Design of a functional organic agroforestry system associating rabbits and apple trees

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ABSTRACT

Intensive animal production is facing a crisis of legitimacy linked to its contribution to pollution, biohazard risks, and animal suffering. With almost 97% of the production coming from intensive systems, rabbit farming is questioned. Similarly, the plant sector is under scrutiny linked to a high input dependency. Among the alternatives, organic farming and agroforestry systems (associating trees and animals) may contribute to a more sustainable agriculture. However, a number of elements should be evaluated when designing agroforestry systems, especially innovative systems with no previous references. Here, we describe the process of designing an agroforestry system combining rabbits and apple trees. We used an incremental process over three rounds of prototyping (**P1**, **P2** and **P3**) to develop, refine and adapt a rabbit housing system to an apple orchard. Lessons learned from multiple measurements (thermal comfort, rabbit growth, etc.) and professional feedback (during a workshop) helped to create a functional system. The P1 focused on the design of two outdoor housing systems (mobile-cage *vs* fixed-pen) inspired by organic rabbit farming practices. Both housing protected the animals from extreme temperatures. However, the main lesson learnt from P1 is the necessity to vaccinate animals to prevent viral diseases. The aim of P2 was to evaluate the feasibility of installing the P1 housing in an apple orchard and to expose it to the observations and comments of professionals during a workshop. On the basis of the experimental observations and the feedback from professionals, the preference was for the fixed-pen over the mobile-cage. The fixed-pen, as opposed to the mobile-cage, allowed the rabbits to graze near the apple tree trunks, where the cleaning services were observed. However, participants questioned the fencing of the fixed-pen. They found it difficult to install and/or dismantle. Based on their comments, the P3 fences were designed to be lightweight and easy to handle. As grazing accounted for about 28% of the rabbits' activities, and 12 rabbits were able to graze 25.5 m^2 of herbage in less than 10 days (P2), the new fencing allowed the fixed-pen to be converted into a mobile-pen. In short, rabbits provide an effective weeding service for the orchard, while benefiting from its microclimate, food resources and living environment, which enhances their well-being. This association was easier to implement in autumn (P2) than in spring (P3), the season of intensive orchard work. In short, this association is feasible and seems to be easily adaptable by farmers.

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Implications

Agroforestry systems associating trees and animals may contribute to a more sustainable agriculture. However, the development of such systems may be constrained by the lack of information and/or technical solutions to associate plants and animals. Here, we describe the steps to design an innovative agroforestry system, a grazed orchard associating rabbits and apple

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trees. Through three prototyping rounds, we identified some benefits and limits of this association and provided several elements making this agroforestry system operational. Rabbits appeared to provide an effective weeding service for the orchard, while benefiting from its microclimate, and food resources.

Specification table

Subject	Livestock Farming Systems
Specific subject area	Conception of an innovative agroforestry system
Type of data	Tables, Images, Graphics, Data sets
How data were acquired	Stabilised weighing scale (max. 15 kg, min. 5 g), direct observation of animals, data logger and CLIMATIK platform (https://agroclim.inrae.fr/climatik/)
Data format	Raw
Parameters for data collection	Scale placed over a levelled surface. Data logger was placed in the resting area at 10 cm from the roof. Behaviour: observer outside the enclosure, at least one meter away from the fence. Two minutes in a steady position before starting the observations.
Description of data collection	Individual live weight of rabbits (in grams): each animal was placed in a cardboard box and weighed using a stable scale. Feed intake: the amount (in grams) of pellets offered and refused over a specified period of time. Apple intake: the amount (in grams) of apples offered (naturally present) and refused over a specified period of time. Temperature and relative humidity inside the shelters: automatically recorded every 10 minutes, 24 hours a day, 7 days a week. Behaviour: scan-sampling method, counts of observed behaviours using a predefined ethogram. Different ages twice a day (morning and afternoon).
Data source location	Institution: INRAE (INRAE - National Research Institute for Agriculture, Food and Environment). City, Region: Toulouse, Occitanie & Saint-Marcel-lès-Valence, Auvergne-Rhône-Alpes. Country: France
Data accessibility	Repository name: https://recherche.data.gouv.fr/fr Data identification number: https://doi.org/10.57745/JBHZSC

Introduction

Intensive farming and animal production are facing a crisis of legitimacy. They are mentioned as responsible for most of the greenhouse gas emission, water, air and soil pollution, deforestation, loss of biodiversity and increased biohazard risks, as well as human and animal suffering (Horrigan et al., 2002; Emel and Neo, 2011). The rabbit farming sector is highly concerned by this situation. Most farmed rabbits (96.5%) are raised indoor in small wired cages (no bigger than 0.64 m^2) with no or limited access to natural light, and antibiotic treatments are widely used to prevent diseases. In this system, rabbit welfare is reduced compared to alternative systems (EFSA AHAW Panel, 2020) and its economic viability is ensured through intensification; a single farmer has to manage about 600 breeding females for a reduced salary compared to other agriculture sectors (INSEE, 2021). The intensive rabbit production system is also highly dependent on inputs (e.g. energy, feed, antibiotics, etc.) and despite the herbivorous nature of rabbits, the environmental impact of intensive rabbit farms is comparable to that of industrial pig farms (Cesari et al., 2018).

In contrast, organic farming (Sundrum, 2001), agroforestry (Broom et al., 2013), and other forms of crop-livestock integration (Bonaudo et al., 2014) are models contributing to a more sustainable agriculture. Organic farming is not only characterised by the absence of synthetic inputs. It is also more energy efficient than intensive farming (at least for dairy farms: Refsgaard et al., 1998), reduces the incidence of metabolic diseases, extends the reproductive lifespan and provides better living conditions for the animals (Sundrum, 2001). Agroforestry and other systems integrating plants and animals are also mentioned as more sustainable. These systems favour the nutrient cycling (less pollution), the preservation of natural resources and biodiversity conservation (Sundrum, 2001; Broom et al., 2013; Bonaudo et al., 2014). They also favour the development of the local economy and land use (Guzmán-Casado and Gonzáles-de-Molina, 2009). However, these alternative systems are not well developed or properly studied.

Organic rabbit farming, for instance, is a niche market. Despite the existence of a growing demand for organic rabbit meat, it represents about 45 farmers in France (Gidenne et al., 2023). Technical information on organic rabbit farming is still scarce, and in the absence of well-developed commercial infrastructures, this activity is usually a minor production on the farm. In contrast, the industrial rabbit sector has a very well-developed network of steakholders, strong support from research and well-defined technical standards. But at the same time, this sector faces a decline in the demand with 14% less consumption since 2010 (IFOP, 2018). To address this situation, the industrial rabbit sector is trying to develop alternative ways of producing rabbits. However, change is not easy, and new knowledge, sharing of experiences and a favourable socio-economic context, may help farmers to adopt alternative practices (Wheeler, 2008). In this respect, the provision of new knowledge and technical information may help farmers consider alternative models, such as organic farming and/or agroforestry.

