



D4.2 *In silico* assessment of harmfulness of weeds for various scenarios (E*M) using the FLORSYS model



Document Summary

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Abstract

Weeds are considered to be the most damaging pest in arable crops and a major lock-in for pesticide reduction. In this context, intercropping – several species grown in the same field for a significant part of their growing periods – is a key non-chemical lever for weed control because it leaves less space and fewer resources (light, nitrogen, water...) for weeds. The objective of the present work was thus to **evaluate the contribution of intercropping to weed management and how to optimise intercropping for weed management**. As the many objectives, factors and scales are next to impossible to juggle in field experiments or field networks, a simulation model was used to run 4 studies to

- identify ideal varieties for pea (*Pisum sativum* L.) – wheat (*Triticum aestivum* L.) intercropping, i.e., the key variety parameters and their combinaisons that maximise crop production and weed control in pea. In summary, a high pea yield in weedy intercrops required a pea variety with a high yield potential combined with a weed-suppressive wheat variety and weed-preventive management.
- optimise species combinations and proportions and sowing patterns for weed management in bi-specific cereal–legume intercrops with unlimiting soil nitrogen availability. In summary, legumes benefitted more from intercropping than cereals in terms of weed suppression, and balanced designs (equal cereal–legume proportions or alternating rows) reconciled legume and cereal production.
- assess how soil nitrogen availability influenced cereal–legume–weed interactions in these intercrops. In summary, with limiting soil nitrogen, intercropping only reduces cereal yields compared to sole crops and intercropping reduced weed-caused yield losses even more than with unlimiting nitrogen.
- evaluate a diverse range of intercrops and regions and to identify the key technical and biological drivers of intercropping success. The results were organized into advice tables showing the optimal choices for intercrop management variables.

Finally, the results of the first two simulation studies were organized into a prototype of a decision support system called DECIFLORMIX, aiming to evaluate the impact of cereal–legume intercrops on weeds and the consequences for crop production. Several scientific papers are in preparation (2), in revision (1) or published (1), together with 8 presentations at national and international conferences.

Some of the studies were initiated during a previous project, i.e., European Union's Horizon 2020 Research and innovation programme ReMIX (N 727217). The funds of three French projects also contributed to the present deliverable, i.e., ANR PPR SPECIFICS (ANR-20-PCPA-0008), ANR PPR MoBiDiv (ANR-20-PCA-0006) and COPRAA funded by the Office Français de la Biodiversité (OFB). The approaches used here will now be used in a new project targeting crop ideotypes and intercropping, i.e., the PEPR SV DIALOG, which focuses on camelina–lentil intercrops.



1. The project in numbers

1.1 Human resources

The scientific group was led by Nathalie Colbach (T4.4 leader) and consisted of two permanent researches (Nathalie Colbach, Delphine Moreau) and two successive fixed-term engineers (Pierre Lebreton, Aurélie Baquet), all from the INRAE Agroecology team in Dijon. Other colleagues provided expertise on specific questions, e.g. Judith Burstin on pea varieties, Jean Villerd on machine learning (both from INRAE Agroecology Dijon), Eric Justes (CIRAD) as well as Laurent Bedoussac and Lionel Alletto (INRAE Agir Toulouse) on intercrop design and management.

1.2 Work stages and links with other projects

The deliverable was based on five successive studies carried out throughout the IntercropValues project. Some of these were initiated during our previous EU project on intercrops, i.e., European Union's Horizon 2020 Research and innovation programme ReMIX (N 727217). In addition, three French projects also partially included questions on intercrops and their funds contributed to the present deliverable:

- ANR PPR SPECIFICS (ANR-20-PCPA-0008)
- ANR PPR MoBiDiv (ANR-20-PCA-0006)
- COPRAA funded by the Office Français de la Biodiversité (OFB)

1.3 Publications

Participants of the IntercropValues projects are in **bold**, with PdD students and fixed-term hires funded by IntercropValues in **bold blue**.

1.3.1 Scientific publications

Lebreton P., Bedoussac L., Bonnet C., Journet E.-P., Justes E. & Colbach N. (2024) Optimal species proportions, traits and sowing patterns for agroecological weed management in legume-cereal intercrops. *European Journal of Agronomy* 159, 127266, <https://doi.org/10.1016/j.eja.2024.127266> (open access) (section 5)

The following papers are still in revision

Colbach N., Burstin J. & Moreau D. (in revision) Which pea traits for agroecological weed management in pea-wheat intercrops. A simulation study. *European Journal of Agronomy* (section 4)

The following papers are still in preparation

- **Baquet** et al (in prep) Results of section 6
- **Colbach** et al (in prep) Results of section 7

1.3.2 Farming and other journals

Colbach N., Burstin J. & Moreau D. (2025) Identification d'idéotypes variétaux pour la gestion des adventices : exemple du pois associé au blé. *Innovations Agronomiques* 01, 60-73. <https://dx.doi.org/10.17180/ciag-2025-vol101-art06>

Lebreton P., Bedoussac L., Bonnet C., Journet E.-P., Justes E. & Colbach N. (2025) Motifs de semis, traits et proportions d'espèces pour la gestion agroécologique des adventices dans les associations légumineuse-céréale. *Innovations Agronomiques* 101, 74-84 (doi.org/10.17180/ciag-2025-vol101-art07)

Colbach N., Burstin J., Moreau D. (2024) Pois/blé et adventices : quels idéotypes de pois ? *Phytoma* 772, 9-12 <https://hal.inrae.fr/hal-04797868>

Lebreton P., Bedoussac L., Bonnet C., Journet E.-P., Justes E. & Colbach N. (2023) Gestion des adventices : L'association céréale et légumineuse à l'essai. *Phytoma* 769-770, 8-12. <https://hal.inrae.fr/hal-04483190>

1.3.3 National and International Conferences

Mix4Agroecology Conference, Paris-Saclay (France), 7-9 Oct 2026

- **Baquet, A., Moreau, D., Bedoussac, L., Alletto, L., Justes, E., Colbach, N. (2026)** Nitrogen stress makes legumes more competitive against weeds in intercrops. In: Mix4Agroecology Conference, Paris-Saclay (France), 7-9 Oct 2026,
- **Colbach, N., Baquet, A., Cavan, N., Cochard, L., Cournault, Q., Lebreton, P., Perthame, L., Queyrel, W., Villerd, J., Moreau, D. (2026)** Mixing knowledge and disciplines into a mechanistic model for designing crop mixtures for agroecological weed management In: Mix4Agroecology Conference, Paris-Saclay (France), 7-9 Oct 2026 (invited keynote)
- **Colbach, N., Cournault, Q., Perthame, L., Villerd, J., Moreau, D. (2026)** FLORSYS - a 3D individual-based model to investigate biological weed regulation in crop and variety mixtures. In: Mix4Agroecology Conference, Paris-Saclay (France), 7-9 Oct 2026

3rd International Crop Modelling Symposium (iCROP2026), Florence, Italy, 2-4 February 2026

- **Colbach N., Angevin F., Baquet A., Cavan N., Colas F., Cordeau S., Cournault Q., Delachapelle Q., Deytieux V., Flament M., Lebreton P., Lefeuvre T., Maillot T., Mosa B., Omon B., Perronne R., Queyrel W., Ripoche A., Skorupinski S., Stefan L., Viaud P., Villerd J. & Moreau D. (2026)** FLORSYS: A mechanistic model bridging scientists, advisors and farmers for designing agroecological weed management. In: 3rd International Crop Modelling Symposium (iCROP2026), Florence, Italy, 2-4 February 2026, (oral)

8th International Farming System Design Conference. Palaiseau, France, 25-29 Aug 2025

