CAPABLE : control of thistle (Cirsum arvense) and docks (Rumex crispus & Rumex obtusifolius) in organic arable farming

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Abstract

The aim of the CAPABLE project was to identify management practices of *Cirsium arvense*, *Rumex crispus* and *Rumex obtusifolius*. To meet this objective, various tasks were carried out, combining design of solutions with practitioners, trials, and the development of management decision-making tool for *Cirsum arvense*. Based on the results obtained, several practices have been identified, including innovative solutions that will need further work to be evaluated. The project also provided an opportunity to highlight the methodological difficulties inherent in work dedicated to perennial weeds.

Keywords: *Cirsum arvense*, *Rumex obtusifolius*, *Rumex crispus*, weed, organic farming, innovation, decision-making tool

1. Introduction and presentation of the work of the CAPABLE project

Canada thistle (*Cirsium arvense*) and docks (*Rumex obtusifolius* and *Rumex crispus*) are perennial weeds that are particularly problematic in cultivated systems and are considered among the most difficult weeds to manage. In Organic Farming (OF), the management of these weeds is complex because it is mainly based on a preventive rather than curative approach. Their impact on the development of main crops can lead to significant yield losses, with a consequent drop in farmers' incomes.

Only a combination of practices can be effective in managing these weeds and depleting them over the long term, while limiting their ability to regenerate. The CAPABLE project therefore aimed to identify innovative strategies and levers for managing thistle and dock, combining mechanical tools, competition/allopathy control, soil management in the timeframe between harvest of the previous and sowing of the following main crop and crop rotation. The aims of the project were to

- Identify and build management strategies, then characterise them and determine the optimum conditions for implementing them.
- transfer to growers the operational elements and the main keys to successful thistle and docks management so that they can translate them into production contexts

In the CAPABLE project, several methods of knowledge production were combined: tracking down innovative practices on farms, field tests on the scale of networks of plots, experiments under controlled conditions, and co-design workshops. The aim has been to evaluate existing strategies, design new ones, study the conditions under which thistles and docks grow, and develop decision-making tools.

The work was carried out under organic farming conditions, so the knowledge gained is transferable to any system aiming to reduce or eliminate herbicide use.

The project was divided into three complementary work packages, as presented in **Figure *1***. The first was to characterise farmers' perceptions of the risk associated with the presence of thistles and docks, and to identify and characterise the management strategies considered to be either effective or counter-productive by practitioners (tasks 1.1 and 1.2). Research avenues were identified during this work, and were able to provide input for T 2.2, which aimed to gain a better understanding of the biology of docks in relation to agricultural practices likely to have a positive or negative effect on its presence in plots. In this task, the project experts were also involved in co-designing the protocol and defining subjects worked on. To complement this work, field trials were set up to test strategies combining several action levers. To interpret the results of these trials more broadly, a multi-criteria analysis was carried out using Systerre® (ARVALIS), which enabled the results to be integrated with socio-economic and environmental criteria (T 2.3).

Thanks to the expertise of the project partners, the decision-support tool ODERA Vivaces (Outil d'Évaluation du Risque en Adventices Vivaces), developed by Agrotransfert,-Ressources-et-Territoires (Favrelière *et al* 2016), has been parameterised for thistle in several French regions. In addition to this tool, various co-design workshops were held on thistles or docks management topics to come up with systems for better control of these weeds (T 1.3). These workshops were based on the results of the project, supplemented by a literature review.

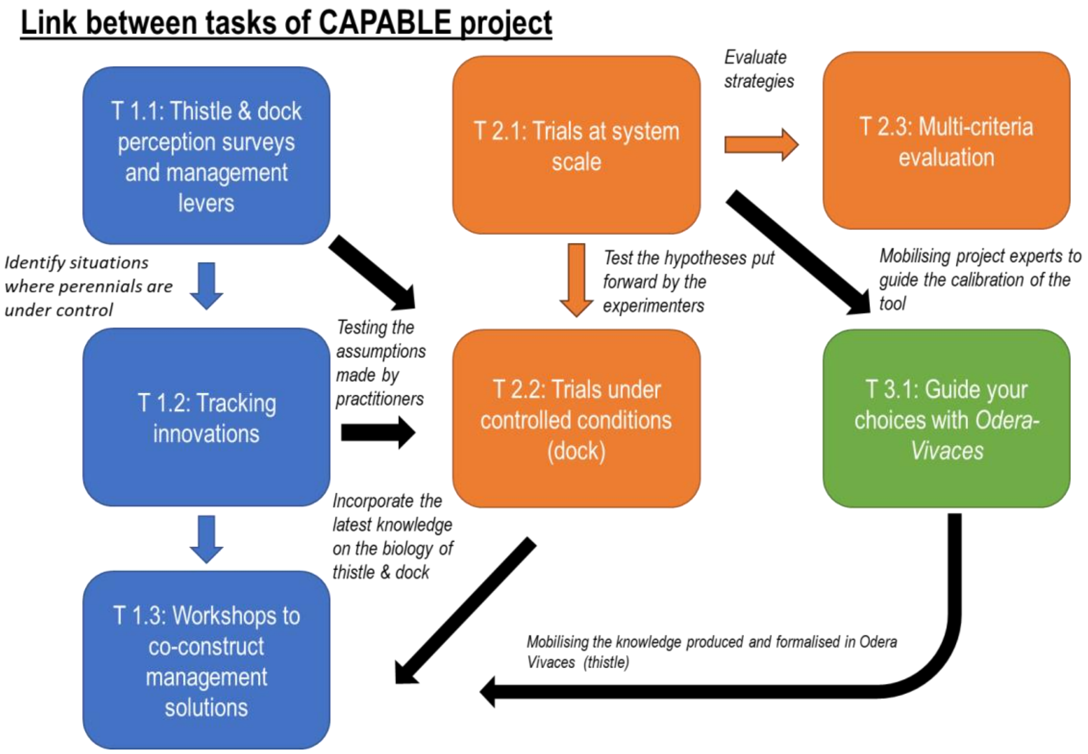

Figure 1 Diagram of the tasks carried out in the CAPABLE project and the arrows represent the links between tacks.

2. An overview of thistle and dock management practices

2.1 The methods used

Two methods were combined: an online survey and innovation tracking.

The online survey aimed to shed light on farmers' main practices for managing dock, as well as the difficulties they encounter. The survey was carried out across the whole of France, from February to December 2019. The work was carried out in 4 stages: 1) design of a questionnaire, aimed at all OF farmers in field crops and mixed farming, 2) distribution of the questionnaire by the CAPABLE project partners to their respective networks (263 responses), 3) cleaning of the data collected (e.g. exclusion of responses from winegrowing) and formatting of the variables, 4) descriptive statistical analysis of the data, using R and Excel software.

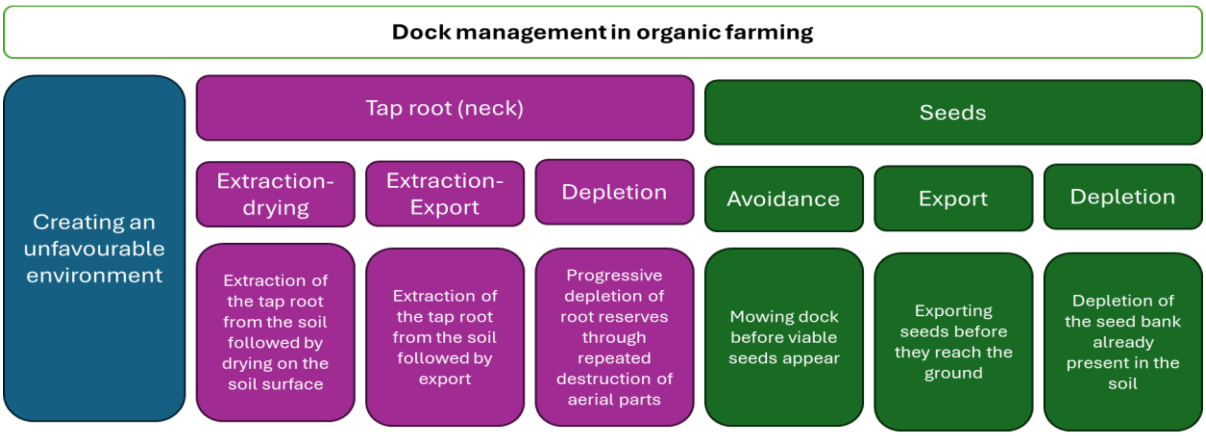

Figure 2 Structuring of the database used to categorise the practices discovered during tracking. From Vancleenputte, 2019.