There are agroforestry systems combining apple trees and small ruminants (mostly sheep: https://www.agforward.eu/high-value-tree-systems.html). Although very effective in managing the grass cover, it can be difficult to prevent sheep from eating the leaves, and sometimes even ring-barking the trees. Farmers therefore invest time, money and a lot of imagination to reconnect animals and orchards. Sheep are also sensitive to copper, which obliges farmers to adapt their practices (e.g. alternative to copper) or to respect a period of exclusion of the sheep after treatment in the orchards to avoid any risk of intoxication of the animals.

Compared to sheep, rabbits are small enough to access and eat the grass just around the tree trunk without attacking the leaves, fruits and branches. They can also ring-bark the trunks, but the use of tree guards to protect the trees against wild rabbits and hares is widespread. In addition, rabbits tolerate and often respond to high copper levels in the diet, up to 250 ppm, about 50 times their requirement (Omole, 1980), which allows organic apple growers to use this mineral fungicide for scab control. Rabbits can also feed on fallen apples and dead leaves, thus providing a sanitation service against scab and codling moth, respectively. Soil fertilisation (urine and faeces), a milder climate and the protection of rabbits from predation (leaves and branches) or an improved animal welfare are additional interspecific benefits that may result from this association. However, before studying the benefits and limits of raising rabbits in apple orchards, it is critical to establish all the conditions for this association.

In this context, the present work focuses on the design, test and construction of a rabbit-rearing system that is compatible with the needs of rabbits and the management of an organic apple orchard.

Material and methods

A prototyping process (in three steps) to develop the association of rabbits and apple trees

We used an incremental approach to design, test, improve and validate a rabbit housing system for their association with apple trees. Three rounds of prototyping, referred to as **P1, P2** and **P3**, were programmed. Each round addressed specific questions/objectives. After each round, the positive features were retained and the constraints were reduced/eliminated.

A first prototyping round to test two outdoor housing systems: P1

The main objectives of P1 were: (1) to collect data on rabbits reared outdoors, (2) to test the measuring equipment (scales, data loggers, etc.) and (3) to adjust the elements of each housing (position of the shelter, drinkers, feeders, etc.). Two outdoor housing systems were constructed, inspired by organic rabbit farming practices: a mobile-cage (**MC**) and a fixed-pen (**FP**). In addition, data collected outdoors were compared with data from rabbits housed in indoor-cages (**IC**).

A second prototyping round to explore the association of rabbits and apple trees: P2

The aims of P2 were: (1) to test the prototypes built in P1 in an apple orchard, (2) to organise the presence of rabbits in the orchard in terms of time and space (*i.e.* the choice of housing system, its position in the orchard and the period of use) and (3) to expose the system to the observations and suggestions of professionals in a workshop, intended to select and refine the chosen housing system for this association.

Professional workshop and feedback leading to a third round of propotyping

The workshop was organised at the end of P2 with professionals gathered at the INRAE UERI – Gotheron. In total, 27 participants from different backgrounds participated in the workshop: apple orchardists, rabbit farmers, veterinary practitioners, agronomists, agricultural consultants, among others. After an introduction to the experiment by the researchers, the participants had one hour to interact with the two housing systems used at P2. The participants were then divided into three mixed groups for another hour, according to their background (evenly distributed between the groups). One group focused on the MC and two groups discussed the FP. All participants were then brought together to start an open conversation.

Participants shared their views on both housing systems and discussed the suitability of each housing system for the association. They agreed that the MC was of less interest because the rabbits could not be placed within the tree line, where grazing is most needed. They also pointed out that the workload involved in moving the MC every other day could be an issue. The fixed-pen, installed within the tree row and later converted to a mobile-pen, was found to be adequate for keeping rabbits in apple orchards. The participants appreciated the weeding and cleaning services provided by the rabbits that live around the apple trees. They were also aware of the ring-barking risk posed by rabbits to the trees. At the end of the workshop, the participants mentioned a mobile-pen that could be easily moved around the rows of apple trees. These comments and suggestions guided the design of the third prototype.

A third prototyping round to test a mobile-pen placed within the apple tree row: P3

The main purposes of P3 were: (1) to test the mobile-pen designed following the comments made during the workshop and (2) to collect data on rabbits living inside or outside the apple orchard.

Common and specific features of the prototyping rounds P1, P2 and P3

The main features of P1, P2 and P3 are shown in Table 1. P1 had three groups of eight rabbits each (1:1 sex ratio). Two groups lived outdoors: one in a MC and one in a FP (Figs. 1 and 2), and one group lived indoors, in IC (Fortun-Lamothe et al., 2000). All three groups of rabbits were reared within the biosecurity zone of the INRAE GenPhySE – Sheep and rabbit experimental facility (https://doi.org/10.17180/ftvh-x393) in Spring 2021.

In P2, two groups of 12 rabbits each (1:1 sex ratio) were placed in Autumn 2021 in a 0.4 ha organic apple orchard at INRAE UERI – Gotheron, planted in 2005. The planting distance was 5 m between tree lines and 2 m within lines. The cultivar was Ariane (INFEL® 6407) grafted on Supporter® 4 (INFEL® 6275), grown in a centrifugal training (Lauri et al., 2004). The ground cover was a heterogeneous mixture of spontaneous species and cultivated grasses and legume forages (https://franceprairie.fr/melange/saint-marcellin). An electric net was installed around the orchard to prevent attacks by foxes or dogs. One group of rabbits lived in a MC placed (Fig. 2) in the inter-row between two rows of apple trees and the other in a FP (Fig. 3) placed within a row of apple trees. Rabbits in the MC had access to a grazing area of 3 m^2 and rabbits in the FP had access to a grazing area of 25.5 m^2. On average, the MC was moved to a new location every other day, originally intended to be fixed for the duration of the trial. However, it was moved every week to avoid overgrazing and health risks to the rabbits due to the accumulation of dejections and therefore the excretion of *Eimeria* sp. oocysts. When moved, the FP was shifted to a new location within the same row of apple trees.

In P3, 24 rabbits (1:1 sex ratio) were housed in two mobile-pens (12 rabbits each) at INRAE Gotheron in Spring 2022: one placed in the apple orchard (**AO**) and one on a fallow-land (**FL**) nearby the AO. The fencing was made of rigid panels (H: 103 $\times$ L: 250 cm) doubled with a 13 mm hexagonal wire mesh (Fig. 4). Each mobile-pen was assembled from 10 panels to form a rectangle of 1 by four panels. They were fixed against steel stakes (H: 1.5 m $\times$ Ø: 14 mm) and placed at the ends of each panel. Compared to the FP in P2, the mobile-pen area was 0.5 m^2 smaller, *i.e.* 25 m^2, for the same number of animals. To ensure that rabbits had constant access to grass, a decision rule was established to change the location of the mobile-pen when the average grass height was $\leq$5.0 cm. Another decision rule concerned the phytosanitary treatment of the orchard. Each time a treatment was applied, the rabbits were moved to the fallow-land in a mobile-cage (the same one that was used in P2). The entire area was protected by an electric net.