- **Colbach N., Angevin F., Baquet A., Cavan N., Colas F., Cordeau S., Cournault Q., Delachapelle Q., Deytieux V., Flament M., Lebreton P., Lefeuvre T., Maillot T., Mosa B., Omon B., Perronne R., Queyrel W., Ripoche A., Skorupinski S., Stefan L., Viaud P., Villerd J. & Moreau D. (2025)** FLORSYS: A mechanistic model bridging scientists, advisors and farmers in order to design agroecological

weed management strategies. In: Proceedings of 8th International Farming System Design Conference. Palaiseau, France, 25-29 Aug 2025, (oral)

20th EWRS Symposium. Lleida (Catalonia, Spain), 1-4 July 2025

- **Colbach N.,** Burstin J. & **Moreau D. (2025)** Which pea traits for agroecological weed management in pea-wheat intercrops. In: Proceedings of Proceedings 20th EWRS Symposium. Lleida (Catalonia, Spain), 1-4 July 2025, <https://hal.inrae.fr/hal-05295352v1> (**keynote**)

18th Congress of the European Society for Agronomy, Rennes, France, 26-30 Aug 2024

- **Colbach, N.,** Burstin, J., and **Moreau, D. (2024)** Which pea traits for agroecological weed management in pea-wheat intercrops. In: 18th Congress of the European Society for Agronomy, Rennes, France, 26-30 Aug 2024, 327-329 (oral)
<https://hal.inrae.fr/hal-04894723>
<https://events.institut-agro.fr/event/1/contributions/218/>
- **Lebreton, P., Bedoussac, L.,** Bonnet, C., Journet, E.-P., **Justes, E., Colbach, N. (2024)** Effect of sowing patterns and species proportions of cereal-legume intercrops on weed control. In: 18th Congress of the European Society for Agronomy, Rennes, France, 26-30 Aug 2024, 330-331 (oral)
<https://hal.inrae.fr/hal-04955949>
<https://events.institut-agro.fr/event/1/contributions/205/>

In the following sections, references to publications produced during the IntercropValues project are highlighted in colour (e.g., **Author, Year**).



2. Context and objectives

Weeds are considered to be the most damaging pest in arable crops and a major lock-in for pesticide reduction. In this context, intercropping – several species grown in the same field for a significant part of their growing periods – is a key non-chemical lever for weed control because it leaves less space and fewer resources (light, nitrogen, water...) for weeds. But weeds are also essential for biodiversity as they contribute to feeding birds, pollinators and other insects. The objective of the present work was thus to **evaluate the contribution of intercropping to weed management and how to optimise intercropping for weed management**.

Weed floras consist of dozens and sometimes hundreds of different species, whose presence and effects depend on regional conditions and management practices. Because weed seeds survive for several years in the soil, management decisions taken in a given year affect weed dynamics and impacts for several years to come. Consequently, the **effect of intercropping on weeds must be assessed in interaction with other management practices, at the multiannual scale and in different environmental conditions**. As these many objectives, factors and scales are next to impossible to juggle in field experiments or field networks, a **simulation model was used** to investigate the following questions:

- How to **optimise varieties for weed management in intercropping**, using wheat–pea intercropping as case study?
- How to **optimise intercropping composition**, i.e. which are the optimal species combinations and proportions and sowing patterns for weed management?
- How does reduced **nitrogen availability modify cereal–legume–weed interactions** in intercropping?
- **Generalize** the conclusions to more types of intercropping and regions.
- Develop a **prototype of a decision support system** to accompany intercrop management.

The simulation model used here was FLORSYS, a mechanistic individual-based 3D model which simulates daily crop–weed seed and plant dynamics over years, from the cropping system and pedoclimate (Colbach *et al.*, 2021). It was chosen because it is to date the only model parameterized for most arable crops and weeds, including all cultural operations and predicting not only yields and weed harmfulness for crop production but also weed contribution to biodiversity.

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3. Material and methods

3.1 Principle of the simulation studies

The general principle was to simulate existing and virtual intercrops and varieties with different pedoclimates, weed floras and arable cropping systems, using the FLORSYS model. Intercrop performance was evaluated in terms of crop production, weed harmfulness for crop production and weed contribution to biodiversity. Only annual weeds were considered in the present studies.

3.2 The FLORSYS model

FLORSYS is a virtual field on which cropping systems can be experimented, producing a large range of virtual measurements of crop, weed and environmental state variables (Colbach *et al.*, 2021). Model inputs comprise all cultural operations in detail over several years, daily climate data (past or future), soil properties and a weed species pool (Figure 1). The model represents each crop and weed plant individually in simple volumes (cylinders and spilled cones), which grow or shrink based on photosynthesis, respiration and damage (frost, chemical, mechanical). Plants compete for light, water and nitrogen, depending on species properties, plant morphology and neighbour plants. Seed death, dormancy, germination and preemergent growth depend on species, seed depth and soil state variables. Functions are the same for all species, only parameter values vary with species. In addition to daily state variables, FLORSYS predicts annual indicators of crop production, weed harmfulness for crop production and weed contribution to biodiversity.

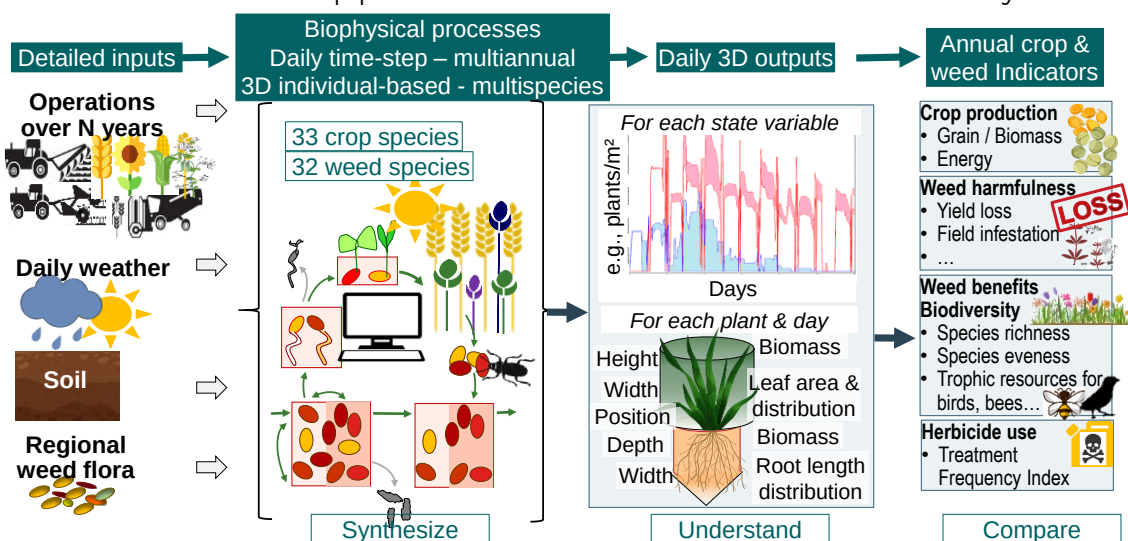


Figure 1. Summary of the FLORSYS simulation model, showing inputs, daily simulated states of crops and weeds, daily outputs and annual performance indicators (Colbach *et al.*, 2021)

FLORSYS allows the user the switch on or shut off different submodels, depending on the simulation plan. The FLORSYS version used in most the studies presented here considered that soil resources (water, nitrogen) were unlimited after plant emergence but included the effect of water stress (resulting from climate and plant uptake) on seed germination and pre-emergent growth. Plants in the canopy, whether crop-weed or crop-crop-weed canopies thus only competed for light, which is usually the resource for which crops and weeds compete in arable temperate cropping systems (Colbach *et al.*, 2023). This FLORSYS version is approx. ten times faster than the complete version, which allows testing a greater number of scenarios.

Only section 6 used a different FLORSYS version, which switched on the submodels for nitrogen cycle in the soil, nitrogen uptake by plants, nitrogen fixation by legumes and impact of nitrogen stress on photosynthesis and plant morphology (Moreau *et al.*, 2021; Perthame *et al.*, 2022). This version was developed in the previous EU project on intercropping, i.e., ReMIX.