Tracking innovations aimed to explore and produce knowledge on practices developed by farmers, which are still little known, to manage dock in AB (Vancleenputte, 2019; Vancleenputte *et al*., 2019). Drawing on previous work (Salembier and Meynard, 2013; *Feike et al.,* 2010; Lamé *et al.,* 2015; Salembier *et al.,* 2021), the innovation-tracking approach was adapted to the questions of the CAPABLE project and organised around four stages. 1) Definition of what was being sought, *i.e.* what was considered innovative and should be tracked down. The partners had decided to focus the tracking on practices that were unknown in the literature and to the project partners, but which were considered effective in managing dock. 2) Identifying the farmers who were using these innovations, both by using the results of the online survey and by exploring the networks of the project partners. 3) Characterisation of practices through comprehensive interviews with the 11 farmers identified, in the Bourgogne Franche Comté region (France). 4) Agronomic analysis of practices, based on 3 aspects:

- Recounting the interview to give an account of the links forged by the farmer during the interview, to explain what he did, why, how and in what situations. Writing the story makes it possible to contextualise the practices, to highlight the combinations of practices over time and the underlying agronomic logic, from the farmer's point of view.
- Analysis of favourable and unfavourable conditions for docks, making the most of farmers' observations and formulating hypotheses on the biology of docks, which is little known in the literature, and comparison of farmers' practices and observations with the scientific literature, grey literature and expertise to formulate plausible hypotheses as to how certain practices work, or to reveal new gaps in knowledge. In some cases, farmers indicated practices that should be avoided, and these were also analysed.
- Cross-analysis of interviews: what are the factors favouring and hindering docks? What are the management strategies? Which practices are considered effective, and which should be avoided? This information was centralised in a database, and management strategies were distinguished based on known mechanisms for managing docks (Favrelière and Ronceux, 2020). This database was used for two types of cross-analysis: (i) to account for the diversity of conditions under which the same practice is applied, and (ii) to account for the diversity of practices encountered for a management strategy (e.g. root exhaustion).

The results of this work have been summarised in a compendium containing a short description of the method and results of the first survey and the accounts obtained during the tracking innovation work (Burel *et al.,* 2022).

2.2 <u>Describe practitioners' perceptions of the risk and management methods for dock and thistle</u>

An online survey conducted from 2018 to 2019 revealed that thistle and docks are considered equally problematic for all growers who responded to the survey: 60% of respondents consider these weeds to be problematic (Vancleenputte, 2019). Nevertheless, farmers tend to accept thistle a little more over time, unlike docks, which appears to be an emerging problem (Figure 3). Farmers who consider that they do not have docks are rarer on farms that have been converted to OF for longer. The survey obviously does not allow to distinguish whether this observation is due to an increase in the presence of docks in AB or to farmers becoming increasingly aware of the problem. In any case, even years after converting to AB, thistle and docks management appear to be major problems for approximately 50% of respondents.

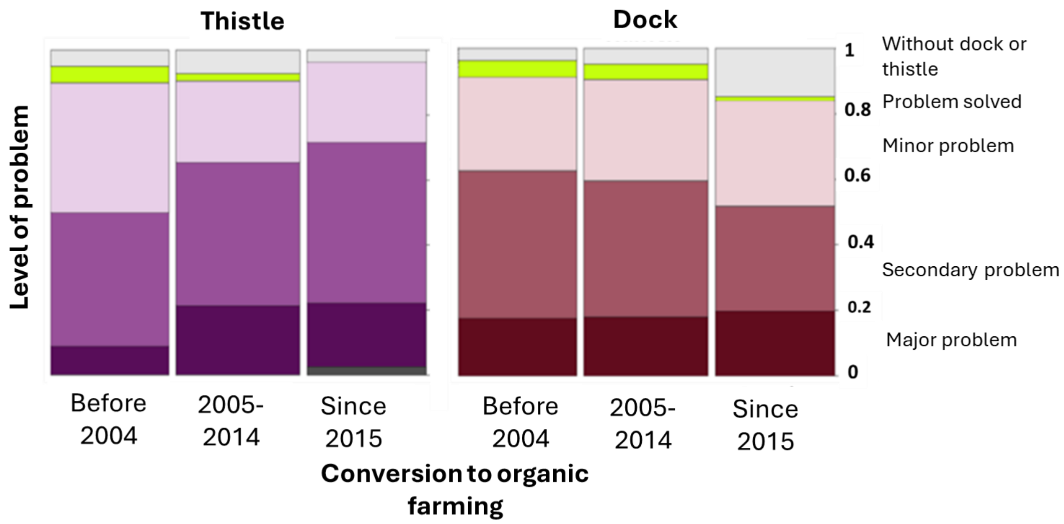

Figure 3 Breakdown of responses to thistle and dock surveys according to conversion period and perceived level of problem (226 respondents for thistle; 219 respondents for dock). (Vancleenputte, 2019)

The only notable difference between arable and mixed farming systems is that farmers are more likely to see no thistle or docks in systems with ruminants. Among ruminant systems, 12% are considered thistle-free, compared with 1% among non-ruminant systems. This is also reflected in the perception of the docks problem: 7% of farmers with ruminant systems consider dock to be a major problem, compared with 23% of farmers with non-ruminant systems. As for docks, 11% of farmers in systems without livestock consider that they have no docks, compared with 3% of farmers in systems with ruminants.

Comparing the practices used by growers and the degree of satisfaction also suggests a great similarity in the practices implemented for the two types of perennials (Figure 4). There is, however, a difference in practices concerning the use of alfalfa and topping in vegetation, which are more frequently used to manage thistles. Manual weeding is more often associated with docks. Liming is sometimes used to manage docks, although it is unlikely that this practice is solely associated with docks management.

Looking at the link between perceived management effectiveness and the frequency of practices, it appears that several practices are linked (Figure 5). In the case of thistle, alfalfa is recognised as an important lever, which is consistent with current knowledge about thistle (Favrelière *et al.,* 2020). Other tools are also associated with a higher level of satisfaction in terms of control, such as deep tillage without inversion, the use of disc tools and the establishment of cover crops. However, ploughing, shallow tillage and the use of tine tools were associated with lower levels of satisfaction. For docks, only tine tools and the use of cover crops were associated with positive results. In contrast to what observed for thistle, disc tools were associated with lower levels of satisfaction. Nevertheless, there was a convergence of satisfaction with the use of cover crops for both docks and thistle. On the other hand, in these surveys, there was antagonism regarding the type of tool, with tine tools being preferred for docks and disc tools for thistle, to maximise the degree of satisfaction. These survey results do not prejudge the actual effectiveness of these practices, but they do help identify avenues of work, both for research and to identify any inconsistencies between farmers' perceptions and the documented effectiveness of certain practices.

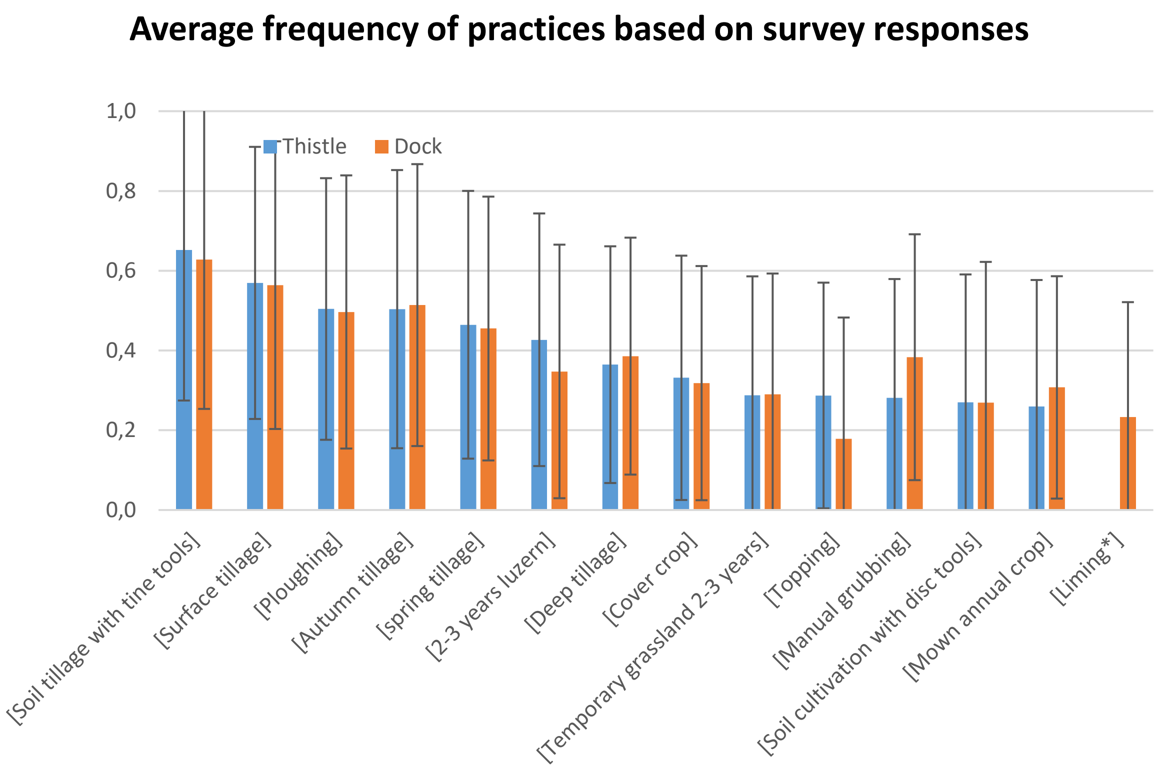

Figure 4 Frequency of intervention for each perennial control lever. The frequency score is estimated on the basis of the answers to the questionnaire, where four responses were possible: never (score 0), sometimes (score 1/3), often (score 2/3), systematically (score 1). The error bars correspond to the standard deviation. * requested only for dock

	Significant positive effect of control	Significant negative effect of control
Dock	• Tine tools • Cover crops	• Disc tools
Thistle	• Lucerne • Deep tillage • Soil cultivation with disc tools	• Ploughing • Surface tillage • Tine tools

Figure 5 Practices significantly related to farmers' perceived effectiveness (significance established via ordinal regressions). From Gautier Vancleenputte's dissertation (2019).

