the alley, (iii) pairs of slanted elastic ropes attached between the top cable and the side cable, allowing the tarpaulin to slide between them. Between rainfall events, the tarpaulin for each half-alley was folded over a plastic gutter attached to the bottom cable on the tree line. When rain was forecasted, the tarpaulins were hoisted using pulleys placed on the top central cable and ropes attached to the tarpaulins. Each tarpaulin was connected to a plastic gutter, installed along the tree line to evacuate collected rainfall out of the covered area. The water was then directed to a reservoir, which acted as a buffer in case rainfall peaked above the flow rate of the outflow pipes. Finally, the water was evacuated through pipes a dozen meters away. This device was designed to intercept rainfall at the scale of the entire root system of three central trees, thereby minimizing the risk of a split-root artifact. The fact that the tarpaulin was deployed only during rain events limited the risk of biases caused by changes in the microclimate. However, this design encountered many operational difficulties, either related to the climatic conditions or to the technical management. For example, strong wind during rainstorms regularly tore the tarpaulin, and heavy hailstorms crushed the system. An insufficiently tightened tarpaulin also resulted in heavy pockets of water on the tarpaulin's surface, causing leakage and eventually tearing of the tarpaulin due to the weight of water. The slanted ropes could also hinder the passage of agricultural machines and required extra people to push them up with rakes during agricultural operations. Due to these difficulties in operating and maintaining this design, it could not be replicated across the agroforestry plot.

To address the operational difficulties of the first design, smaller rainout shelters were designed to exclude rainfall at the scale of the crop only (Fig. 1B). The structure was designed with limited height to reduce wind load and could be easily disassembled to allow for the passage of machinery and prevent microclimate modifications between rain events. Each rainout shelter consisted of two distinct parts: (i) a fixed mounting base made of metal tubes was installed on the ground, and (ii) a removable circular structure (4.5 m in diameter) made of metal tubes and covered with a tarpaulin, which was only installed during rainfall events. Intercepted rainfall was directed through a gutter, which weighed down on the tarpaulin towards a reservoir and discharged further away through pipes. A set of four rainout shelters (covering 64 m^2 in total) was laid out around a tree to cover as much of the surface explored by the roots of this tree as possible (Blanchet 2021). However, the risk of split-root effect could not be ruled out. Furthermore, this design did not allow exploring the full heterogeneity of the crop across the cultivated alley. However, due to the relative ease of installing/removing the tubular structure, it was possible to replicate the design across the plot, allowing a paired statistical design controlling the variability of the light irradiance that resulted from the heterogeneity of the trees. The four-shelter set around a tree was paired with a shelter-free set of control quadrats around a similar and neighbouring tree, and pairs were replicated four times within the plot.

A third design (Fig. 1C) came about out of the necessity to create a shelter that was more manageable than the first one, while still covering the entire gradient of distance from the tree line to the center of the alley. This design also covered most of the area explored by the roots of a tree to significantly minimize split-root effects. The shelter consisted of a fixed aluminum tunnel-like structure with a transparent tarpaulin that was rolled down just before each rain event, and rolled up at its end. The tunnel was perpendicular to the alleys so as to cover half of the alley on both sides of the tree line (approx. 14 m). It also covered half the distance to the nearest tree along the tree row, on both sides (6.5 m). Therefore, each tunnel covered 95 m^2. Plastic gutters were fixed on the outer sides of the tunnel with a gentle slope to evacuate water to the next alley. The bottom of the tarpaulin was attached to a wooden beam, which served both as a rigid core around which the tarpaulin could be rolled, and as a weight to hold the tarpaulin down inside the gutter when the tarpaulin was deployed. This design was replicated three times within the plot. The fixed structure was only possible because no machinery was used in the field after the initial soil tillage and sowing. Fertilizer application and weeding were done manually.

Discussion

Our three designs of rainout shelters, aiming at creating drought conditions in an alley cropping system, represent different compromises between scientific targets and operational aspects. We compare these designs to assess the experimental designs permitted by their use, their efficiency, the unwanted confounding factors, the installation, operation and maintenance aspects, and finally their compatibility with the agricultural management (Table 3).