3.3 Simulation plans

The scenarios including the intercrops (or their pure-crop controls) were always run over 30 years to consider weed impacts on future crops. The scenarios were also repeated 10 times with different weather series from their region of origin, using the same 10 series for each scenario of the region. This resulted in a complete factorial experimental design for each region, with the scenarios as experimental treatment and the weather series as blocks. The simulation duration and number of weather repetition were reduced to 12 years and 5 repetitions in one study testing several thousand scenarios to reduce simulation time.

The simulation plan combining scenarios $\times$ weather repetitions was always run twice, once without any weeds to estimate potential weed-free yields, and once again to obtain weed-infested yields. Crop yield loss was then calculated as the relative yield difference of the two simulation series. The weed-free simulation runs allowed better estimation of potential yields and yield losses, which tend to be underestimated in field experiments as it is next to impossible to ensure pest-free controls or homogeneous weed infestations (Colbach *et al.*, 2020).

3.4 Statistics

A large range of statistical methods was used to analyse the data, depending on the question and the experimental plan. In single-region studies testing a small number of factors in a complete factorial block design, analyses of variance were used to compare scenarios (e.g., section 5). In studies with huge numbers of scenarios, classification and regression trees (CARTs) and/or random forests were used to identify key practices or crop traits (e.g., section 4). A CART predicts a continuous response variable (e.g., crop yield, weed-caused yield loss) from a set of discrete or continuous predictors (e.g., proportion of legumes in intercrop, tillage frequency in rotation, species base temperature). The data set is recursively split into two subsets along a threshold value of a predictor in order to maximize the difference between subsets. Random forests are a combination of CARTs.

To identify weed traits selected by cropping practices or driving weed impacts, RLQ and fourth-corner analyses were used. These methods establish Pearson correlation coefficients between cropping techniques or weed impacts (R matrix) and species traits (Q matrix) via weed species densities (L matrix), using Correspondence Analyses, Principal Component Analyses, and permutation tests (Chessel *et al.*, 2004).



4. Ideotypes

4.1 Objective

The objective was to identify, depending on the type of cropping system and weed flora, (1) the key pea parameters that drive crop production and weed control in pea (*Pisum sativum* L.) when intercropped with wheat (*Triticum aestivum* L.), (2) optimal combinations of pea and wheat parameter values as well as intercrop management techniques (tillage, sowing date and density, interrow width...), to maximise these goals (Colbach *et al.*, in revision).

4.2 Tested varieties and scenarios

The simulation approach was developed in a previous work on pea varieties in sole pea (Colbach *et al.*, 2022) and adapted here to pea–wheat intercropping. At the time of the study (Colbach *et al.*, in revision), the FLORSYS model was parameterized for seven pea varieties (among which five winter varieties) and three winter wheat varieties. To extend the range of tested varieties, virtual varieties (5 pea and 10 wheat) were created by randomly combining variety-parameter values according to a Latin Hypercube Sampling (LHS) plan, respecting parameter ranges and correlations observed in the actual varieties.

Then, a global sensitivity analysis was run, using another LHS plan to combine pea and wheat varieties, crop rotations (ranging from 2 to 6 years) and management techniques in nine contrasting situations (e.g., conventional vs organic, no-till, type of weed flora). The LHS plan resulted in 3600 cropping systems, all including pea–wheat intercrops once in their rotation. These systems were simulated another four times, replacing intercrop with either sole pea or sole wheat which were sown either at the same densities as in the intercrops, or at the standard sole-crop densities. The total $5 \times 3600 = 18000$ systems were simulated over 12 years and repeated with 5 weather series.

4.3 Key results

In wheat–pea intercrops, intercrop management and the pea variety were more influential than the wheat variety for yields. Yield loss due to weeds and field infestation depended mostly on the management of intercrops and other crops of the rotation, with little effect of variety parameters.

Because of wheat–weed competition, intercropping reduced pea yield loss due to weeds (by 30% for the least weed-tolerant varieties, e.g. Enduro) and field infestation (by 14% for the least weed-suppressive varieties, e.g., 886-1) (Figure 2). But because of wheat–pea competition, pea yield in weed-free intercrops decreased by 28 to 81% depending on the pea variety (average 55%) compared with sole pea crops sown at the same pea density.

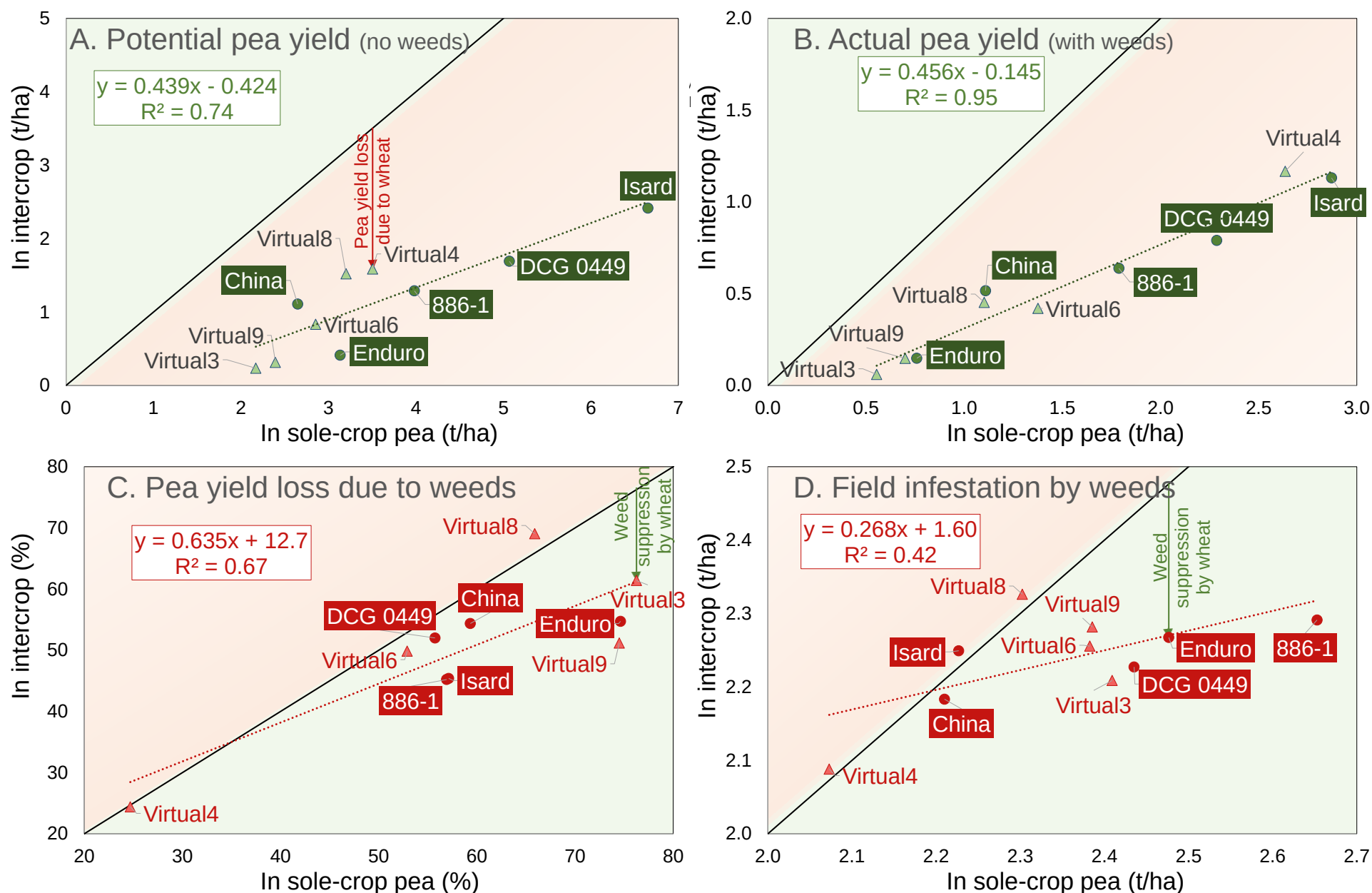


Figure 2. Pea variety ranking in pea-wheat intercroppings and in sole-crop pea. A. Potential (weed-free) pea yield, B. Actual (weed-infested) pea yield, C. Pea yield loss due to weeds, D. Field infestation by weeds. Expected Marginal Means after analyses of variance of yields, yield losses and field infestations from years with intercroppings from the 3600 cropping systems $\times$ 5 weather repetitions simulated with FLORISys over 12 years in the intercropping simulation experiment and from years with sole-crop pea from the control simulation experiment with the same sowing densities as in the intercrop. Broken lines show linear regressions fitted to data points, continuous lines are $y=x$. Areas shaded in green (respectively red) show benefits (respectively detriments) due to intercropping (taken from Colbach et al., in revision)