2.3 Tracking down innovative Rumex management practices

Three main results emerge from the tracking:

2.3.1 Knowledge of interesting practices and practices to be avoided, which were previously little known.

Several practices were revealed by the tracking, such as "sowing wheat to allow interrow hoeing and competition", whereas this crop is generally sown on equidistant rows (not allowing hoeing). For example, a farmer sows his wheat alternating two rows close together and two rows 25 cm apart so that a weeding tool can be used in the inter-row. From his point of view, this hoeing is particularly effective in the spring against young docks that have grown from the same year's seeds. The denser plant cover between close rows is competitive against weeds. Other farmers we met take advantage of summer crops such as sunflower, maize or soybean to carry out mechanical weeding in the inter-rows in addition to mechanical weeding in the spring. Another example is "harvesting chaff" using adapted equipment - as one farmer has been doing for the last four years. Since he doesn't have the time to collect straw by hand, this farmer harvests the straw with dock if there is any, which enables him to extract the straw and small weed seeds from the field. Farmers also mentioned practices to be avoided, such as "stubble ploughing with disc tools". For example, one farmer explained that he had increased the presence of docks in his field by using a disc tool, whereas he had previously used a tine tool with Lemken Smaragd crow's feet. Another farmer commented that it was preferable not to follow up the stubble cultivator with a roller, as this would mean "planting the ripped-out pivots". Following this observation, the farmer adapted his tool by replacing the roller with a triple harrow, which leaves the dock pivots on the surface, which is conducive to their drying out.

2.3.2. Research avenues to be explored on the biology of dock

The farmers' observations of changes in docks populations on their plots revealed environmental conditions that they felt favourable to their development, and which were not well known in the literature. For example, according to 8 out of the 11 farmers interviewed, temporary leys of alfalfa, red clover or dwarf white clover create a favourable environment for docks and stimulate its development. Two hypotheses were put forward by the farmers: docks seeds were present in the seeds of legumes sown in the field (seeds of the same size), and/or alfalfa and clover stimulated the germination of dock seeds present in the soil. To date, there has been no research into the interactions between legumes and docks. To fill this gap, the hypothesis was tested in trials under controlled conditions.

3.2.3. Comparisons between practices useful for action

The database allows interviews to be cross-analysed from three different angles. The first concerns the ways in which practices can be combined. For example, a farmer wishing to reduce docks on his farm to a minimum has invested in various types of equipment and labour (observation, manual removal, etc.) to combine : repeated stubble ploughing (extraction-desiccation of the pivot), manual and systematic removal of dock throughout the year (extraction-exportation of the pivot and seeds), grinding his alfalfa several times a year to a height of 5 cm (seed avoidance), and carrying out false seeding (depletion of the seed stock). The second concerns the various practices that can be implemented to promote the same weed management mechanism. For example, the pivots can be extracted from the soil and removed from the plot by hand, or by using tools with tines fitted with crow's feet, followed by extraction of the pivots left on the surface.

As well as differing in the way they are carried out, these practices differ in the time of year they are carried out: May to June for manual weeding, and after the harvest or after winter ploughing (March-April) for tine tools fitted with crow's feet, followed by collection. Also, to create an unfavourable environment for the development of docks, farmers can use soil improvers, planting summer crops to allow mechanical weeding in the spring, reducing the length of time alfalfa is grown, etc. Third, the same practice can be adapted to different implementation conditions (humidity conditions, depth of tillage, number of passes, etc.). In dock management, stubble ploughing using disc implements has proved counter-productive because it breaks up the pivots, which is why most of the farmers we met use tine stubble ploughs. However, one farmer whose knotweed prevented the use of tine tools adapted his practices by making an initial very shallow pass with a disc tool, followed by several passes with tines fitted with crow's feet at a depth of between 5 cm and 15 cm to scalp the roots. In this particular case, the practice-based approach in the cross-analysis provides solutions to a problem in different environmental conditions.

3. Towards a better understanding of the biology of dock and its response to practices

3.1 Methods and working hypotheses

Trials under controlled conditions were carried out on *Rumex crispus* to supplement the lack of knowledge about its biology and potential control methods. The aim of this work was to gain a better understanding of the development conditions of *Rumex crispus* using a functional approach, in order to develop effective control techniques via agricultural practices based on the specific features of three key stages: germination, seedling development and root regeneration at the adult stage. The idea was to assess the sensitivity of dock life traits during these stages to environmental factors.

3.2 Trials on the germination capacity of dock

The Table 1 summarises the germination experiments on *Rumex crispus*, with the treatments tested

Table 1 Summary of germination experiments on *Rumex crispus*. Water was not limiting in the various tests presented.

	Effects of temperature and photoperiod			**Effect of depth of lift**	**Effect of interactions**
Themes	Influence of tillage and thermal weeding			Influence of tillage	Influence of cutlery
Assumptions	Positive effect of thermal amplitude	Positive effect of photoperiod duration	Synergy between photoperiod and heat treatment	Reduced germination with burial	Decrease in germination with canopy density
Methods	Under constant darkness 1 constant temperature control (22°C) 3 temperature treatments (15-30°C, 10-35°C or 5-40°C)	4 treatments at constant temperature (22°C) + 1 dark control and 3 photoperiod treatments (8 h, 12 h or 16 h daylight)	4 photoperiod treatments (8 or 16 hours of daylight) x 2 temperatures between day and night (15-30 or 10-35°C)	5 lift depths (0, 1, 3, 4 or 5 cm) x 5 populations x 3 repetitions	5 varieties of clover and 3 varieties of alfalfa x 3 densities of legumes in relation to dock (5/3, 8/3, 12/3) + Control dock alone + Control legumes alone

Several factors with a potential influence on germination were identified in the literature or in the surveys carried out as part of the project. They were therefore selected for the trials on the biology of dock.

- Temperature and light influence the germination capacity of docks: *Rumex crispus* and *Rumex obtusifolius* (Zaller, 2004)
- The germination of *Rumex crispus* is also encouraged by tillage, which brings the seeds to the surface (Le Deunff, 1980).
- Germination is favoured by wide temperature variations, or even thermal shock, even in the dark (Meneghini *et al*., 1968; Le Deunff, 1980; Takaki *et al.,* 1985).
- Photoperiod, as seeds are highly photosensitive and germinate easily in the presence of light (Le Deunff and Chaussat, 1968; Le Deunff, 1980).
- There is a combined effect of temperature fluctuation and photoperiod duration (Vincent and Cavers, 1978; Le Deunff, 1980).

Another objective was to determine to what extent the germination of *Rumex crispus* is affected by the depth of burial. Burying dock seeds induces them to enter dormancy, as shown by Zaller in 2004. The hypothesis tested is that germination is greatly reduced from a burial depth of around 1.0 cm (Weaver and Cavers, 1979) and that germination no longer occurs from a depth of 2.5 cm (Vacher, 2008). Five depths were tested: 0 cm (surface), 1 cm, 3 cm, 4 cm and 5 cm. In this trial, to avoid an inclusion bias linked to a certain inter-population heterogeneity in germination capacity, several populations of different origins were collected (5 populations from Occitanie, Bourgogne-Franche-Comté and Ile-de-France).

Finally, according to the farmers interviewed in Axis 1, the emergence of docks with legumes is possibly unfavourable to docks. So another question we worked on was to see to what extent legumes interact with *Rumex crispus* germination. The literature tends to show that dock germination and subsequent development seem to be adversely affected by competition with legumes if they develop quickly (Pye *et al.,* 2011; Alshallash, 2018). A germination experiment in the presence of different species and varieties of clover and alfalfa (*Medicago sativa* variety Luzelle, Melissa and Greenmed; *Trifolium incarnatum* variety Cegalo; *Trifolium alexandrium* L. variety Sacromonte, *Trifolium pratense* variety Formica; *Trifolium repens* variety Merida & Pipolina) was therefore set up.

3.3 Identifying the key stage for dock management

Another hypothesis put forward in the surveys carried out under Axis 1 of the project was that dock seedlings develop rapidly and need to be managed quickly and effectively before they become too difficult to manage. The phenology of docks was therefore studied in order to determine the optimum stages for intervention with the chain harrow. According to the farmers surveyed, mechanical weeding loses its effectiveness at the three- or four-leaf stage, whatever the dock population.

3.4 An attempt to understand the regeneration capacity of dock depending on age and fragmentation

For dock control, it is important to know the effect of the type of fragmentation and burial on root regeneration capacity (Pye *et al.,* 2011). The hypotheses put forward regarding the impact of interventions on dock regeneration were therefore assessed. The regeneration favoured by fragmentation of the root system (Zaller, 2004; Pye *et al.,* 2011) would essentially be provided by the upper root part: crown and underground stems, the latter including root buds (Pye, 2008; Pye *et al.*, 2011; Alshallash, 2018).

Regeneration rate and seedling development are a priori affected by burial depth (Pino *et al*., 1995; Pye *et al.,* 2011) and regeneration conditions and root characteristics (depth, root section, age and mass of the pivot) (Dobinson, 1976). To test dock root regeneration, 125 *Rumex crispus* pivots were recovered from individuals present in an oat and pea plot at Sèges, near the commune of Boudou in the Tarn-et-Garonne. A distinction was made between young and old pivots. Regeneration capacity was tested at 3 depths: 1 cm, 10 cm and 25 cm.