In terms of experimental design, the first rainout shelter, which will be referred to as the "large rainout shelter" (910 m^2) from now on, has a big advantage in the fact that it excludes rain by covering not only the crop but also nearly the entire alley on both sides of the tree row, while including several trees in the row. Rainout shelter 3, or the "medium shelter" (95 m^2), covers half the distance of the alley on both sides of the tree row as well as around half of the distance of the intra row between the covered tree and the neighboring trees in the row. Therefore, the large and medium shelters allow conducting experiments on both the tree and the crop, taking into account the drought inflicted on the trees. Another advantage of the large shelter, which is shared with the medium shelter, is the fact that it excludes rain from the entire gradient of heterogeneous crop growth along the entire alley. The second design, or "small rainout shelter" ($4 \times 16 = 64$ m^2) covers a smaller portion of the surface area surrounding one tree, therefore it is difficult to estimate the proportion of available water being excluded and thus the intensity of drought that is imposed on the tree. Another limitation of this small shelter in terms of experimental design is that it allows only one measurement quadrat under each circle, at one distance to the tree line, i.e. the gradient of crop heterogeneity across the alley cannot be studied. However, a strong advantage of the small shelter in terms of experimental design is that it can be easily replicated (four replications were achieved in the experiment), while the first design is difficult to replicate, because of the large amount of material and manpower needed. The medium design is of medium difficulty of replication (three replications were achieved in the experiment).

In terms of effectiveness, contrary to expectations, the large shelter performed less well than the others. There is a high risk of water entry from the facade and ridge of the large shelter (where the two tarpaulins do not meet closely enough), while this risk is non-existent for the small shelter, since there are nets around the circular shelter all the way to the ground. For the medium shelter, this risk is intermediate, since there could be some water entry from the border of the plot

Table 3 Comparative analysis of the three proposed rainout shelters

Performance	Criteria	Rainout Shelter 1 (two 13×35 m tents)	Rainout Shelter 2 (four 4.5 m discs)	Rainout Shelter 3 (one 14×6.5 m tunnel)
Experimental design	Rain exclusion from tree roots	+	−	±
	Rain exclusion from crop alley	+	−	+
	Possibility to make repetitions	−	+	±
Confounding effects	Absence of split-root effect	+	−	±
	Absence of soil compaction by trampling of crops	−	+	±
	Regularity of seeding	−	+	+
Effectiveness	No water entry	−	+	±
	No formation of rainwater pools	−	+	+
	No risk of tearing	−	+	+
	No risk of tree breakage	−	+	+
Ease of installation, operation and maintenance	Initial installation	−	+	±
	Quick activation	−	+	+
	Possibility of activation by 1 person	±	−	+
	Ease of activation	−	+	+
	No need for supervision during rain events	−	+	+
	Ease of maintenance	−	+	+
Agricultural management	No hindrance of the passage of machinery	±	+	−

+ indicates a positive performance, − indicates a negative performance and ± indicates a medium performance

if wind speed is higher than 35 km/h, which might lift the wooden logs attached to the bottom of the tarpaulin and then leave it outside of the gutters, on the wrong side of the plot. There is also a high probability of formation of pockets of rainwater on the tarpaulin for the large shelter, which can lead to water leakage. This is not a problem for the medium and small shelters thanks to a higher slope in the tarpaulin. There is also a high risk of tearing and breakage of the large shelter when wind speed is faster than 50 km/h, while there is no risk of tears or breakage for the other shelters thanks to their lower wind load. Finally, for the large shelter only, the risk of trees breaking cannot be ignored, if they are not sturdy enough, since they are used as support for tensing the tarpaulin.

The different shelter designs also affect artifacts and biases differently. The first shelter eliminates the risk of a split-root effect for the monitored trees, while the small shelter induces a split-root effect. The medium shelter has a medium risk of split-root effect: while we assume the majority of the roots are covered, we cannot be certain of covering the entirety of the tree roots. The risk of trampling the crops on the other hand is high for the large and medium shelters, because the tarpaulin is unfolded from the interior of the plot. In theory, the tarpaulin in the large shelter could be hoisted when standing on the understory vegetation strip thanks to pulleys, but in reality, the crop row closest to the tree line was often damaged. Furthermore, the high frequency of water pocket formation in the large shelter also increased the risk of trampling. In the medium shelter, the fact that the crop (sorghum) had widely spaced rows allowed walking and placing a stepladder in the inter-row space, but this would not have been possible with a denser crop. This risk is non-existent for the small shelter, the activation of which is done from the outside of the plot. Another possible bias caused by the large shelter, could be irregular sowing, since low-hanging cables disturbed the passage of machinery near the understory vegetation strip. As a result, there was a strip of double density where the last tractor passage overlapped on the previous one. Seeding is done without any obstacles with the small and medium shelters, which are installed after seeding thanks to the relative ease of installation compared to the large shelter (however, installation of the medium shelter was a race against time to install it after seeding of the sorghum but before the end of the spring rains).