Table 1 summarizes a series of pea ideotypes (i.e., optimal combinations of pea parameter values) that were selected for different objectives (maximise potential yield, actual yield in the presence of weeds or weed tolerance). They were either generalists (the best ideotype regardless of the intercropped wheat variety or the intercropping design) or adapted to particular wheat varieties and/or intercropping designs.

This analysis highlighted that:

- Key pea parameters that drive potential (weed-free) yield and competitiveness against weeds (e.g., biomass allocation to leaves until full maturity, increased plant width per unit biomass when shaded, frost tolerance). These are pointers for breeding varieties that regulate weeds in intercrops by better competing for light;
- Rules to guide farmers to choose the best pea variety, depending on the production goal, the intercropped wheat variety and the intercropping design.
- Pea and/or intercrop yields as well as weed suppression improved when pea ideotypes were tailored to intercropped wheat varieties (e.g., iPeaYield2 produced better results when intercropped with wheat ideotype iWC) and/or intercropping designs (e.g., iPeaYield2 produced better results in additive designs).
- The best pea ideotypes had a small root system and prioritised above-ground plant growth and light interception
- Contrasting pea ideotypes could achieve similar performances, if the associated wheat varieties and/or intercropping design were optimised (e.g., iPeaYield3 vs iPeaYield2).

Intercrop sowing densities were analysed, showing that:

- For pea yield:
 - Additive designs (relative sowing density > 1.1) did not systematically result in higher yields than substitutive design ([0.9, 1.1]) or incomplete designs (< 0.9).
 - Pea yields increased up to a total relative sowing density of 1.33 seeds·m⁻²/seeds·m⁻², additive designs with a higher density reduced pea yields below yields of substitutive and even incomplete designs.
 - In additive designs, the best pea yield was reached around pea and wheat sowing densities of 0.64 seeds·m⁻²/seeds·m⁻². In other designs, pea sowing densities showed be as high as possible and wheat densities needed to be low (~0.32 and 0.14 seeds·m⁻²/seeds·m⁻² in incomplete and substitutive designs, respectively).
- For wheat yield:
 - Wheat yield, which consistently increased with total relative sowing density, with little increase above 0.90 seeds·m⁻²/seeds·m⁻² approx.
 - The best wheat yield was reached with an additive design, with a wheat density of 1.13 seeds·m⁻²/seeds·m⁻² and a a pea sowing density of 0.30 seeds·m⁻²/seeds·m⁻².

In addition, the key intercrop management techniques driving yield, weed tolerance and weed suppression in pea-wheat intercrop were identified and summarized in an advice table, including th reasons for their success or failure (Table 2).

Table 1. The pea ideotypes and pea varieties aiming to maximize potential yields (iPeaPot), actual yields (iPeaYield1 to 4) and tolerance to weeds (iPeaTol) in pea-wheat intercrops, depending on intercropped wheat varieties and/or intercropping design, identified with classification and regression trees. Rules in sections A-D in green improve yield and weed suppression compared to some (standard) or all (bold) existing pea varieties used here, those in red show trade-offs, i.e., rules that potentially decrease performance and result from correlations with beneficial characteristics and/or have no influence in the tested cropping systems; white cells show rules respected by current varieties. Empty cells show non-significant variety parameters. Cells in section F are coloured from red (lowest pea or wheat yield, highest infestation) through yellow to green (vice-versa) (based on Colbach *et al.*, in revision)

			iPeaPot	iPeaTol	IPeaYield	IPeaYield2			IPeaYield3		iPeaYield4
Adapted to weeds?			No	Yes	Yes	Yes			Yes		Yes
Which wheat varieties?			All	All	All	All	iWC	iWA2	iWC2	iWA	iWS
Which intercropping designs?			All	ALI	All	All	All	Additive	All	Additive	Substitutive
A. Pre-emergent features: emerge earlier and better than weeds&wheat											
Seed dormancy				More					Similar		
Germination onset				Earlier					Similar		
Pre-emergent root growth speed (reduces dro					Slower	Faster			Faster		Faster
Pre-emergent seedling loss due to seed depth				Less					Similar		
Pre-emergent seedling loss due to soil compac				More					Similar		
B. Above-ground plant morphology: increase light interception & shading of neighbours											
Post-emergent growth					Faster	Slower			Faster		
Variability in post-emergent leaf area					Similar	Smaller			Smaller		Smaller
Maximum plant height				Smaller	Smaller	Taller			Smaller		
Plant height homogeneity	reproduction	Better							Better		
Plant width homogeneity	vegetative	Better							Better		Better
Plant width per biomass	vegetative	Narrower							Narrower		
	reproduction				Similar	Wider			Wider		Wider
%biomass allocated to leaves	emergence		Leafier	Similar	Less			Less		Less	
	reproduction	More		Similar	More			More		More	
Leaf area distribution along plant height	emergence			Lower	Higher			Lower		Higher	
	vegetative			Lower	Higher			Higher		Higher	
C. Shading response: avoid shading by neighbours and increase shading to neighbours											
Effect of shade on	Plant height per biomass	emergence	Smaller		Smaller	Taller			Smaller		Smaller
	Plant width per biomass	reproduction			Wider	Narrower			Wider		Narrower
	% biomass allocated to leaves	vegetative	More						More		More
		reproduction	More		More	Less			More		Less
	Leaf area per leaf biomass	emergence			Smaller	Larger			Smaller		Smaller
		reproduction	Smaller						Smaller		Smaller
	Leaf area distribution along plant height	vegetative	Higher	Lower	Higher	Lower			Higher		
reproduction		Higher	Similar	Lower			Lower		Lower		
D. Root system prioritize aboveground structures for light intercection and leave less water for wheat&weed germination&emerger											
Root-system width (maximum)			Narrower	Wider					Similar		
Root biomass distribution			Shallow		Shallow	Deeper			Shallow		
Root growth in compacted soil			Better		Better	Worse			Better		
E. Temperature sensitivies: reduce frost damage andimprove biomass production											
Frost sensitivity	reproduction		Lower								
Photosynthesis in warm conditions			Worse		Worse	Better			Worse		Better
F. Pea varieties answering to the rules											
Actual varieties			Isard		Isard	DCG0449			Isard		DCG0449
Virtual varieties				4	4						
G. Intercrop performance											
Pea yield			1.14	1.60	1.30	1.10	4.20	4.40	3.40	4.90	2.90
Potential pea yield			2.44	1.16	2.40	2.10	5.50	5.60	3.80	5.70	3.00
Wheat yield			1.69	1.00	1.60	1.90	0.60	0.60	2.20	1.30	0.60
Potential wheat yield			3.99	2.20	3.50	4.00	0.60	0.60	2.60	1.30	0.90
Field infestation (opposite of weed suppression)			2.22	2.10	2.30	2.40	1.10	1.00	0.90	0.50	0.90