Specific measurements

We monitored the local climatic conditions daily using a meteorological station located near the apple orchard (https://agroclim.

Table 1
Common and specific features of the three prototyping rounds (P1, P2 and P3) to design the association of rabbits and apple trees.

Features	Prototyping Round		
	P1	P2	P3
Rabbits per housing (n)	8	12	12
Sex ratio (male: female)	1:1	1:1	1:1
Genotype[1]	F1	F2	F2
Housing system[2]	MC, FP, IC	MC, FP	MP (two fields)
Vaccines[3]	Myxomatosis	Myxomatosis VHD 1 & 2	Myxomatosis VHD 1 & 2
Vaccination (age in days)	36	26	34
Weaning (age in days)	42	44	34
Outdoor access time (age in days)	42	44	45
End of the experiment (age in days)	70	76	80
Place of birth[4]	GenPhySE	GenPhySE	GenPhySE
Place of growing[4]	GenPhySE	UERI – Gotheron	UERI – Gotheron
Season/Year	Spring/2021	Autumn/2021	Spring/2022
Diet[5] and water provision	Free access	Free access	Free access
Herbage cover species[6]	Spontaneous	Cultivated	Cultivated
Antibiotic treatments	None	Individually	Individually
Measurements			
Climatic conditions[7]	Shelter	Shelter	Shelter
Live weight at (age in days)	42, 49, 56, 63 and 70	45, 52, 59, 66, 73 and 76	45, 54, 58, 61, 66, 70, 74 and 80
Health status[8]	VE	VE, DL, OPG	VE, HL, OPG,
OPG[9] counts at (age in days)	None	46, 53, 60, 67 and 74	47, 56, 59, 61, 67, 75 and 80
Behaviour at (age in days)	44 and 58	47, 57, 62, 68 and 75	46 and 66
Feed intake periods	See live weight	See live weight	See live weight
Herbage biomass[10]	None	None	Rising plate

P1: Prototypes round 1; P2: Prototypes round 2; P3: Prototypes round 3.
[1] Genotype: F1 crossbreed (Fauve-de-Bourgogne × INRA-1777) and F2 crossbreed [Belier × INRA-1777) × F1].
[2] Housing: MC for mobile-cage, FP for fixed-pen, IC for indoor-cage, and MP for mobile-pen.
[3] Vaccines: against myxomatosis and the variants 1 and 2 of the virus of the rabbit haemorrhagic diseases (VHD).
[4] Place of birth/growing: GenPhySE – Sheep and rabbit experimental facility or UERI – Gotheron Apple Orchard.
[5] Pelleted commercial diet: 11.3 MJ of DE per kg of DM, 17.8% of CP, 2.8% of fat, 40.1% of NDF, 22.7% of ADF and 7.9% of ADL on a DM basis.
[6] Herbage cover species: spontaneous grass cover or cultivated mixture of grass and legume forages (https://franceprairie.fr/melange/saint-marcellin).
[7] Data Logger (OM-CP-RHTEMP101A; OMEGA, France) placed at 10 cm from the shelters' roof, sampling frequency: one point every 10 minutes, 24 hours a day, 7 days a week.
[8] Health status: VE for visual evaluation of the body (at weighing), DL for dehydration level (at weighing or if some changes in the normal behaviour), OPG for oocysts per gram of faeces (once a week from samples taken inside the shelter).
[9] OPG: oocysts per gram of faeces (*Eimeria* sp.).
[10] Herbage biomass was measured using a rising plate meter as described by Plagnet et al. (2023).

inrae.fr/climatik/). Temperature and relative humidity inside the shelters were recorded using a data logger placed approximately 10 cm from the shelter's roof (OM-CP-RHTEMP101A; OMEGA, Northbank, Irlam, Manchester, UK). The logger was set to record one data point every 10 minutes, 24 hours a day, 7 days a week.

We checked the rabbits twice a day during the experimental period. Once a week, we recorded the live weight of each rabbit using a stabilised balance (accuracy 5 g), followed by a visual assessment of their health status. In addition, *Eimeria sp*. excretion counts (oocysts per gram of faeces, **OPG**) were performed on each group of rabbits (P2 and P3) using the McMaster method (Adams et al., 2022). We used various ways to monitor food intake depending on feed origin. Pelleted feed intake was monitored at fixed time intervals, corresponding to the interval between two consecutive live weight records. As the feeder is the statistical unit (one per group of rabbits), this information is descriptive only. Herbage biomass was assessed in P3. This was done using a rising plate meter (Plagnet et al., 2023). Measurements were taken at each placement of the mobile-pen at AO and at FL (n = 5 locations per field) before the rabbits had access to the pasture. Herbage was not the only biomass available to rabbits. Downgraded apples, discarded during the harvest, were also present in the ground. Apple intake was estimated twice: once during the P2 and once during the P3. Before introducing the animals, the fruits present in the pen were picked up, weighed and randomly redistributed in the area. After moving the pen to a new location, the remaining apples were weighed.

We assessed the specific behaviours of rabbits using the scan-sampling method. An adapted version of the ethogram described by Fetiveau et al. (2023a) was used. We added new potential actions to the ethogram, such as eating apples, when rabbits were in the orchard (P2 and P3). In P1, rabbits were observed at 44 and 58 days (n = 8 repetitions/group). In P2, observations were made at 47, 57, 62, 68 and 75 days of age (n = 24 repetitions/group). In P3, observations were made at 46 and 66 days of age (n = 22 repetitions/group). In all prototyping rounds, observations were made twice a day (early morning and late afternoon) for 10 minutes each.

Statistical analysis

Air temperature and humidity outside and inside the shelter (daily minimum, maximum and average values) are descriptive. Health, survival, feed intake and OPG counts (P2 and P3) are also descriptive. No statistical inferences have been made due to the small number of replicates. Herbage biomass estimations are presented in Plagnet et al. (2023). Live weight and behaviour data were analysed using the R-language (R Core Team, 2022; version 4.4.2).