3.5 The results obtained

The optimum conditions for Rumex germination have also been determined in the laboratory. The combination of photoperiod and amplitude has an effect on the germination rate: short photoperiods with a low thermal amplitude are more favourable to germination (8 h of light and a thermal amplitude of 15-30°C). The depth to which the seed is buried also has a strong impact on germination. A seed placed on the surface has a low germination rate, *in contrast to* a seed placed 1 cm below the surface (

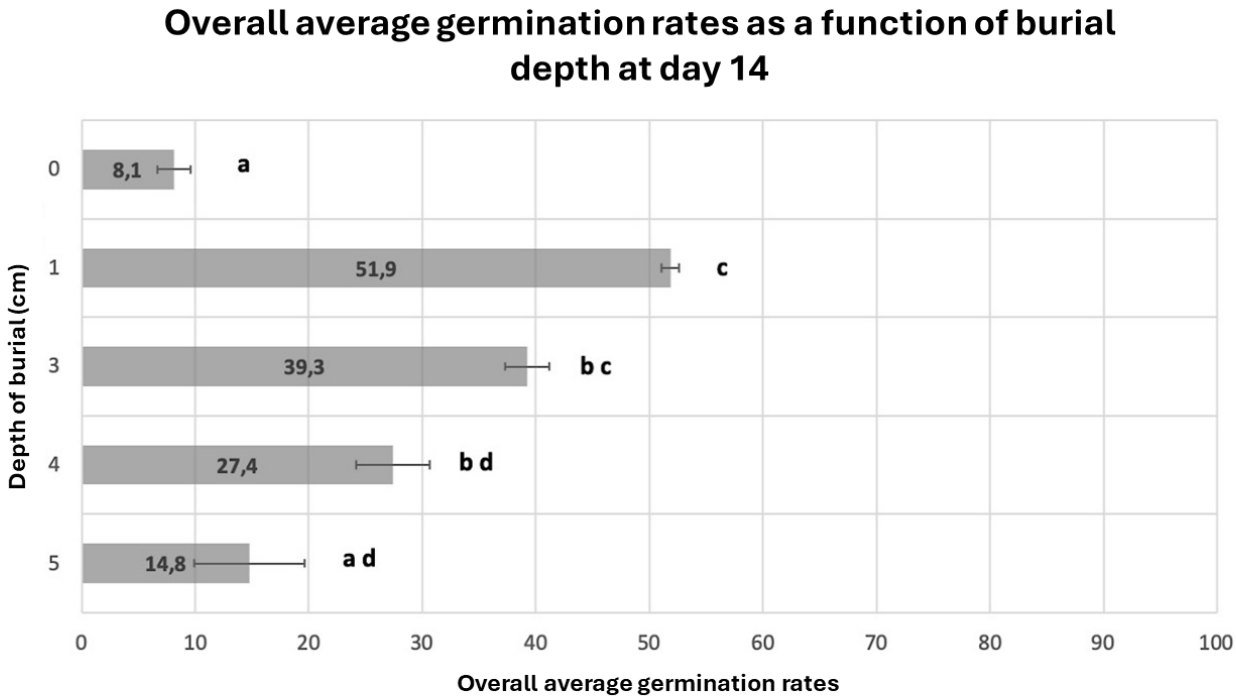

Figure 6). Germination capacity decreases with depth of burial, with an effect of seed size on the rate and duration of germination. Smaller dock seeds have more difficulty germinating.

The study of phenology and in particular the growth of roots and aerial parts showed that after the 3-leaf stage the seedling has a root and aerial surface area that increases very sharply. This increase can be seen to a lesser extent in the leaf/root surface area and biomass ratios. This validates the 3-leaf stage as the limit stage for optimal seedling destruction.

The trials also showed that, without fragmentation, the dock regeneration rate is very close to 100%, without any influence from the age of the dock (Figure 7). However, after fragmentation, the regeneration rate is affected: the upper part has a regeneration rate close to that of the whole plant without fragmentation, but the lower part has much more difficulty starting up again. It is even very likely that the rare fragments that regenerate correspond to situations in the trial where the location of the collar was poorly qualified.

The germination experiment in the presence of different species and varieties of clover and alfalfa (*Medicago sativa* varieties Luzelle, Melissa and Greenmed; *Trifolium incarnatum* variety cegalo; *Trifolium alexandrium* L. variety Sacromonte, *Trifolium pratense* variety Formica; *Trifolium repens* varieties Merida and Pipolina) did not show any significant reduction in dock emergence, nor any effect on the dry mass produced afterwards. Dock populations are considered denser in clover and alfalfa meadows (CasdarDM data sheet, 2012, CAPABLE survey results). However, some authors, such as Pye (2008) and Alshallash (2018), report a reduction in germination and weaker development of dock seedlings in the presence of these legumes. This contradiction may be due to the protocol (legume stage too early) or to interpretation bias. In fact, dock could be more easily visible in multi-annual legume crops than in annual crops. The protocol itself does not allow us to conclude on the effect of a well-established temporary grassland. Tests under controlled conditions show that lower temperature amplitudes are favourable to the germination of dock, conditions that could be provided by a well-developed plant cover. It is therefore difficult to determine the effect of legume cover.

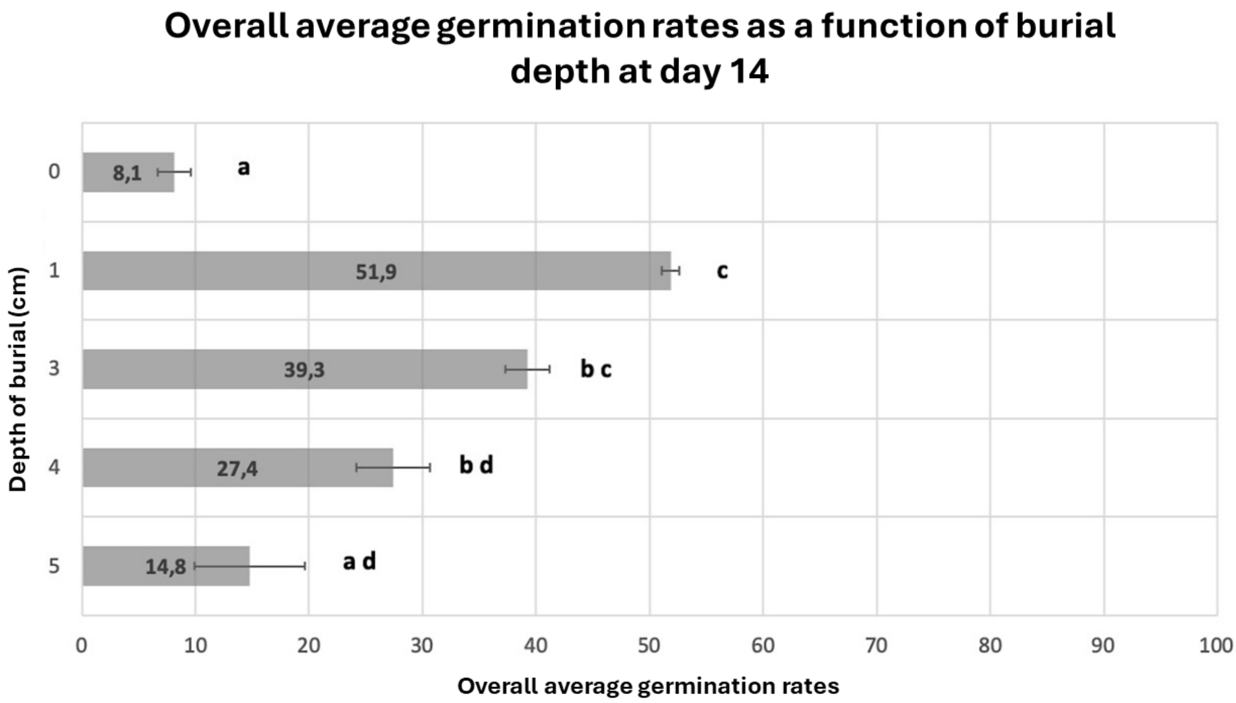

Figure 6 Germination of dock seeds at 14 days according to depth of burial. Letters correspond to statistically consistent groupings. The error bars represent the variation between the dock populations tested. Figure from Clément Dusserre's dissertation (2019).

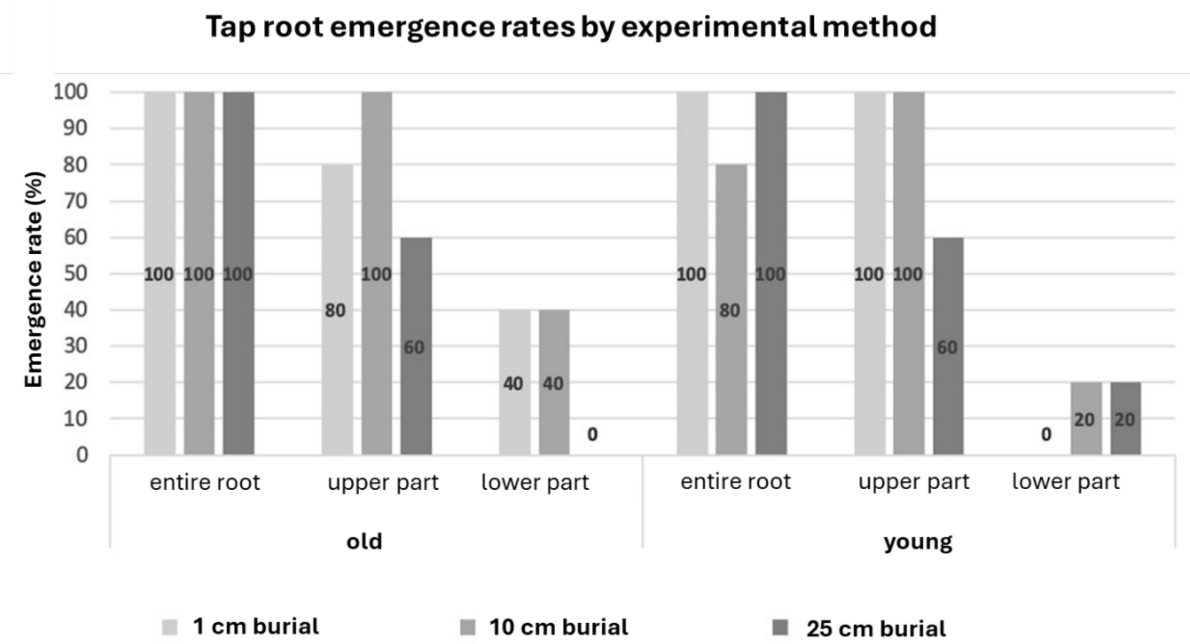

Figure 7 Effect of dock plant fragmentation on its ability to regenerate. Figure taken from Clément Dusserre's dissertation (2019).