Table 2. The key intercrop management techniques driving yield, weed tolerance and weed suppression in pea-wheat intercrop. The most influential techniques per indicator were selected based on relative variable importance predictor (VIP) summed over indicators in classification and regression trees. Probabilities ≥ 0.90 in green (an increase in technique values results in an increased indicator value) and red (an increase in technique values results in a decreased indicator value). Empty cells indicate that the techniques had no significant effect on the indicator, or cumulated VIP < 0.01 or probability of stable effect < 0.90 . For complete results, see (Colbach *et al.*, in revision)

Intercrop management technique		Unit	Simulated variation		Potential yield		Weedy yield or weed tolerance		Weed suppression	Total VIP	Reasons for effect (based on the analysis of simulated state variables)
			Min	Max	P	W	P	W			
Tillage											
Superficial tillage		operations per year	0	10			+			0.02	Reduces weed seed bank by triggering germination during summer fallow ("false seed bed"), kills weed plants before sowing
Tillage after 1 Nov		operations per year	0	10				+		0.03	More weed destruction and late sowing (see sowing date)
Time from last tillage to crop sowing		days	0	147			-	-	-	0.23	Leaves more time for weeds to reinfest the field after the last tillage operation cleaned out all weeds
Crop residue shredding operations		operations per year	0	4			+	+		0.04	Destroys weeds during summer fallow
Sowing											
Sowing date			01 Oct	30 Nov				+		0.07	Leaves more time for false seed bed techniques; shortens the time during which weeds can grow inside the crop
Proportion of pea rows in intercrop		rows/ rows	0.20	0.80			-			0.02	Pea plants occupy more space in field and leave less for companion wheat
Interrow width		cm	4	52			-	-	-	0.15	More competition between crop plants inside a given row, more light missed by crops
Crop species are sown in separate rows		yes (1) or no (0)	0	1	+	-				0.03	Pea suffers more from interspecies competition but wheat plants suffer more from intraspecies competition
Total sowing density vs sole crop density		seeds·m ² / seeds·m ²	0.06	4.89	+	+				0.03	More pea and wheat plants in field, intercepting more light and leaving less space and resources for weeds
Pea sowing density	vs pure pea	seeds·m ² / seeds·m ²	0.03	3.23	+	+			+	0.05	More pea plants and leaf area to produce pea biomass and shade weeds (but not on wheat)
Wheat sowing density	vs pure wheat	seeds·m ² / seeds·m ²	0.02	2.50	-	+	+			0.07	More wheat plants and leaf area to produce wheat biomass and shade weeds and companion pea
Other											
Multi-entry herbicides		number per year	0	4				+	+	0.01	Destroys weed plants (and more efficiently than herbicides entering only via either leaves, roots or meristem)
Anti-monocot herbicides		number per year	0	4					+	0.01	Fewer monocot weeds survive and compete with the crop
Anti-dicot herbicides		number per year	0	4					+	0.01	Fewer dicot weeds survive and compete with the crop
Mechanically weeded field area		m ² / m ²	0.00	1.00					+	0.02	More weeds are destroyed
Harvest date			06 Jun	15 Aug	+	+	+	+	-	0.76	Leaves more time for crop biomass accumulation BUT leaves more time for weeds to grow and reproduce

4.1 Conclusions and perspectives

The present pea-parameter rules provide guidelines for farmers to choose their pea varieties in cereal-legume intercrops and for breeders to screen existing germplasm collections and to identify traits for which the select during breeding. In summary, a high pea yield in weedy intercrops required a pea variety with a high yield potential combined with a weed-suppressive wheat variety and weed-preventive management. In addition, advice on optimal management practices were identified.

This type of work needs to be extended looking at other species and intercrops, pedoclimates and levels of soil resources.



5. Optimal intercropping composition

5.1 Objective

The objective of this study was to optimise species combinations and proportions and sowing patterns for weed management in bi-specific cereal-legume intercrops (Lebreton *et al.*, 2024a). The focus was on cereal-legume-weed competition for light.

5.2 Tested intercrops

This study simulated:

- seven species proportions for wheat (*Triticum aestivum* L.)–faba bean (*Vicia faba* L.) and barley (*Hordeum vulgare* L.)–pea (*Pisum sativum* L.) mixtures (hence "species-proportion design"),
- nine spatial sowing patterns for triticale (*Triticosecale*)–faba bean, durum wheat (*Triticum durum* Desf.)–faba bean and wheat–pea mixtures (hence "sowing-pattern design").

In both cases, mixtures were compared to their corresponding sole crops (controls), resulting in a total of 100 scenarios. Intercrops and controls were inserted into rotations and simulated over 30 years with weed, weather and soil data from Toulouse (South-Western France), using 10 weather repetitions. Weed management was organic-based or with reduced herbicide use. Soil resources (nitrogen, water) were non-limiting after plant emergence but soil water could be limiting during germination and pre-emergence growth.

5.3 Key results

Simulations showed that, in the absence of weeds, the yield per plant in intercrops varied from 13% of the sole-crop yield (pea intercropped with wheat in the species-proportion design) to 173% (triticale intercropped with faba bean in the sowing-pattern design). In other words, in the latter case, triticale greatly benefitted from intercropping (because the intercropped faba bean was less competitive than neighbouring triticale plants in the sole crop were) whereas in the former case, pea suffered from intercropping (because the intercropped wheat was much more competitive than neighbouring pea would have been).

In average, intercropping reduced weed-free yield per plant by 42% for legumes and had no effect for cereals. When weeds were included in the simulations, the average legume yield per plant decreased by only 24% compared to sole legumes, whereas the average cereal yield per plant decreased by 18%. In other words, the more competitive cereals protected legumes against weeds in intercrops but suffered more from weed competition than in sole cereals. Indeed, the weed biomass in intercrops was greater than or equal to that of the sole cereals, and less than that of the sole legumes (Figure 3.A and B). The intercrops that best controlled weeds were barley–pea and triticale–faba bean.

In presence of weeds, the spatial pattern alternating one cereal row with one legume row (50% cereal–50% legume) as well as the 67% cereal–33% legume and the 100% cereal–50% legume in the species-proportion design were those that both maximised yields of both legumes and cereals and minimised losses due to weeds (Figure 3.C and D). Additive designs were not more weed-suppressive than substitutive designs.