Live weight data were analysed using the mixed model function of the R- package {*lme4*}. Pairwise comparisons of estimated marginal means were performed using the R-package {*emmeans*}. The model included housing system (housing) and rabbit age as fixed factors. Animal (rabbit) was included as a random effect. The statistical model in R-notation was:

$$lmer(live\ weight \sim housing * age + (1|rabbit),\ Data\_Set)$$

Animal behaviour data were analysed using quasi-poisson logistic regression for count data. The statistical model was implemented using the {*glm*} function of the R-package {*stats*}. The housing system (**housing**) was the only explanatory variable. Data are presented in the supplementary material (available at https://doi.org/10.57745/JBHZSC) as percentages. The statistical model (for each behaviour) in R-notation was:

$$glm(Behaviour\_count/Total\_count \sim housing,\ family = "quasipoisson",\ Data\_Set)$$

Results

Climatic conditions in P1, P2 and P3

The outdoor temperatures during P1 (April to May 2021 in Toulouse, France) varied from −1.2 to 23.8 °C (Supplementary Fig. S1 –

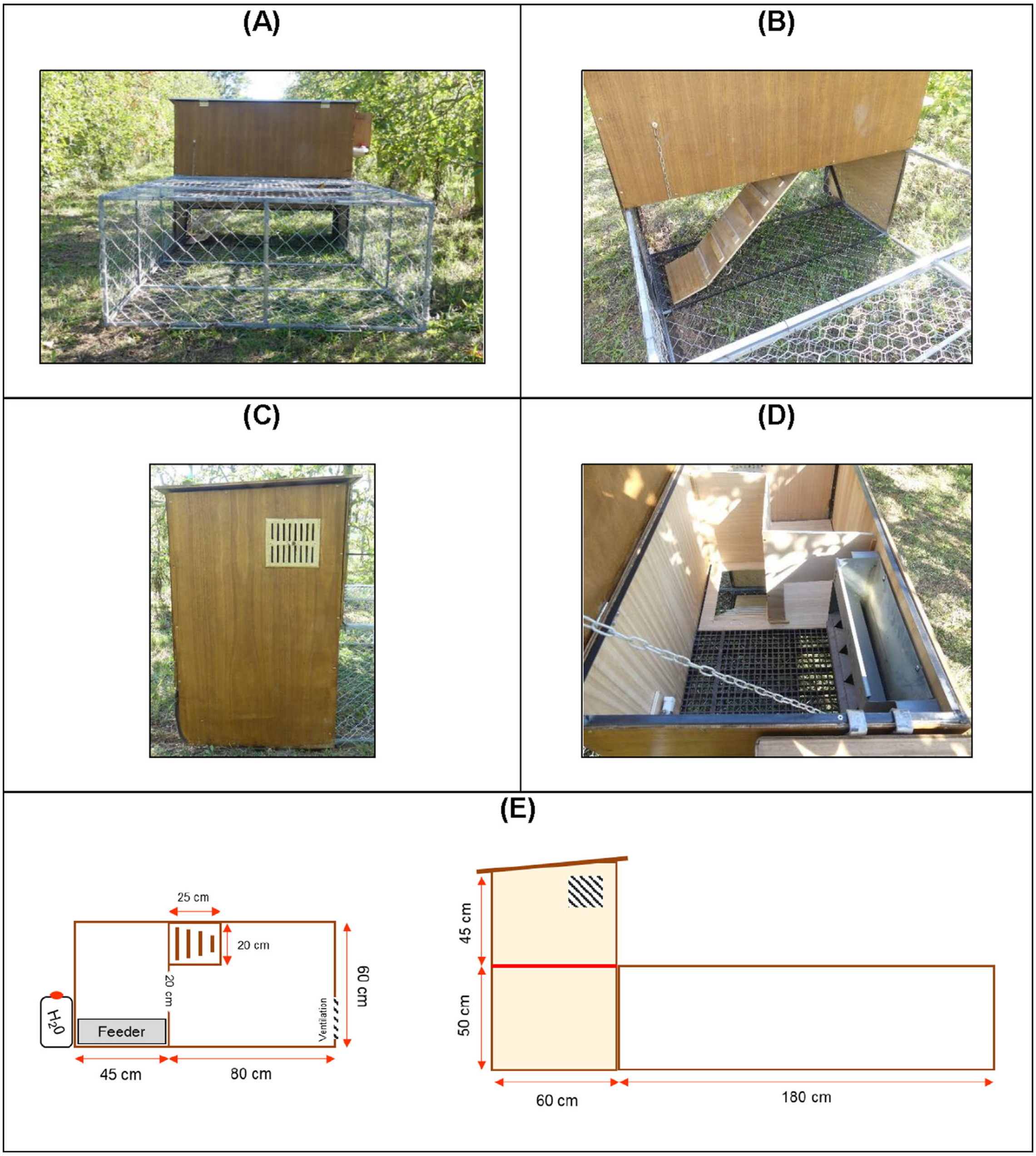

Fig. 1. Photos and blueprint of the mobile-cage (P1 and P2). (A) Overview of the grazing area (bottom) and wooden shelter (top). (B) Detail of the opening-trap to the grazing area and the stairs to the shelter. (C) Lateral view of the shelter, detail of ventilation opening. (D) Top view of shelter subdivided into two areas: the feeding area with plastic slat floor and the resting area with a wood floor. (E) Blueprints: detail of the feeding and resting areas (on the left). Rabbits had access to a grazing area of 3.0 m^2 and 0.75 m^2 in the shelter.

available at https://doi.org/10.57745/JBHZSC). The daily thermal-amplitude range in this period was 3.6 to 21.0 °C for an average relative humidity and wind speed of 63% and 4.6 m/s (max 15.0 m/s). The cumulated rainfall was 22.5 mm. Conditions inside the building, where caged rabbits lived, were stable: average temperature and relative humidity of 18.7 °C and 46.5%, for a daily thermic-amplitude variation below 8.4 °C. The average temperature and relative humidity inside the MC shelter were 17.4 °C and 63.2%, for a daily thermic-amplitude variation of 6.9 to 40.9 °C. Similar values were recorded in the FP shelter: 17.6 °C and 54.1%, for a daily thermic-amplitude variation of 5.0 to 33.6 °C.

In P2, using the same shelters tested in P1, the outdoor temperatures varied from −2.2 to 11.3 °C for a daily thermal-amplitude range of 1.2 to 8.2 °C (Supplementary Fig. S2 – available at https://doi.org/10.57745/JBHZSC). Air moisture varied from 55 to 100%, the average wind speed was 5.3 m/s (max 13.0 m/s) and the cumulated rainfall was 59.0 mm. Both shelters protect animals from low outdoor temperatures (below 5 °C). The average temperature recorded in the MC shelter was 9.8 °C (range: 1.1 to 28.3 °C) for a daily thermic-amplitude range of 3.2 to 25.7 °C. The average relative moisture was 88.4%. The temperature range in the FP shelter was 1.6 to 28.8 °C, the daily thermic-amplitude varied from 3.5 to 24.9 °C, and the average relative humidity was 88.6%.