4. Evaluation of thistle and dock management strategies

4.1 Management strategies tested and evaluation methods

Each trial partner tested *at least* 2 management strategies for thistle or dock on dedicated large plots. As the protocols were different for the two types of weed, the trials were only followed on one of the two weeds.

There were 4 strategies evaluated on dock; they had to be implemented on dock patches and/or strips. Despite the absence of intra-plot repetition, the multiplication of sites made it possible to increase the power of the system and to make statistical calculations by grouping the strategies (these are repetitions on the scale of a network). The strategies evaluated were (Roques *et al*., 2022) :

- **Scalping (strategy 1):** between-crops management intervention to be started in the summer: several successive passes with a tool for scalping dock (crow's foot or winged stubble cultivator).
- **Scalping and extraction (strategy 2)**: between-crops management intervention work to be started in the summer: an initial pass to scalp the dock (crow's foot or winged stubble cultivator type tool) then several passes to stir up and extract the dock (vibrocultivator type tool).
- **Extraction / Desiccation (strategy 3):** between-crops management intervention to start in the summer: use a stubble plough (work at 15 cm) then a straight-tine tool no more than 2 days later to extract the dock.
- **Sandbox**: innovative strategy defined with the farmer. The strategies tested in this 4ème model were not intended to be included in the grouping of trials, but were designed to identify innovative and alternative management options.

The plots chosen had to have sufficient dock infestation (5-10 pl/m²) and their rotation had to allow a crop to be harvested in early summer in the 2018 campaign. Each trial contained *at least* strategies 1 and 2. Each was located on an area significantly infested with dock, but not necessarily contiguous. The minimum size of the trial had to correspond to two tool widths over a minimum length of 50 m, centred on the area of infestation.

The various measurements and observations were carried out in a fixed area at the heart of the infestation. The monitoring area measured 32 m² or 130 m² and was divided into 32 cells (of 1 m² or 4 m² each). For each cell (1 m² or 4 m²), the number of dock shoots present and the minimum, maximum and most frequent stages were recorded. Monitoring was carried out on different dates: at the initial and final stages, and at crop flowering, with an intermediate note once a year. In addition to this monitoring, a number of site characterisation data had to be collected: precise description of the tools used, characterisation of the plot's soil: soil type, depth, hydric functioning (risk of hydromorphy, drainage speed, etc.), pH, organic matter level, plot history: crop succession, tillage and mechanical weeding, fertiliser inputs (risk of seed inputs), how long the dock has been present.

For thistle management trials, 3 strategies were tested (Vuillemin *et al.*, 2022):

- **Strategy 1** involved tilling the soil as often as possible to kill off the thistle: several stubble ploughings in the summer, work in the spring before sowing the summer crop, etc.
- **Strategy 2** combined repeated summer tillage with a smother crop.
- **Strategy 3 relied** on maximum soil cover with smothering cover crops between crops.

Each site experimented with strategy 1 and a choice of the other two. The trials all started with a crop harvested in July and ended with a winter crop also harvested in July.

As with dock, the areas monitored had to follow the material constraints in terms of tool widths, but with a minimum of 2 tool widths and this time with at least 2 counting zones. The two counting zones were used to see if there was a difference between the centre of the thistle circle and its periphery. The fixed thistle counting areas were 8 m² quadrats (2 x 4 frames) with a maximum mesh size of 1 m² (finer on one site). The 2 strips were set up on at least 2 different thistle patches. The rest of the monitoring and the information gathered were identical to the dock trials.

None of the results from the systems trials were significant at the 5% alpha level, apart from one case in the thistle trial. There are several reasons for these results; one of the most obvious is the high frequency of protocol deviations due to climate variability between trial years and the complexity of implementing tillage and cover crops.

Particularly with thistles, the 3 stubble ploughings planned were not always carried out, notably because it was impossible to work on soil that was too dry for the trials located in the south-west. Finally, the different start-up years for the different trials had an impact on the heterogeneity of the network. Nevertheless, although the results were not statistically significant, some trends did emerge, and the experimenters' experience was invaluable in interpreting the results.

4.2 Lessons learned from system testing

Firstly, in the dock trials, all the sites where the initial dock density was between 2 and 10 pl/m² benefited from between-crops management intervention. Dock density was reduced by up to 70% in some cases, thanks to alternating short and long between-crops management intervention and repeated tillage.

Alternating winter and spring crops, or even including a summer crop, seemed to have an effect at different periods in the dock's life cycle. The introduction of a spring crop allows intervention before sowing, in early spring before the dock replenishes its root reserves, depleted after the winter. A summer crop provides an opportunity to intervene when the flowering stems appear, before the seeds have matured. Finally, harvesting the winter crop weakens the reserves by repeated passes in the summer, insofar as these can be made (difficulty of intervention in the event of drought).

In cultivation, harrow is not very effective on developed dock. In a trial where young docks were controlled, the adult dock population, although low (< 0.3 docks/m²), remained constant and thus reached the flowering and granulation stages. In the presence of dock over 6 leaves, it would therefore be wiser to opt for a more aggressive tool (e.g. two passes with a hoe).

The value of between-crops management intervention, cover crops could not be demonstrated in these trials. Only three sites were able to plant them, and their development was very unsatisfactory. However, in Burgundy, in the trial where infestation was highest, tillage combined with the planting of a cover crop resulted in the greatest reduction in dock density compared with tillage alone (Roques *et al.*, 2022).

For thistles, the strategy for using cover crops could not be analysed either (only 2 trials were set up). Nevertheless, it emerged from the experiments that a successful cover crop could contain the thistle provided that it was combined with tillage (a strategy validated in just one trial). In fact, soil cover alone is not enough to control thistles. Otherwise, the most effective strategy for thistle management seems to be a combination of more frequent ploughing and the planting of winter cover crops with the aim of stubble ploughing repeatedly during the summer after the winter crop has been harvested. Strategy 1 resulted in a thistle reduction of 79% or more compared with the initial state in 2/3 of the trials, compared with ¼ of the trials for strategy 2. However, the variability of the trials and of the thistle responses raises questions about the transposability of these results to strategies 2 and 3. In fact, despite the results tending on average towards a decline in thistles, in some trials there was an increase in the number of thistle regrowths. It is very likely that the conditions under which practices are carried out are the key factor in controlling thistle. However, it is recommended that ploughing be used sparingly, as its short-term effectiveness may mask longer-term management difficulties: the thistle may grow back deeper, which will limit the effectiveness of future interventions. (Vuillemin *et al.*, 2022)

The most effective tools in both cases are those that provide good coverage (tools working 100% of the surface, tines fitted with wings, for example). In the case of rumex, to maximise the expiration effect, tine tools seem to be preferable. Finally, whatever the tool, it is very important to choose a passage window in dry conditions to avoid restarting the fragments or plants extracted. In addition, certain geographical areas should opt for spring passes: in fact, post-harvest between-crops management windows are limited by drought, which makes it difficult to pass tools, on the one hand because the soil is too hard to get the tools in, and on the other because thistle and dock develop very little in these circumstances.