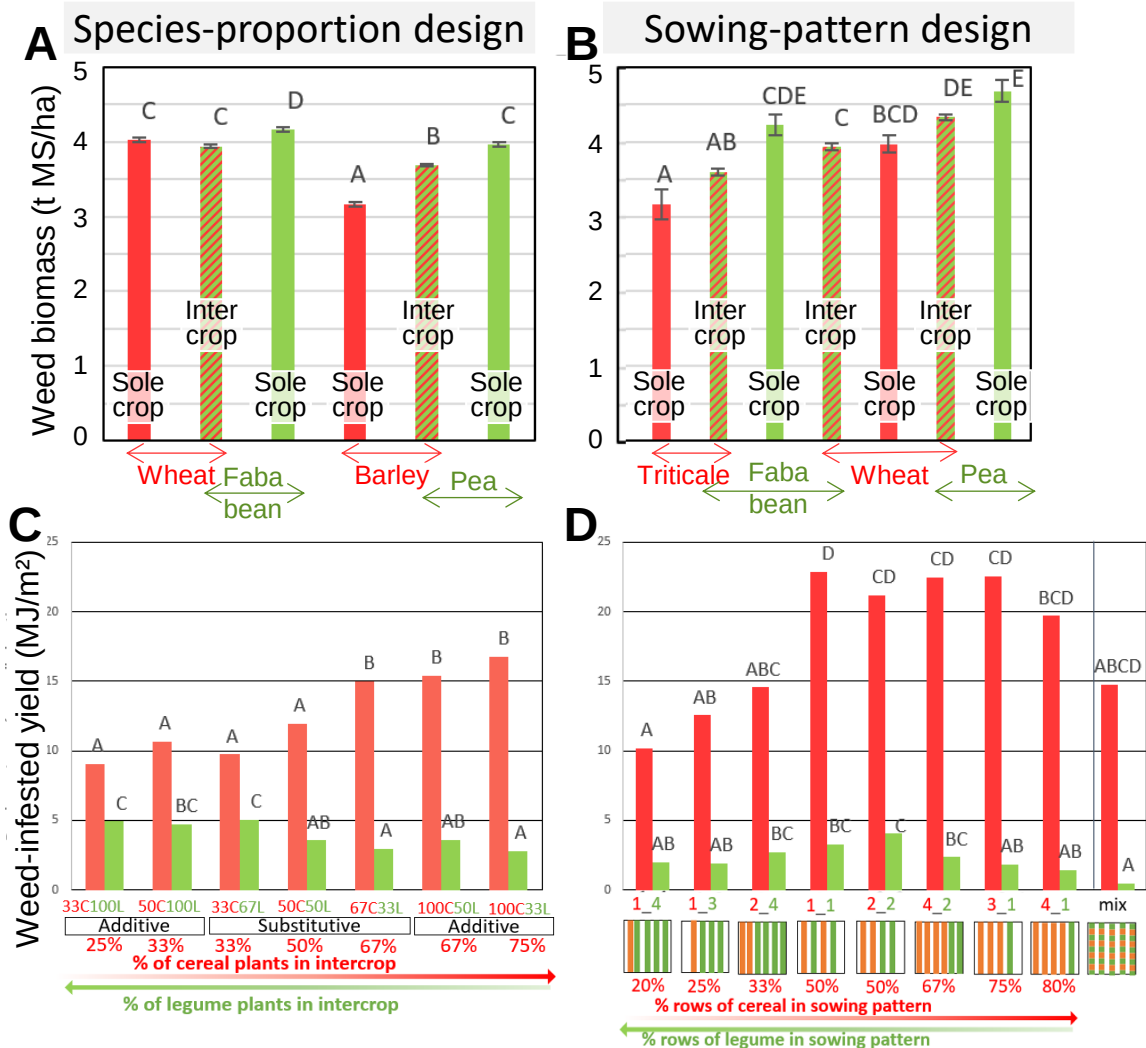


Figure 3. Effect of cereal–legume intercropping on weed suppression (A, B) and weed-infested yield (C, D) (Lebreton et al., 2024a). A and B show the effect of intercropping vs pure crops for different cereal and legume species combinations, in average over all species proportions (A) or sowing pattern (B). C and D show cereal (red) and legume (green) yields in intercrops depending on species proportions (C) or sowing patterns (D), in average over all species (taken from Lebreton et al., 2024b).

The comparison of the expected yields (based on species sowing densities and per-plant yields in pure-crop controls) to the actual yields in intercrops, further conclusions were drawn (Lebreton *et al.*, 2024a):

- Pea suffered more from cereal competition than faba bean, and wheat suffered more from legume competition than triticale.
- Legume yields were always better than expected in the presence of weeds in balanced designs (equal cereal–legume proportions or alternating rows)
- Cereal and legume yields were lower than expected for on-row mixtures compared to most row-sown patterns, particularly for less competitive species such as pea or wheat.

The analysis of intercrop traits (average trait values and variability in the intercrop, differences between species) showed that (Lebreton *et al.*, 2024a):

- Long crop growth and complementarity in height and leaf biomass drive intercrop yield.
- Early, high and homogeneous crop establishment is essential to suppress weeds.

5.4 Conclusion and Perspectives.

This study highlighted the value of intercropping for weed management, and identified sowing proportions and sowing patterns depending on the objectives being pursued. In the presence of weeds, legumes benefitted more from intercropping than cereals because legumes are less competitive against weeds. The study identified two future avenues of research:

- How to improve the competitiveness of the two least competitive species (i.e., pea and wheat)?
- Are the present conclusions also valid when soil resources (and particularly nitrogen) were limiting?



6. The impact of limited nitrogen availability

6.1 Objective

The previous study (Lebreton *et al.*, 2024a) (section 5) determined optimal species combinations and proportions and sowing patterns for weed management in bi-specific cereal–legume intercrops, with unlimiting soil resources. Here, the objective was to assess how soil nitrogen availability influenced cereal–legume–weed interactions in these intercrops.

6.2 Tested scenarios

The simulation plan used here was exactly the same as in section 5. But the latter used a FLORSYS version, which considered that soil resources were unlimiting, regardless of the cropping system (notably the nitrogen fertilization), soil or climate. Conversely, the present study used a different version, which includes submodels for nitrogen cycle in the soil, nitrogen uptake by plants, nitrogen fixation by legumes and impact of nitrogen stress on photosynthesis and plant morphology (Moreau *et al.*, 2021; Perthame *et al.*, 2022). The scenarios of section 5 were simulated three times in the present study:

- With the old FLORSYS version, considering that nitrogen was always non-limiting,
- With the new FLORSYS version and usual fertilization practices, resulting in various levels of nitrogen availability,
- With the new FLORSYS version and without nitrogen fertilization, resulting in low levels of nitrogen availability.

6.3 Results

In the absence of weeds, switching from unlimiting nitrogen to unfertilized plots with limiting nitrogen decreased yields in all crops, except in legumes whose yield remained stable in sole crops (●●■ on $y=x$ line in Figure 4.A and C) and even improved in intercrops with cereals (▲▲ above $y=x$ line).

With unlimiting nitrogen, all yields decreased when weeds were added to the simulations (lower x values in Figure 4.B vs. A). This decrease was the most extreme for soya (x divided by more than 100 for ■) and the smallest for mustard (similar x values for ■). In the presence of weeds, switching from unlimiting nitrogen to unfertilized plots favoured legumes even more (●▲▲●■ above the $y=x$ line in Figure 4.B), with nearly no weed-caused loss for pea and faba bean (similar y values for ●▲▲● in Figure 4.B vs. A). But some non-legumes such as maize (■ above $y=x$ line) and camelina (■ close to $y=x$ in Figure 4.B vs A) also had better weedy yields with limiting vs non-limiting nitrogen.