The outdoor temperatures during P3 (Mars to April 2022 in Saint-Marcel-lès-Valence, France; Supplementary Fig. S3 – available at https://doi.org/10.57745/JBHZSC) varied from 0.0 to 23.4 °C for a daily thermal-amplitude range of 3.5 to 19.0 °C. Relative humidity varied from 18 to 99%, the average wind speed was 5.3 m/s (max 14.0 m/s), and the cumulated rainfall was 55.0 mm. The average temperature and relative humidity inside the AO shel-

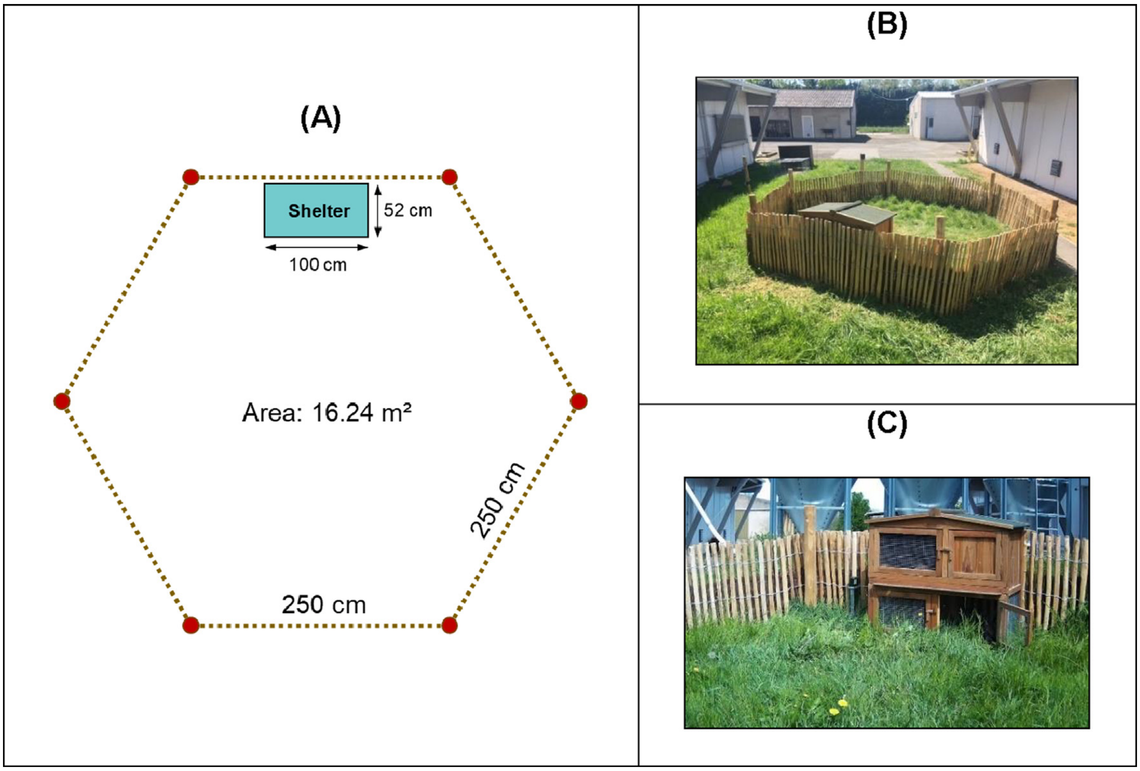

Fig. 2. Blueprint and photos of the fixed-pen and the shelter used in P1. (A) Rabbits had access to a pasture area of 16.24 m^2. (B) Photo of the fixed-pen for eight rabbits with an outside fence made from chestnut wood spaced 2 to 3 cm away and 80 cm height doubled with a heather band of 50 cm height on the outside. (C) Photo of a commercial shelter (L: 100 × W: 52 × H: 92 cm).

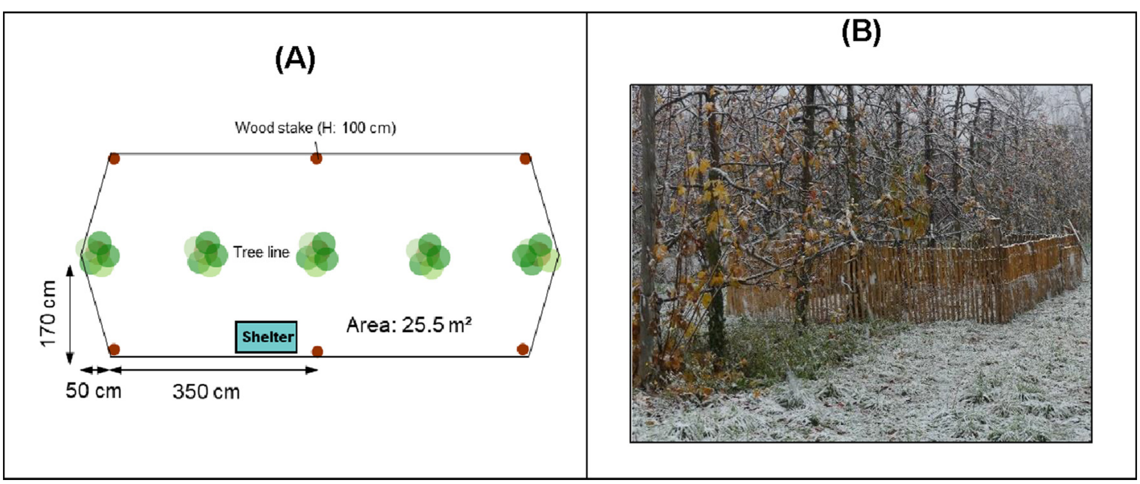

Fig. 3. Blueprint and photo of the fixed-pen for rabbits around the apple trees in P2. (A) Distances from the tree trunks, position of the shelter and pasture area. (B) Photo of the fixed-pen within the apple tree row in a snowy day.

ter were 15.1 °C and 67.4%, for a daily thermic-amplitude variation of 8.2 and 33.0 °C. Air temperature and moisture recorded inside the FL shelter were 17.0 °C and 67.1%, and the daily thermic-amplitude varied from 8.7 to 35.3 °C. The maximum thermic-amplitude in the FL was 2.3 °C higher compared to the values recorded at AO shelter.

Growth and pelleted feed intake of rabbits in P1, P2 and P3

At 42 days old, the average live weight (Fig. 5) of P1 rabbits in the MC (1 266 g), FP (1 236 g) and IC (1 246 g) did not differ. In the first week outdoors, the average daily gain (**ADG**) of rabbits in the MC and FP (7.4 and 3.2 g/day, respectively) was negligible compared to IC (39.4 g/day). Between 42 and 63 days, the ADG of rabbits in the MC and in the FP did not differ (26.7 *vs* 29.5 g/day; $P = 0.11$), resulting in a similar live weight at 63 days old (1 691 *vs* 1 671 g, respectively). At 63 days old, IC rabbits were 393 g heavier than rabbits living outdoors ($P < 0.001$). The pelleted feed intake of P1 rabbits in IC was numerically higher compared to outdoor rabbits. Roughly, IC rabbits ingested 96.1 g/day while outdoor rabbits did not reach 80 g/day (MC = 79.8 g/day and FP = 60.7 g/day) in the first week (between 42 and 49 days old). In the following periods, IC rabbits ingested 28.1% more than rabbits living outdoors (on average, 153 g/day *vs* 110 g/day; no statistics performed).