4.3 Multi-criteria evaluation of thistle and dock management strategies

To complete the assessment of the effectiveness of the practices, a multi-criteria analysis was carried out in two typical cases (

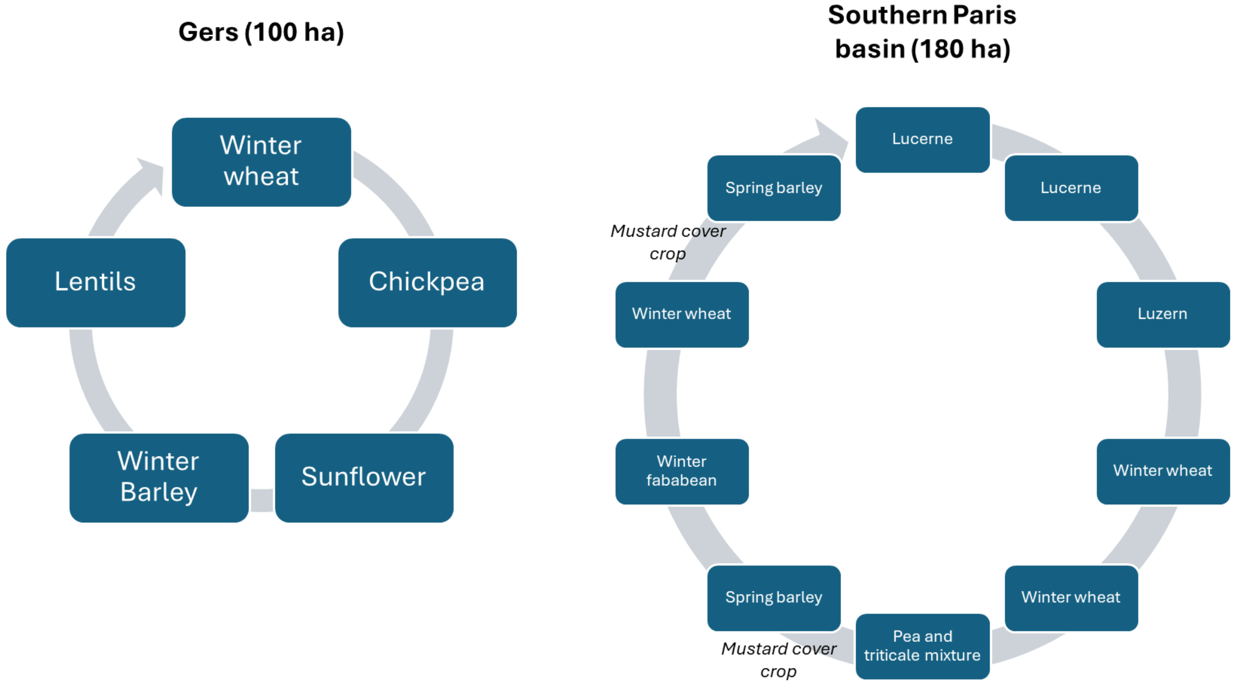

Figure 8) in the Gers (UAA[1] 100 ha, 1 family labour unit +0.3 occasional labour unit, superficial clay-limestone soil) and the southern Paris Basin (UAA 180 ha, 1 family labour unit +0.3 salaried labour unit, medium loam soil with good potential). The reference case studies were modified to incorporate a change in practices in line with the strategies evaluated in the trials (strategies 1 and 2). The changes were as follows:

1. Thistle management strategy 1: repositioning of crops to increase tillage windows + increase in the number of passes between crops. No between-crops management cover to maximise work windows.
2. Thistle management strategy 2: replacement of spring crops in the rotation with a smothering winter combination (triticale/pea) + increase in the number of passes of between-crops management. No cover crops between two main crops cover to maximise intervention windows.
- Rumex management strategy 1: the main change is in the type of tool used: tools with shallow tines are preferred (vibrocultivator, disc stubble cultivator).
3. Rumex management strategy 2: the main change is also a change in the type of tool used: tools with shallow tines are preferred (vibrocultivator, disc stubble ploughing) but with a more accentuated alternation of winter/spring/summer windows and later interventions (delayed sowing wherever possible).

Practices were assessed at farm level by calculating organisational (time spent in the field), economic (net margin) and environmental (GHG emissions) indicators using the SYSTERRE® tool. The impact of changing thistle and dock management practices was very slight on the amount and distribution of time spent in the field (from +0.4 h/ha to -0.1 h/ha). Overall, the net margins of farms varied negatively, with moderate variations for dock (-€13/ha in the worst case). The differences in net margin linked to system

[1] Useful Agricultural Area: standardised concept used in European agricultural statistics. It includes arable land (including temporary grassland, fallow land, crops under shelter, allotments, etc.), productive grassland and permanent crops (vines, orchards, etc.). (INSEE definition)

adaptation are greater for thistle: -4 €/ha (Paris Basin) to -37 €/ha (Gers) for strategy 1 and -57 €/ha (Paris Basin) and +60 €/ha (Gers) for strategy 2.

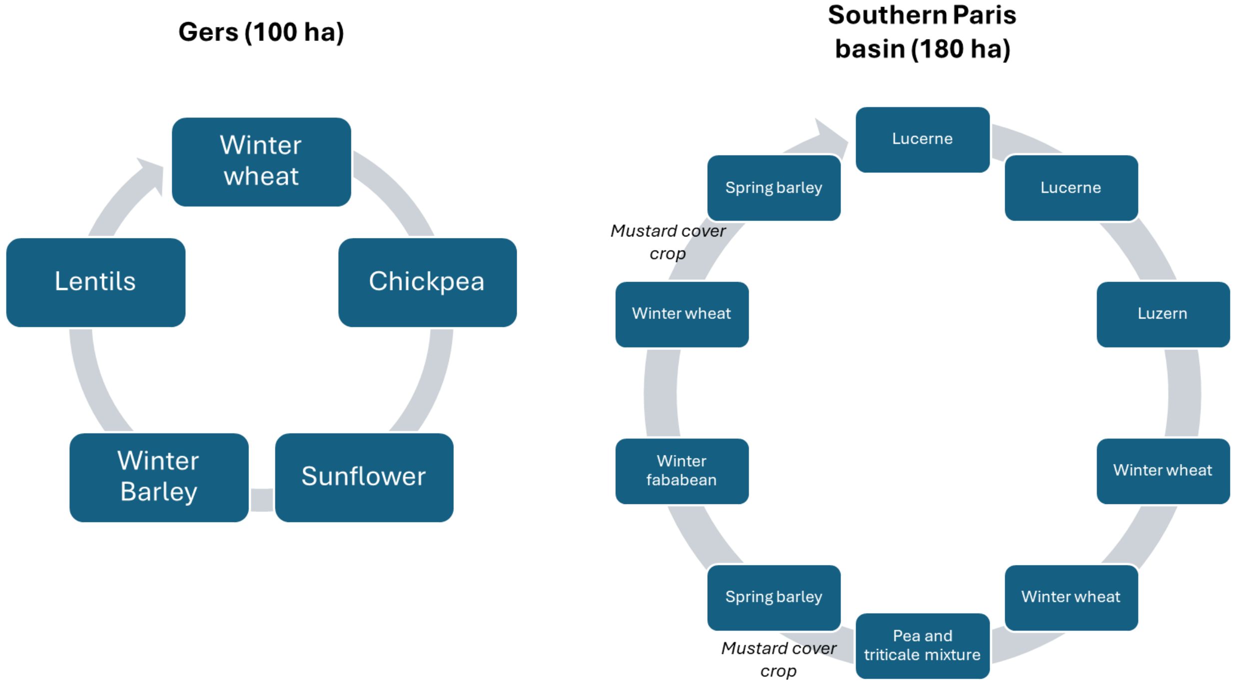

Figure 8 Rotations of typical cases selected for multi-criteria analysis with SYSTERRE®.

The impact on greenhouse gas (GHG) emissions is limited overall. Emissions fell slightly in three of the four situations studied for dock (lower emissions linked to fuel or fertilisation). Similarly, a drop was observed for the thistle strategies applied to the Southern Paris Basin. GHG emissions rose more sharply for thistle management in the Gers: +61 to +198 kg_{eq} CO_2 /ha (i.e. +8% to +25%). This increase is mainly due to the greater use of fertilisers in the rotation because of the crops that have been replaced in the rotation. This impact can be contained by reducing or eliminating the fertilisation of these crops. In some cases, fertilisation can be avoided, particularly in cases of high weed pressure or where the practice is not profitable, as has been observed in certain production contexts (CREABio 2013).

Adapting practices and rotations to manage thistle and dock has a moderate, and not necessarily negative, impact on socio-economic and environmental indicators. The variations in performance are very different depending on the typical case studied and the lever applied (change of crop rotation and between-crops management). In addition, some impacts can be partially offset in the short term, such as the environmental impact of adjusting fertilisation, which has a significant impact on greenhouse gas emissions.

5. Towards an operational tool to guide thistle and dock management choices

5.1 The OdERA Perennials tool and its settings

OdERA Vivaces is a Perennial Weed Risk Assessment Tool. It is used to assign a thistle development risk rating based on the farmer's technical itinerary at the level of the cropping system or a given plot. It is used to assess the effectiveness of a change in cropping practices and to compare different strategies. This tool is intended for farmers and advisers. It is based on a literature review and the knowledge acquired by the partners in the AgriBio (2013-2017) and VivLéBio (2017-2019) projects. It was developed for the Hauts-de-France region with the expertise of researchers, experts and agricultural advisors, and with the support of data from surveys of 55 local farmers' plots, before being computerised as part of VivLéBio in 2017.

The thistle risk calculation is based on 5 criteria, for which there are several response modalities. To calculate the risk score, a value is assigned to each response mode and each criterion is weighted by a factor relating to the impact of the practice on thistle reduction. The criteria linked to the most effective practices thus have the highest weighting. When the user has given a response to all the criteria, the value of the response is multiplied by the weight of the criterion, and the scores thus obtained for each criterion are added together to form the "total score". The total score is then transformed into a risk score of between 1 and 10, with 1 corresponding to a probability of thistle decline on the plot and 10 representing the maximum risk of thistle proliferation.