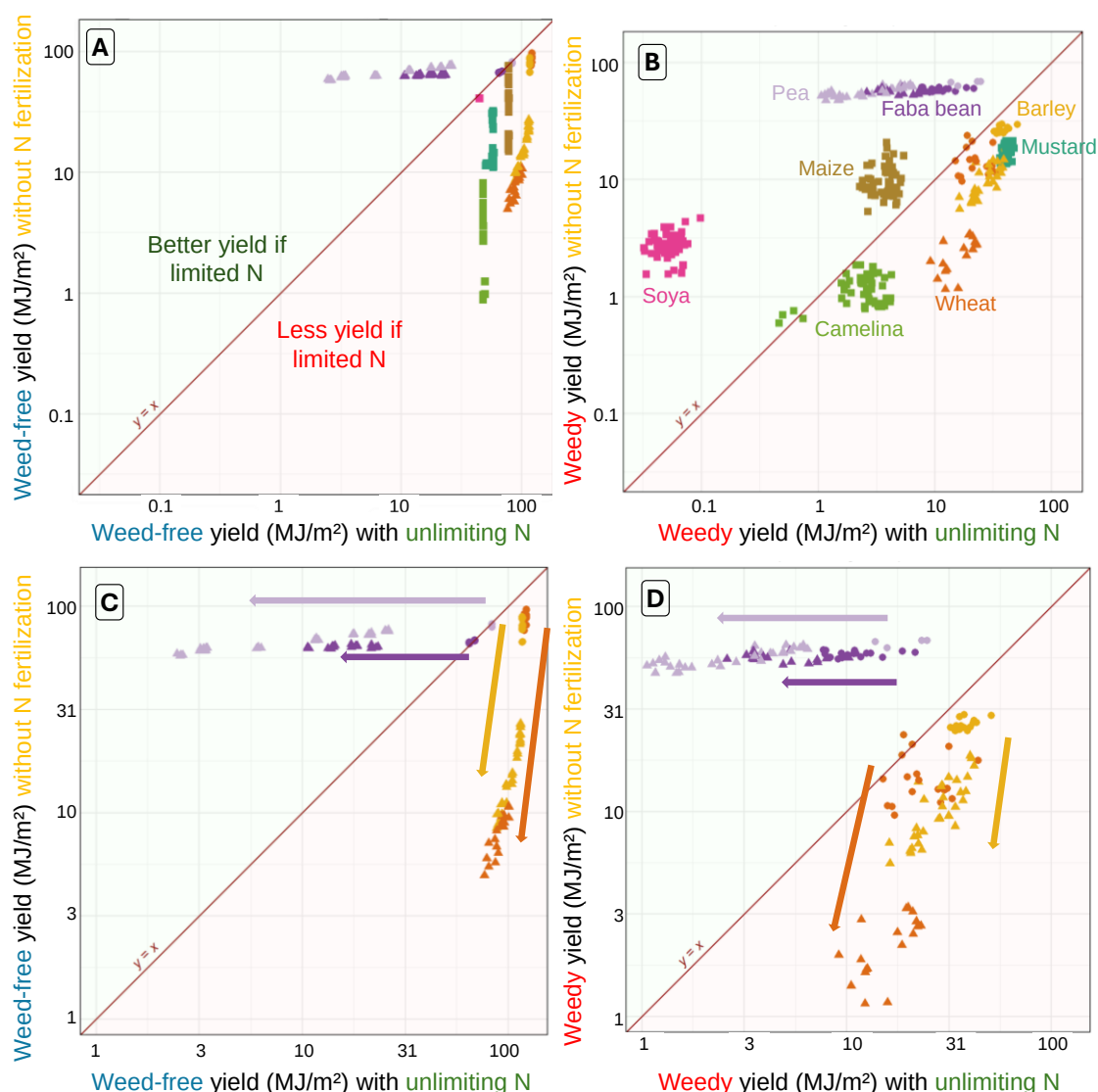


Figure 4. Effect of limiting soil nitrogen availability on crop yield in the absence (A, C) and presence (B, D) of weeds in sole crops (●) and intercrops (▲) depending on crop species (legumes ▲●▲●■, cereals ▲●▲●■, oilseed crops ■■). C and D focus on intercrops vs their sole-crop controls, with arrows showing the average variation in yields per species between control and intercrop (i.e., the yield decrease due to the lower sowing density and the presence of a companion crop). Intercrops were sown with varying legume vs cereal proportions; fields also differed in terms of fallow management (cover crop vs mouldboard ploughing)

In the absence of weeds, intercrops caused all species yields to drop (arrows in Figure 4.C) because individual species were usually sown at a lower density than in pure crops. The less competitive legumes such as pea saw their yields divided by up to 10 because of the competition from the stronger cereals. But this was only the case when nitrogen was unlimiting as only the x-values decreased in intercrops vs sole crops for legumes (▲ vs ●, ▲ vs ●). Conversely, cereal yields only decreased approx by 10% with unlimiting nitrogen but was divided by up to 100 in the absence of nitrogen fertilizer (▲ vs ● and ▲ vs ●).

The species yield decrease due to intercropping was much lower in the presence of weeds (less decrease in y and x values for ▲ vs ● in Figure 4.D vs C). In other words, intercropping reduced the weed-caused yield loss even more when nitrogen was limiting. This was particularly the case for legumes whose yield was only divided by up to 4 with limiting nitrogen. But the relative effects remained the same, i.e., legume yields only decreased in intercropping vs. sole crops when nitrogen was unlimiting whereas cereal yield mostly decreased in unfertilized fields.

6.4 Conclusion and Perspectives

The present simulation study showed that cereal-legume-weed interactions greatly change with soil nitrogen availability. In summary,

- when soil nitrogen is non-limiting and the cereal-legume-weed canopy only competes for light, then
 - o cereals and weeds outcompete legumes,
 - o intercropping reduces field infestation by weeds and weed-caused yield loss in legumes compared to sole legumes.
- when fields are unfertilized and soil nitrogen is limiting and the cereal-legume-weed canopy competes for both light and nitrogen, then
 - o some legumes outcompete cereals and weeds,
 - o intercropping does not affect legume yield,
 - o intercropping reduces weed-caused yield losses even more than with unlimiting nitrogen.

These results will be presented in autumn at the Mix4Agroecology conference (Baquet *et al.*, 2026) and written up as a scientific paper.



7. Increase the range of analysed intercrops

7.1 Objective

The previous simulation studies were limited to legume–cereal intercrops in a small number of rotations in two locations, Burgundy, Eastern France (section 4) and Midi-Pyrénées, South-Western France (section 5). The objective of the present study was to evaluate a more diverse range of intercrops and regions and to identify the key technical and biological drivers of intercropping success.

7.2 Tested scenarios

The tested 590 intercropping scenarios were extracted from a data base of more than thousand cropping systems collected from farm surveys, cropping-system trials and participatory workshops, mostly from France (Colbach and Cordeau, 2022; Colbach *et al.*, in prep). The rotations in which the intercrops were included were simulated over 30 years and repeated with 10 weather series from their region of origin. Random forests were used to identify the most influential drivers of crop yields, yield loss due to weeds and field infestation by weed biomass, their general effects and their optimal values to maximise yields and/or minimise weed harmfulness.

7.3 Results

Altogether, the variables driving canopy structure (sowing dates, densities, patterns) were the most influential driver of yields and weed control in intercrops (Table 3). Herbicides and tillage were the second most influential drivers, followed by crops during and prior to the intercrops.

When looking more in detail at the drivers of field infestation, other than weather, the choice of the intercropped species was the most influential factor, with triticale-vetch resulting in the lowest infestation in average (Table 4). The other most influential drivers were related to tillage, requiring frequent and deeper tillage in general, with early post-harvest tillage, 2-3 operations during summer and 1-2 operations during winter (also meaning either spring crops or late-sown winter crops).

The last table (Table 5) identifies the general effects of the variables defining the intercrop canopy structure and their optimum values to minimise field infestation. For instance, the average minimum distance from cereal to legume plants in the intercrops should exceed 23 cm. Thanks to the process-based nature of the model, the underlying reasons for these effects can be identified: cereal plants need to keep a certain distance from other crop plants to suppress weeds rather than crop plants.

Other management descriptor variables refer to dates. For instance, the intercrop should best be sown in October: this leaves more time for weed seeds to germinate during the fallow period (particularly when stimulated by frequent superficial tillage operations) and thus fewer weed seeds that can germinate and emerge during the intercrop.

Table 3. Ranking of weather, crops and types of intercrop-management factors in terms of their effect on crop production and weed control in annual intercrops, identified with random forests on 590 intercropping scenarios. % Increase MSE is the increase in prediction error when an input variable is deleted from the random forest and was summed here over all inputs belonging to a given type. Types were ranked according to their decreasing effect on field infestation. Management of previous crops was disregarded.

Type	Details	% Increase MSE			
		Potential (weed-free) yield	Actual (weed-infested) yield	Grain yield loss due to weeds	Field infestation by weed biomass
Sowing → canopy structure	Dates, densities, species proportions, interplant distances, patterns, interrow width, depth	116	86	144	174
Herbicides	Dates, frequency, efficiencies, spectrum, mode of entry	0	87	134	127
Tillage (before sowing)	Dates, frequency, depth, speed, tools	83	81	133	115
Crop	Species, number, duration of cover, duration of coexistence	62	73	97	105
Rotation	Families and sowing seasons of previous crops	57	64	90	103
Manure	Dates, frequency, amount, origin	22	27	23	42
Harvest	Dates, cutting height, biomass export	17	22	32	38
Mechanical weeding	Dates, frequency, depth, speed, tools	30	27	30	32
Roll	Dates, frequency	30	26	30	26
Shredding	Dates, frequency	14	12	21	18
Mow	Dates, frequency, cutting height, biomass export	21	21	21	17
Cover crops	Frequency, duration	17	7	14	15
Topping	Dates, frequency, cutting height	6	8	10	10
Irrigation	Dates, frequency, water amount	18	17	18	9
Weather repetition		9	11	71	48
Total R²		0.74	0.74	0.41	0.45

Table 4. Effects and optimal values of the most influential descriptors of crop species and intercrop management driving field infestation by weed biomass in annual intercrops, identified with random forests on 590 intercropping scenarios.