At 45 days old, the average live weight (Fig. 6) of P2 rabbits in the MC (1 196 g) and in the FP (1 199 g) was similar. Rabbits in

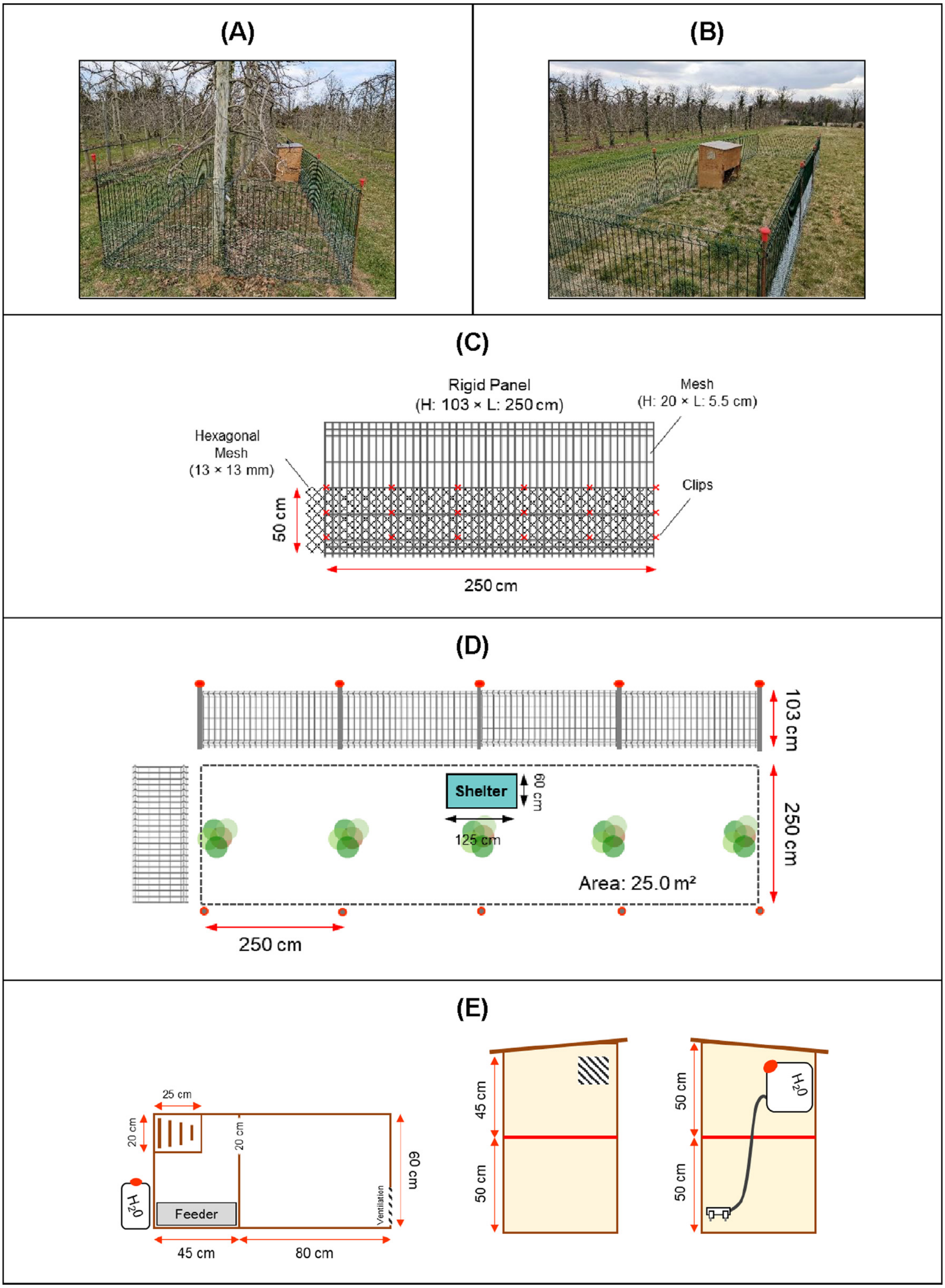

Fig. 4. Mobile-pen (L: 1 000 × W: 250 × H: 103 cm; surface: 25.0 m^2) and wood shelters (L: 125 × W: 60 × 100 cm; surface: 0.75 m^2) for 12 rabbits in P3. (A) Placed in the apple orchard and (B) at the fallow-land. (C) Scheme of one rigid panel, doubled with a hexagonal wire mesh (13 × 13 mm). (D) Representation of the mobile-pen set up. (E) Blueprint of the shelter, detail of the top floor plan (left side) with staircase, feeder and a resting area.

the MC (33.9 g/day) grew 6.7 g/day faster than rabbits in the FP (27.7 g/day; $P < 0.01$). At 76 days of age, MC rabbits (2 246 g) were heavier than FP rabbits (2 042 g; $P < 0.01$), probably related to their higher pellet feed intake, which was on average 1.4 times higher in the MC than in the FP (4 012 *vs* 2 907 g/rabbit in 31 days).

At 45 days, the average live weight (Fig. 7) of P3 rabbits in the AO (1 267 g) and in the FL (1 282 g) was similar. For a similar ADG (AO: 25.5 and FL: 29.5 g/day; $P = 0.08$) between 45 and 80 days, AO and FL rabbits had a similar live weight at 80 days (2 148 and 2 286 g, respectively; $P = 0.58$). Numerically, the overall

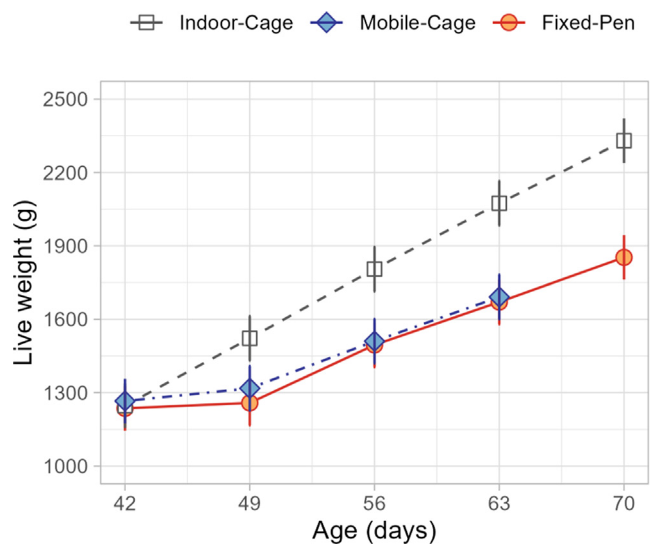

Fig. 5. Live weight of rabbits between 42 and 70 days of age according to the housing conditions (P1: Indoor-Cage, Mobile-Cage or Fixed-Pen). Vertical segments represent the 95% confidence interval around the estimated marginal means.