The tool was initially developed for use in the Hauts de France region. One of the aims of the work was to adapt the tool to new regions, while improving the parameters thanks to the partnership of the CAPABLE project. Experts from the Ile de France, Centre-Val-de-Loire and ex-Midi-Pyrénées regions were brought together to consider how the tool could be adapted to their region. The experts' discussions also highlighted possible improvements to the model for the Hauts-de-France region, for which the parameters were improved. It became clear that the Centre-Val-de-Loire and Ile-de-France regions had the same types of cropping systems and the same soil and climate conditions, so it was decided to create a single parameter setting for these 2 regions. The experts discussed the following points :

- The relevance of each criterion to their region
- Conditions for the effectiveness of each criterion, or conditions for taking practice into account in the assessment
- The weighting of each criterion in the final score
- New criteria to be incorporated into risk assessment

This information was used to guide the online questionnaires used to set up the tool. In this respect, 2 surveys were co-written with partner experts. The first was for the Centre, Ile-de-France and Hauts-de-France regions, and the second for the former Midi-Pyrénées. The partners were then asked to distribute the survey to their networks of producers, by e-mail and on social networks.

The survey covered one parcel at a time, for which the following information was collected:

- Year of conversion and duration of rotation;
4. Information on criteria validated by experts, in the number of years the practice is carried out (except for multiannual crops);
- Thistle development on the plot at rotation scale;
- Other: hydric characteristics of the plot, other perennials present.

The minimum number of plots required for parameterisation was set at 30. This objective was met for the Centre and Hauts-de-France regions, but not for the Ile-de-France and Midi-Pyrénées regions. As the Ile-de-France region had to be parameterised in the same way as the Centre region, the dataset for this parameterisation was 56 plots, which is sufficient. For the Midi-Pyrénées region, on the other hand, the tool was adapted on the basis of the 28 responses received. However, the dataset was not sufficient for an independent validation of the tool.

5.2 Results after setting parameters

Eight levers were identified by the groups of experts involved in setting up the thistle management tool:

5. Multi-annual crops
6. Competitive crops
7. Repeated summer stubble ploughing
8. Spring tillage
9. Ploughing
10. Weeded crops

11. Manual weeding (Centre/Ile de France & Hauts-de-France regions only)
12. Topping

Among these techniques, two did not appear to be significantly correlated with rotation frequency and thistle development: pollarding and competitive crops. For the first, this can be explained by the fact that the thistle reproduces mainly vegetatively. The effect of crop competition appears to be very uncertain. These two criteria have therefore been excluded from the tool.

Multi-annual cropping did not appear to be as effective in the surveys as in the literature, with 70% of plots in the Hauts de France region showing an increase in thistle pressure despite a mown crop (50% tending to stabilise). In the Centre and Ile de France regions, the multi-annual crop lever appeared to be more effective, with 60% of plots where thistle pressure was stable. In the South-West, the lever appeared to be effective, with only 2 plots out of 14 seeing thistle pressure increase with multi-annual cover crops.

Repeated stubble ploughing also appeared to be an important management tool, except in the south-west where conditions do not always allow it to be effective. This clearly shows that a lever, even an effective one, is not valid in the same way depending on the soil and climate conditions. The results on the use of ploughing tend to show its effectiveness in thistle management. However, there were no significant differences between the different frequencies of use, which suggests that one-off ploughing is sufficient and avoids the potentially negative effects of over-frequent use.

Manual weeding is only carried out to a very limited extent in the south-west, and it was not possible to provide information on the tool in this context. Nevertheless, in the other two regions surveyed, it appears to be a very effective lever, with a significant link between stabilisation and frequency of use (up to more than once every two years). Despite the arduous nature of the intervention, it remains a very important control lever.

The frequency of spring tillage is positively correlated with stability in the south-west, but not in the other regions. The effect of spring tillage appears to be effective according to the expert opinions and bibliographical references on the subject. As far as the significant effect of tillage in the south-west is concerned, we can assume that it is all the more effective because dry conditions are more frequent in spring in the south of France.

These various findings enabled the tool to be calibrated in these new regions, and made it possible to apply weightings to the effectiveness scores. Evaluation of the tool shows fairly satisfactory results for Hauts-de-France and Ile-de-France, but less so for Midi-Pyrénées (Figure 9). The latter does not necessarily reflect a poor calibration of the tool, as the responses to the surveys were low. In the end, the tool will need to be further developed before it is operational. To do this, it will be necessary to carry out additional surveys to consolidate the results and evaluate the tool independently. The importance of having an independent dataset is all the greater given that the strong development of thistle observed in 2021, the year of the survey used to calibrate ODERA perennials, has certainly had a significant impact on the responses obtained. Nevertheless, these initial results are very promising and warrant further work.

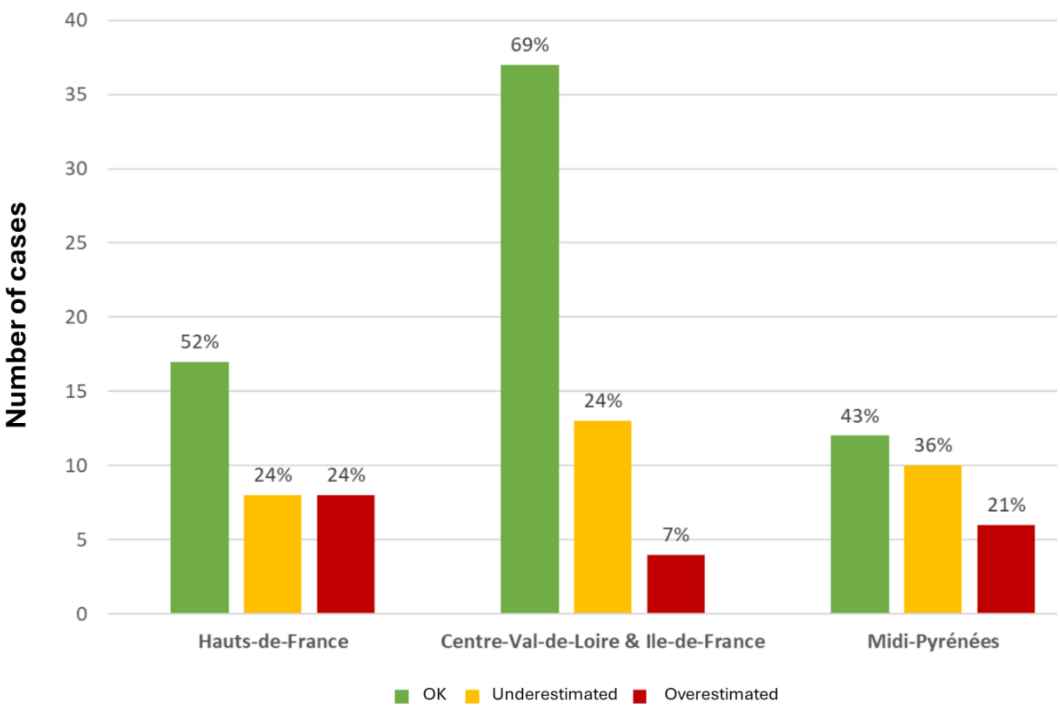

Figure 9 Evaluation of ODERA based on survey responses after parameterisation. The number of cases represents the number of survey results that were compared with the results obtained with ODERA perennials. The "OK" situations (left histogram) correspond to situations where ODERA Vivace was able to predict the evolution of thistle observed by the practitioners in the calibration database. In yellow (middle histogram) are represented the situations where the evolution was underestimated and in red (right histograms) the situations where it was overestimated.

6. Co-design workshops to develop dock and thistle management strategies

6.1 The method

The aim of this work was to capitalise on the knowledge acquired and the expertise of practitioners to improve the control of thistle and dock by co-constructing management solutions. The workshops resulted in proposals for locally adapted thistle and dock management strategies, as well as a list of available levers. Initially, 3 workshops were planned for the duration of the project, to provide input for the other tasks relating to trials under controlled conditions and *in situ,* but the project encountered various organisational problems and the workshops were held late. Nevertheless, there are many advantages to this approach. They are detailed in the guide to co-design workshops developed as part of the Innovative Cropping Systems Joint Technology Network (Reau *et al.*, 2021).

Aimed at sharing information between regional players, the workshop was designed to capture the scientific and empirical knowledge of participants in order to understand the rationale behind actions to control thistle and dock. To do this, the partners leading the workshops were asked to review the practices of the farmers present, to present the latest knowledge on the biology of the weed and known management techniques (including the results of the project). The discussions that took place were intended to lead to regionalised lists of management levers (both known and innovative), with the emphasis on the underlying agronomic rationale. In order to apply these management levers and build an overall strategy to be explored, it was also proposed either to opt for discussions based on the adaptation of existing rotation(s) or to build prototype rotations. A guide has been created to help workshop leaders set up their workshops, containing tools to help build the day, as well as presentation materials based on the literature on thistle and dock.

The 3 workshops were held in three different geographical areas: 2 on dock (run by BioBourgogne and the chambers of Tarn (81) and Tarn-et-Garonne (82)) and one on thistle (run by the Lycée de La

Saussaye) (Figure 10). However, the partners highlighted a number of methodological concerns which led to the decision to set up a single workshop per region. These workshops require a considerable amount of preparation time, and it is difficult to bring farmers together even at times when they are most available. On top of this, the workshops took place at the height of the COVID period, which made them even more complex to run. The results of the discussions were also difficult to transcribe: despite the richness of the discussions, it proved difficult to add value to them because of the very many elements of the discussions that were brought forward. On the other hand, the discussions did provide a lot of food for thought, both in terms of management levers that had not been dealt with much in the other parts of the project and in terms of avenues for further research.