Moving on to the installation, operation and maintenance of these shelters, the small shelter fares the best and the large shelter the worst. For the small shelter, initial installation, as well as dismantlement, are easy. The large shelter on the other hand is difficult to install initially, needing high levels of manpower and physical strength. The medium shelter presents medium difficulty in installation, as it took several weeks and people to set it up, but did not require any physical strength. When it comes to the operation of these shelters, the large shelter is activated relatively slowly by pulling the large tarpaulins, which requires around 2 h with two people. Both the medium and small shelters have fast activation: for the small shelter, 15–20 min per group of four rainout shelters consisting of one repetition, and for the medium-sized shelter, around 10 min with two people, thanks to the help of gravity, which pulls down the weight of the wooden logs attached to the bottom of the tarpaulin, rolling it down from its resting position at the top of the tunnel. Another advantage of the medium shelter is that it could be activated by a single person, while two people are required for the activation of the small shelter (to lift the structure on which the tarpaulin is fixed). The large shelter could also be activated by one person, however this required about 3 h. This activation is also very physically demanding, which is not the case for the other two shelters. To note, the height of the medium shelter was around 2 m, therefore the use of ladders was sometimes necessary depending on the height of the person(s) handling the shelter. It should also be noted that the large shelter requires supervision during rain events, in order to evacuate pockets of water and quickly react in the case of tears of the tarpaulins. The other two shelters do not require supervision. Lastly, the large shelter is difficult to maintain, because of both its height and the risk of trampling the crops underneath. The medium and small shelters do not require maintenance.

Last but not least, when it comes to agricultural management, it should be noted that the medium shelter does not allow machinery to pass at all. Therefore, plowing and sowing must be done before the installation of the shelter. Other operations like weeding and harvest had to be done manually. The small shelter allows the passage of machinery without any disturbances, while the large shelter, as mentioned previously, slows down the passage of machinery and requires manpower to accommodate it, especially when it comes to plowing (due to the fact that the plowshare cannot be offset), and harvesting (due to the height of the combined harvester).

It is evident that rainout shelter 2 (small shelter) fares the best in terms of effectiveness, installation, operation and maintenance, and agricultural management, while presenting some negative results when it comes to aspects of experimental design and artifacts/biases. Rainout shelter 1 (large shelter) fares the best in terms of ability to study the effect of climate change on both crops and trees, but does not easily allow replication and performs negatively in some aspects of confounding effects, effectiveness and ease of installation, operation and maintenance. Rainout shelter 3 provides a good compromise between all aspects, except agricultural management.

In conclusion, there is a need for rain manipulation experiments to test the effect of drought on the agronomic performance of agroforestry systems. Using total rain interception shelters allows to achieve not only changes in mean precipitation but also simulating extreme drought events, which has been recently shown to be a major knowledge gap (Quandt et al. 2023). However, agroforestry, as a combination of agriculture and forestry, but also as an intermediate between simple monocultures and complex natural ecosystems, has specificities that constrain the design of a rain interception shelter, compared to experiments in other systems. To date, there was a lack of total interception mobile shelters capable of limiting artifacts, withstanding different climatic conditions, all the while remaining manageable with limited budget and manpower. We presented three case studies of total interception mobile rainout shelters capable of being realized with limited financial and human resources. They provided different compromises between flexibility in terms of experimental design, risks of artifacts/biases, effectiveness, ease of installation, operation & maintenance, and agricultural management. These prototypes provide the starting point for achieving well-performing rainout shelters and testing the effect of drought in agroforestry experiments.

Author contributions According to CRediT typology (https://credit.niso.org/): Conceptualization: C.D. Funding

acquisition: C.D. Investigation: G.B., L.B. Methodology: G.B., L.B., J.B. Writing—original draft: L.B., G.B., M.G. Writing—review and editing: L.B., G.B., M.G., C.D. Supervision: M.G., C.D.

Funding This work was supported by funding from the European Union's Horizon 2020 research and innovation programme under grant agreement 862993 (AGROMIX project). Additionally, the doctoral research of G. Blanchet was financially supported by La Fondation de France.

Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

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