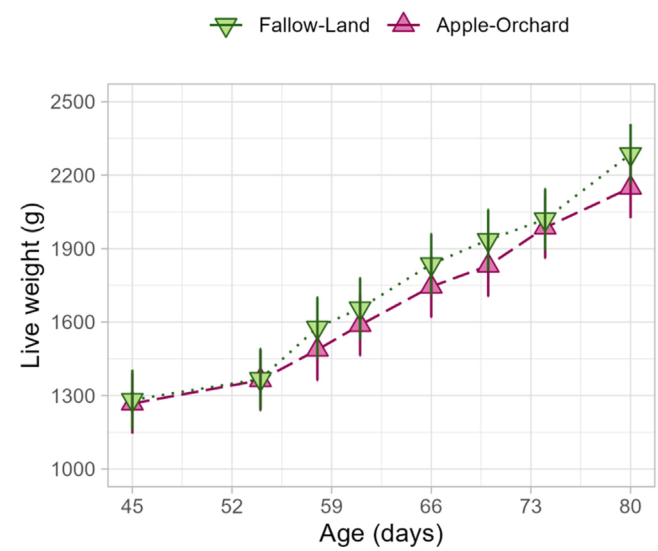

Fig. 7. Live weight of rabbits between 45 and 80 days of age according to the field (P3: Fallow-Land or Apple Orchard). Vertical segments represent the 95% confidence interval around the estimated marginal means.

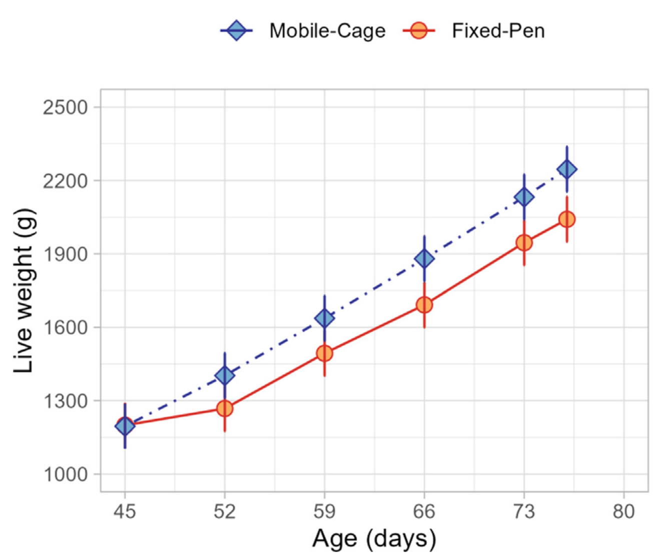

Fig. 6. Live weight of rabbits between 45 and 76 days of age according to the housing system (P2: Mobile-Cage or Fixed-Pen) placed in an apple orchard. Vertical segments represent the 95% confidence interval around the estimated marginal means.

pelleted feed intake of P3 animals in the FL was 1.19 times higher than that observed at the AO (3 913 *vs* 3 292 g/rabbit in 35 days).

Health status of rabbits in P1, P2 and P3

There were no signs of any disease in P1 until 63 days of age. However, between 68 and 70 days, an outbreak of the rabbit haemorrhagic diseases (**RHD**) decimated all rabbits in the MC. At 70 days, rabbits in the FP started to die, and by the end of that week, all rabbits living outside died. No losses were observed in the IC rabbits.

All P2 rabbits reached 76 days of age in good health. However, FP rabbits had high OPG counts (100 100 OPG) in the second week. Three rabbits in this group showing clinical signs of coccidiosis were transferred to the nursery. After five days of treatment (30 mg/kg of trimethoprim-sulphamide twice a day), they were reintroduced to their group. In the following period, the oocyst count did not exceed 5 000 OPG. The oocyst count for MC rabbits never exceeded 25 000 OPG.

Two days after P3 started, one rabbit in the AO entered the nursery with clinical signs of coccidiosis. Despite treatment, this animal died of coccidiosis after 11 days in the trail. A second rabbit in the AO entered the nursery and died 10 days after P3 started. No further losses were reported in the AO, but one additional animal was treated in the field. After seven days in the FL, one rabbit with coccidiosis was withdrawn from the study. Four other rabbits in the FL received antibiotic treatment in the field.

Behaviour of rabbits in P1, P2 and P3

In P1 (Supplementary Fig. S4 – available at https://doi.org/10.57745/JBHZSC), IC rabbits were more frequently observed '*Resting*' (32.8%) compared to MC rabbits (12.0%). '*Body-contact*' was also more often noted among IC rabbits (27.4%) compared to MC (9.7%) and FP (19.4%) rabbits. '*Grazing*' was the most frequent behaviour observed outdoors (MC: 30.8% and FP: 13.3%).

'*Grazing*' (MC: 24.4% and FP: 32.3%; $P = 0.12$) was the most frequent behaviour observed in P2 (Supplementary Fig. S5 – available at https://doi.org/10.57745/JBHZSC) followed by '*Body-Contact*' (MC: 12.1% and FP: 11.0%; $P = 0.65$), '*Hopping*' (MC: 9.9% and FP: 12.7%; $P = 0.09$) and '*Watching*' (MC: 10.2% and FP: 6.7%; $P = 0.07$). '*Rearing-up*' (MC: 9.34% and FP: 5.55%; $P < 0.05$), '*Capering*' (MC: 3.72% and FP: 1.76%; $P < 0.05$), and '*Chasing-other*'' (MC: 5.06% and FP: 1.88%; $P = 0.051$) were more frequently observed in MC compared to FP rabbits.

No differences in the expression of behaviours between rabbits living in the AO and in the FL were observed in P3 (Supplementary Fig. S6 – available at https://doi.org/10.57745/JBHZSC). '*Grazing*' (AO: 34.7% and FL: 31.2%), '*Hiding*' (AO: 20.8% and FL: 24.9%) and '*Hopping*' (AO: 9.0% and FL: 6.6%) were the most observable behaviours.

Apple and biomass intake in P2 and P3

Within a week (45–58 days old), P2 rabbits in the FP ingested 7.78 kg of apples (49.9 g/rabbit per day, up to 54% of the available fruits). In P3, 11 rabbits ingested 1.74 kg of apples (31.7 g/rabbit per day, up to 80% of the available fruits) within 5 days (54–59 days old). Visually, rabbits also foraged on the fallen leaves and branches present on the ground. Measurements on the ingestion of these two kinds of biomass were not performed. Concerning the herbage intake, results are presented in Plagnet et al. (2023). Roughly, between 45 and 80 days of age, we estimated that each rabbit in the AO and in the FL ingested 45.2 and 43.4 g of grass/day (on a DM basis), respectively.

Author's point of views

Advantages of the prototyping process including professionals

The prototyping process was a powerful approach for designing this grazed orchard while collecting biological data on the system. In each prototyping round, we gathered data on the association of rabbits and apple trees while improving the prototype. By the end of P3, a functional housing system was obtained. In that matter, the workshop organised at the end of P2 was a key moment. It allowed a cross-examination of the proposed systems and the FP was considered as the most appropriate for this association. Workshop participants made several arguments to support the FP, provided it was made mobile. The FP allowed rabbits to forage around the trees and provided a quick and effective weeding service in this area (Supplementary Photo 1 – available at https://doi.org/10.57745/JBHZSC). Participants also felt FP provided a richer environment for the rabbits than the MC.