Descriptor	Range and unit	% increase MSE	Effect [§]	Optimum value
Weather repetition		48		
Intercrop species	12 combinations	26		Triticale + Vetch
DaysHarvest1stTill	days	19	+	1
Previous crop: family	Cereal, Legume, other crops	19		Cereal
Previous crop: seasonal type	Winter, Spring	17		Winter
Tillage April-Oct	[0, 9] ops / year	16	U	2-3
TillageDepth	[0, 30] cm	16	-	> 12 cm
CropDuration	[100-365] days	16	U	170-203
nbSuperficialTillage	[0, 14] ops / year	15	-	≥ 7
Tillage Nov-Mar	number/year	14	U	1-2
Cer_Leg_plant_distance	[0,0.38] m	13	-	≥ 0.23 m
NbSpeciesPerDay	[0,5] number/day	13	U	1.5-2
...				
R2		0.45		

[§] + (resp. -) indicates that field infestation increases (resp. Decreases) with increasing descriptor values. U points to a u-shaped relationship, i.e., decrease followed by an increase in field infestation.

Table 5. Effects and optimal values of the most influential canopy factors driving field infestation by weed biomass in annual intercrops, identified with random forests on 590 intercropping scenarios. Red (resp. green) cells show systematic increases (res. decreases) in field infestation with increasing descriptor value.

Descriptor	Range	% increase MSE	Effect	Optimum value
Cer_Leg_distance [§]	[0,0.38] m	13	-	≥ 0.23 m
MeanSowingDate	[10 Jul, 15 May]	11	U+	1-26 Oct
Leg_Cer_distance	[0, 0.38] m	10	-	≥ 0.07 m
propLegumes	[0, 0.99] g seeds/g seeds	9	+	<0.80 g/g
Leg_Leg_distance	[0, 0.45] m	9	~	0.12-0.20 m
SowingDensityLegumes	[0,180] g seeds/m ²	8	-	>45 g/m ²
propOtherSpecies	[0, 1] g seeds/g seeds	8	+	0 g/g
SowingDensityOther	[0,6.6] g seeds/m ²	7	+	0 g/m ²
MeanInterrowWidth.	[6, 75] cm	7	U+	17-37 cm
Leg_Oth_distance	[0.01, 0.7] m	7	-U	0.18-0.42 m
Oth_Leg_distance	[0.01, 0.5] m	7	+	0.01 m
MeanSowingDepth.	[0.67, 4] cm	7	+	0.67 cm
PatternWidth.	[7, 200] cm	7	+	7 cm
sumSowingDensity	[0, 180] g seeds/m ²	7	~-	≥ 50 g/m ²
propBroadcastSeeds	[0, 0.9] seeds / seeds	7	U+	0.50-0.75
Cer_Cer_distance	[0.04, 0.38] m	6	-	>0.22 m
propCereals	[0, 1] g seeds/g seeds	6	U+	0.05-0.20 g/g
SowingDensityCereals	[0, 19] g seeds/m ²	6	-U	7-9 g/m ²
Oth_Oth_distance	[0.01, 0.31] m	5	+	0.01-0.03m
Cash or companion crops	Cash only, with Companion	3		Cash only
Cer_Oth_distance	[0.02, 0.43] m	2	-U	0.24 m

[§] Cer_Leg_distance is the average minimum distance from cereal plants to legume plants in the intercrop. Same principle for the other XXX_XXX_distance variables. Note that Leg_Cer_distance is generally not equal to Leg_Cer_distance.

7.4 Conclusion and Perspectives

This study confirmed the detailed simulation study carried out in one location (Toulouse-Auzeville) with a limited number of crop species and cropping systems. It went further and evaluated the impacts of all intercrop management variables in large range of contrasting situations (locations, weather, weed floras) and was able to identify the best ranges to optimize yields and weed control.

In addition to writing a scientific paper, the results will be organized into advice tables and decision support systems in the future, similarly to what we already started with the DECIFLORMIX tool (section 8).



8. DECIFLORMIX

8.1 Objective

The results of the first two simulation studies (sections 5 and 4) were organized into a prototype of decision support system called DECIFLORMIX, aiming to evaluate the impact of cereal–legume intercrops on weeds and the consequences for crop production. The tool focuses on two questions:

- The effect of species choice and management of legume–cereal intercrops, focusing on organic and herbicide-scarce cropping systems,
- The effect of pea variety choice and of the management of the pea–wheat intercrop and a few major crops of the rotation.

8.2 Model development and interface

The tool is a metamodel of FLORSYS, i.e, a model of a model. It is based on two linear multi-variable models linking indicators of crop production and weed harmfulness for crop production predicted by FLORSYS (section 3.2) to variables describing the species, intercrop management practices and other cropping-system variables fed into FLORSYS. The resulting equations were implemented into Excel sheets, together with instructions for use and explanations of results.

The tool allows the user to compare up to 10 intercrops in a single table, listing both the input information and the corresponding intercrop performance. The latter is similar to Table 1.G. The tool was tested in a workshop with advisors and breeders in March 2025 organized by the Mobidiv project. It is currently available at FLORSYSsteam@inrae.fr and later at florsys.hub.inrae.fr.

8.3 Conclusion and Perspectives

The DECIFLORMIX model will be improved and extended to include more intercrop species and conditions, once further intercrop simulation results will be available. The statistical approach can then be improved, using random forests rather than linear models, similarly to what is used in our DECIFLORSYS decision support system. DECIFLORMIX will then be included in DECIFLORSYS (<https://florsys.hub.inrae.fr/modeles-et-oad/deciflorsys>), to benefit from the latter's graphic interface and user network.



9. Conclusion and Perspectives

The present used a crop-weed simulation model to (1) identify ideal varieties, species combinations and proportions and sowing patterns for bi-species cereal-legume intercropping, (2) assess how soil nitrogen availability influenced cereal-legume-weed interactions in these intercrops, (3) identify the key technical and biological drivers of intercropping success, and (4) develop a prototype of decision support system called DECIFLORMIX. The simulations produced practical conclusions on intercropping management, i.e., ideal variety profiles for intercropping depending on production goals (e.g., legume yield, weed suppression), ideal intercrop composition (e.g., balanced species proportions and row placements) and advice tables for management operations. The simulations also produced new knowledge on plant-plant interactions in the crop-crop-weed canopy, in terms of:

- the benefits of intercropping (better weed suppression than in sole crops),
- the role of soil nitrogen availability for these benefits (more weed suppression vs sole crops), or
- the "winning" crop in the mixture (with unlimiting soil nitrogen, legumes have a lower yield potential and a lower weed-caused yield loss than in sole crops, with limiting nitrogen, this applies to cereals).

Currently, the authors are still working on the analysis of the studies of intercropping with limiting soil nitrogen (section 6) and in a larger range of cropping systems and pedoclimates (section 7). The results will then be published in scientific papers and conferences as well as in journals aiming at farmers and breeders. The results will also help to improve the DECIFLORMIX decision support tool (section 8). The approaches used here will now be used in a new project targeting crop ideotypes and intercropping, i.e. the PEPR SV DIALOG (led by Alexandra Jullien and J.D. Faure) that started in spring 2026 and which focuses on camelina-lentil intercrops.



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INTERCROP VALUES



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