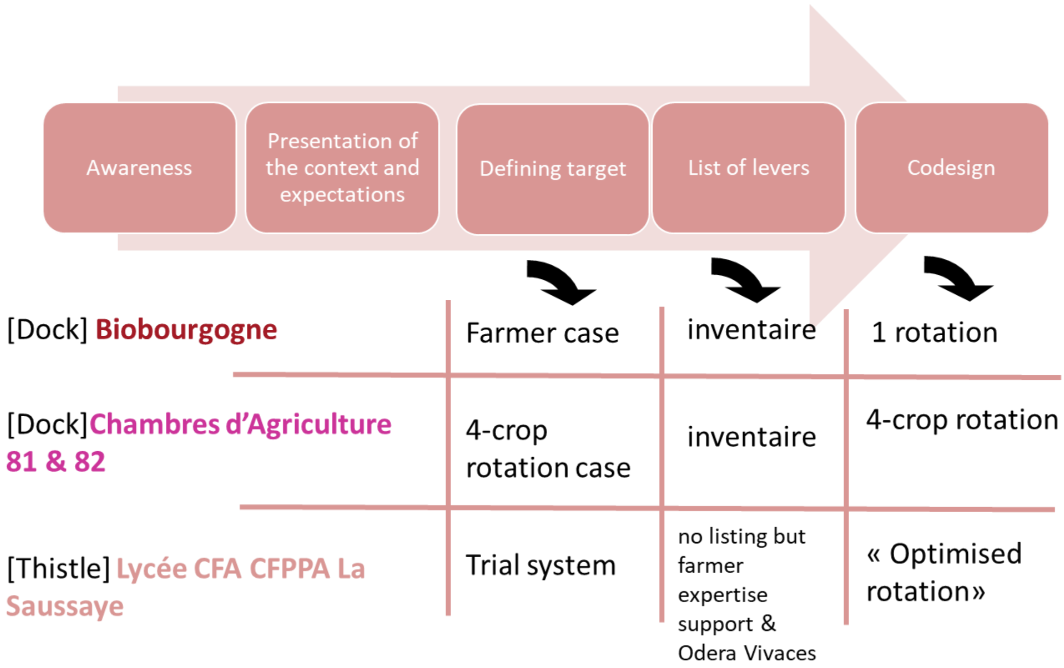

Figure 10 Diagram summarising the stages in the co-design workshops.

6.2 Summary of thistle and dock workshops

The workshops resulted in a list of levers that can be used to build systems/rotations to contain dock (Table 2). Several levers were identified in common by the two groups: maintaining soil cover, the choice of competitive/allopathic species, and the conditions for using tools. These are generic levers that can be applied to all situations, with a few local adaptations, such as in the south-west where stubble ploughing is more effective in the spring. To some extent, control of the environment in which dock grows was noted in both workshops, with fertilisation adjusted on the one hand and soil properties adjusted on the other (limiting compaction, pH changes, etc.). It should be noted that the choice of less demanding crops is linked to the fertilisation reduction strategy. One aspect that was not worked on during the project came up during the discussions, namely the quality of seed sorting. Other levers discussed in the Bio Bourgogne workshop included the possibility of mowing/planting, an interesting lever to investigate for dock control.

As the CAPABLE project focuses on arable farming, production techniques linked to livestock systems have not been studied. Similarly, exporting biomass to a methaniser could be a solution. In fact, dock biomass and seeds could become less viable after anaerobic digestion. In addition to the list of levers identified in the workshops, a number of innovative strategies have been identified, such as using dock as food for humans and animals, using robots/drones for management and biological control.

	Biobourbogne	Chambre d'agriculture 81 & 82
Competition	Maintains soil cover	Maintains soil cover
	Choice of allelopathic/competitive species	Choice of allelopathic/competitive species
	Rotation: duration/diversification	Choose species from the same family
	Crop mixtures	Avoid spring crops and certain cover crops
		Choosing low-demand crops
Weed control	Manual removal	Manual removal
	Choosing the optimum intervention period	Choice of passage period (spring)
	Grazing	Choosing the right tool/tool combination
	Swathing	Stubble plough before sowing wheat
	Weed control window in the rotation	Take action as soon as possible
	Tilled set-aside	
Prevention	Modifying fertility	Adapting fertilisation strategy
	Tool cleaning	Easy sorting of the main crop
	Seed Quality	Seed Quality
	Methanisation/composting	

Table 2 Table showing the levers that can be used to manage dock and that were identified in the co-design workshops**.**

The rotations developed in the workshops led to different strategies: in the case of the Bio Bourgogne workshop, a long rotation was proposed incorporating a wide variety of crops with two years' alfalfa. In south-west France, the workshop came up with two short 4-year rotations, one irrigated and the other dry. It was suggested that, as in the long rotation, soil cover should be maintained as much as possible, with a cover crop planted in the cereal. Hoe crops (soya, maize, sunflower) and the development of intervention windows remain among the key elements in the construction of all the rotations. Weeds are included twice in rotations in the south-west.

The thistle workshop (co-organised by the Lycée de la Saussaye and Agro-transfert) resulted in optimised practices: the initial rotation was already well rated by ODERA Vivaces, so the aim was to add new management criteria specific to thistle. Among the changes proposed to the 10-year model rotation.

- A "cleaning" rotation head with an alfalfa field planted for 3 years
- Substitution of weeded crops for field-seeded crops (7 crops over 11 years compared with 4 crops over 10 years in the model)
- Using rapeseed regrowth instead of planting a cover crop
- More stifling crops
- Windows for repeated stubble ploughing at the end of the rotation rather than spread out over the rotation.

7. Conclusion and outlook

The project has enabled progress to be made on a number of points, leading to the formalisation of scientific and empirical knowledge about the management of dock and thistle. Having worked on two weeds at the same time has enabled us to benefit from the thoughts of all the project partners, and has also highlighted, through comparison, significant differences between the two perennials, particularly in terms of the issues of challenges: thistle tends to be considered less and less predominant by farmers over time, unlike dock. In addition, it was noted by the experimenting partners that there is an antagonism between thistle and dock management: in fact, it was sometimes observed that in thistle trials, dock increased and vice versa.

Knowledge of dock biology has been improved thanks to tests under controlled conditions, which have made it possible to validate, invalidate and objectify the knowledge gained from the literature and farmers' observations. On this last point, a comparison of the various surveys carried out shows that there is a need for further research into innovative management methods such as hoeing cereals. In terms of current knowledge of the management levers that can be used, the project's added value has been to highlight farmers' *preconceived ideas*, which are not necessarily true, and which can lead to poor decisions regarding their technical itineraries.

The results, which fell short of expectations in the systems trials (apart from the methodological problems encountered), tend to show the absence of a strategy with a radical effect on perennial populations. Nevertheless, the regressive evolution of thistle in the trials carried out is reassuring. This is not the case for dock, which could explain the difference in perception of management issues by growers during the surveys.

Looking ahead, it seems necessary to continue work on dock and thistle, with a number of points to watch out for:

- Propose system trials (a certain time step is required to see effects) but anticipate the risks involved in setting up system trials (in particular that the partners themselves are responsible for the interventions; a strict minimum duration for trials of 3 to 4 years).
- Taking account of the rest of the flora (risk of conflicting practices)
- A good knowledge of the development history of perennials or start monitoring the establishment of perennials on a historically healthy plot.
- Continue work on the regeneration capacity of perennials *in situ*
- Consideration of indicators for monitoring perennials

In fact, in retrospect, there will have been a lack of additional information to enable us to make a real judgement on the development of the thistle. The CAPABLE project focused on the number of regrowths, but a biomass indicator could also be relevant. Allometric approaches, if functional, could provide access to this information. With regard to the protocols, an analysis of the methodology used had not been planned, but the representativeness of the monitoring zone could be questioned in view of the heterogeneity observed in certain monitoring zones. On this point, work has nevertheless been carried out on the data from the Hourre site and on thistle monitoring (Gers) showing that the minimum area for characterising the zone is close to 1 m² (inferential statistics based on random selection). However, in other trials, the variance between monitoring frames was higher, so it cannot be ruled out that in some cases a larger monitoring area is required than those used in the project.

The calibration of the ODERA Vivaces tool in new regions has shown promising results. In order to produce a tool that can be used more widely than in the Hauts de France region, it will be necessary in future to complete the process by validating the tool with independent data sets.

Finally, the project partners emphasised at the end-of-project seminar that a great deal of knowledge is still lacking about the biology of the two weeds. In particular, the following gaps were identified:

- No hindsight on fertilisation practices and the risk of perennial development
- Study genotypes and see the impact on the biology of dock & thistle
- Knowledge of sugar storage/withdrawal cycles in thistles in particular to see if there are any differences between regions.

This knowledge, particularly of the storage/withdrawal conditions in thistles, would enable better management of practices (monitoring the sugar content of regrowth, etc.). Remote sensing tools could also be used to facilitate and extend the monitoring of perennials. On the first point, there is nevertheless an answer in the literature for thistle: a meta-analysis published in 2018 shows the absence of effect of fertilisation on the risk of thistle development (Davis *et al.,* 2018).

Ethics

The authors declare that the experiments were carried out in compliance with the applicable national regulations.

Declaration on the availability of data and models

The data supporting the results presented in this article are available on request from the author of the article.

Declaration on Generative Artificial Intelligence and Artificial Intelligence Assisted Technologies in the Drafting Process.

The authors used artificial intelligence in the translation process from French to English.

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All the authors mentioned were directly involved in the project. This article was written by Enguerrand Burel and reviewed by the co-authors.

Declaration of interest

The authors declare that they do not work for, advise, own shares in, or receive funds from any organisation that could benefit from this article, and declare no affiliation other than those listed at the beginning of the article.

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