Participants to the workshop also suggested improvements of FP. They were sceptical about the fencing material used. They found it impractical and emphasised the importance of having a fencing system that could be quickly erected (and dismantled). Autumn was found to be a good compromise in terms of the timing for the association. In autumn, phytosanitary treatments are scarce or null, and the harvest is complete. Autumn is also a period of less intensive work for orchardists, but there are still plenty of resources for the rabbits. There are fruits and leaves on the ground, and the grass is still green. Participants also mentioned that the final system should be flexible, allowing its use throughout the year.

In summary, prototyping combined with a professional workshop was a powerful approach for developing this innovative association of rabbits and apple trees. The advantage of designing a prototype is that it may be used as a proof of concept. The whole process also contributed to raise interest of professionals in a system combining rabbits and trees. The prototype allowed discussions during the workshop attended by several professionals, and we organised additional visits for more professionals and policymakers. This may help us enrolling stakeholders, a crucial issue to the future development of this new type of association.

Towards a proof of concept

The design and the materials used in the construction of the P1 shelters were adequate. The temperature inside the shelters reached high values at midday (data not shown). Fortunately, the design of both shelters allowed rabbits to avoid very high temperatures by the presence of a shadow area below it. Rabbits had a free choice on space use. Latrines were spread in the pasture area, perhaps related to a territorial marking behaviour of the rabbit (Ziege et al., 2016). This resulted in a clean shelter interior. The technical choices made in P1 appeared to be correct, and no modifications were made between P1 and P2.

Rabbits living outdoors (P1) tended to reduce their pellet feed intake in the first week compared to caged rabbits, probably related to the availability of a new food source (grazing was the main behaviour outdoors). In the presence of additional feed resources (pasture and hay), Fetiveau et al. (2023a) observed a peak in the pelleted feed and hay intake six weeks after providing rabbits access to a pasture area, when the amount of grass available to the rabbits was low. Moreover, these authors have shown that rabbits with a shorter access time to pasture adjusted their daily herbage intake by increasing their grazing speed almost two-fold over the whole growing period. Together with a less favourable climatic condition and a higher physical activity when outdoors (also observed by Fetiveau et al., 2023b), these factors affected their growth. The choice to not vaccinate the animals in P1 had a high cost: in less than a week, all animals living outdoors died. Therefore, the main lesson from P1 is that all rabbits raised outdoors must be vaccinated against myxomatosis and RHD.

In P2, the main challenge has been revealed to be the assessment of the two tested systems (FP and MC), and especially the management of the availability of the new food source (grazing was the main behaviour outdoors, as noted by Fetiveau et al., 2023b). Indeed, rabbits in the FP ingested all the grass available (in 25.5 m^2) in less than 10 days. Therefore, we had to displace them (whenever needed) to a new location within the tree row to reduce the potential bias of grass availability when comparing their growth to those in MC which had access to fresh grass every other day. This management converted the fixed-pen into a mobile-pen with constraints in terms of handling. In total, the FP was displaced five times for a total grazing area of 127.5 m^2, while the MC was displaced 20 times for a total grazing area of 60 m^2. This affected the pelleted intake and the growth of rabbits (both higher in the MC). The health status of rabbits was improved by vaccination against myxomatosis. Only minor interventions were needed to control the coccidiosis, naturally present outdoors due to the wild rabbit fauna (Grès et al., 2003). Coccidiosis is a threat. In P3, coccidia counts performed two days after rabbits' arrival (AO: 63 000 OPG and FL: 137 100 OPG) suggest that several stress factors (early weaning, transportation, new environment, new social group, etc.) contributed to the outbreak of coccidiosis. From our experience, a way to manage such disease is to carry out observations on the rabbits and to isolate symptomatic individuals from the group. Visually, in the most critical cases of infestation, rabbits had a shaggy hair, some discharge (dirty hair) in the tail and urogenital zone, signs of dehydration, loss of appetite (stopped pelleted feed intake), and had a bloated belly. All these signs were observed in the animals transferred to the nursery. Animals presenting a shaggy hair and signs of licking in the urogenital zone, but no signs of dehydration, should be closely monitored and it may be a good practice to proceed with a prophylactic treatment. In addition, the displacement of the housing to a new location also helps to reduce the parasite load in the field.

The FP system was supported by the practitioners. Therefore, this prototype was used in the P3 trial. To overcome the challenge of regularly moving the fence, a time-consuming process, we improved the prototype with a light fence which revealed easy to manage, quick to install and to move (less than 10 minutes in two persons; authors personal communication). During this trial, rabbits had to be removed three times from the apple orchard for 48 h, to be not exposed to copper ($CuSO_4$) applications used to control scab. This allowed us to understand that early spring, with intense preventive treatment of apple trees, is not the most suitable season for the rabbit/apple orchard association since their presence increases the number and nature of the different tasks to be performed.

Outdoor conditions can be challenging for rabbits. They are exposed to viral diseases, parasites and predation. Vaccination is essential and monitoring the excretion of intestinal parasites as well as the physical status of each animal helped to reduce both treatments and animal losses. The use of electric net seems to be effective against the wild fauna and dogs. Despite their presence on the farm, no losses due to birds of prey or other potential predators were recorded.

The results of the present study are preliminary. Most of the measurements and observations have helped us to create a functional housing system that allows the association of rabbits and apple trees. The final system tested in P3 is not optimal. However, it serves as a basis for the development of this association. To prove the concept of mutual benefits for both rabbits and apple trees, further studies with more replicates are needed.

Final considerations

In conclusion, this prototyping process allowed us to produce a practical system while obtaining scientific knowledge on its effectiveness in terms of rabbit welfare and potential productivity gains for apple growers. Adaptations of this mobile-pen are still possible for the production of an actionable proof of concept.

We have shown that rabbits in the apple orchard benefit from a milder climate and a rich environment with a variety of food sources. As rabbits ring-barked the trees, trunk protection is mandatory. Apple trees benefit from the weeding service provided by rabbits, probably reducing the competition with weeds for water and nutrients. Rabbits may also provide a sanitation service by eating the fruits and fallen leaves, and their urine and droppings may improve the soil fertility. However, further studies are required to confirm these direct benefits for the trees.

The data collected here and the lessons learnt from each of the prototypes can help animal and plant scientists in the construction of the proposed association. It could also be used by organic apple growers and organic rabbit farmers to diversify their production by introducing rabbits or apple trees to their farms.

Ethics approval

Animals were handled in accordance with the recommendations on the protection of animals used for scientific purposes (EU Directive 2010/63/EU, Official Journal of the French Republic – Decree No. 2013-118). All the protocols were approved by the French Ministry of National Education, Higher Education and Research (Number: 27970-2020111315299053).

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) did not use any AI and AI-assisted technologies.

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Declaration of interest

We declare no conflict of interest of any sort.

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