*The objective of the H2020 project **ReMIX** is to exploit the benefits of species mixtures to design agro-ecological cropping systems that are productive, diverse, resilient, environmentally virtuous. They are also less dependent on external inputs than current systems, and acceptable to farmers and stakeholders in the food and agro-industrial value chains, in both conventional and organic agriculture, and for diverse soil and climate conditions. Cover crops are combining many of the desired advantages, but they need to be carefully chosen depending on the farmer's cropping system and strategy. The project is spanning from the specification of end-user needs and the co-design of in-field and on-farm experiments to demonstrations with the evaluation of new varieties and practices. The project is running from May 2017 to April 2021*

INTERCROPPING WITH COVER CROPS

Choosing suitable species

Farmers are still using a very limited array of species as cover crops. Yet, for each situation there are appropriate species that, in that given context, will maximise expected benefits while reducing poor establishment and plant health risks.

There are many species on the market for intermediate crops, semi-permanent cover crops, or companion crops for oilseed rape for example. Around sixty were identified when the decision support tool (DST) *Choix des couverts* (Choosing cover crops)[1] was updated. And yet, according to the 2017 SSP (the French Department of Agriculture's Statistics and Forecasting Service) survey, eight species sown singly still account for 55% of the cover crop area, 33% of which is sown with white mustard.

However, the last decade has seen a reduction in the dominance of white mustard and a significant increase in the use of mixed species. In 2017, the latter accounted for 40% of the overall cover crop area in France. About half of it is sown with mixtures of non-legume species, and the other half with mixtures of non-legumes and legumes.

Not all species are suitable for all situations. Their choice must take into account the desired benefits, as well as the cover crop management (sowing window, sowing method and planned destruction method), the rotation and the following crop.

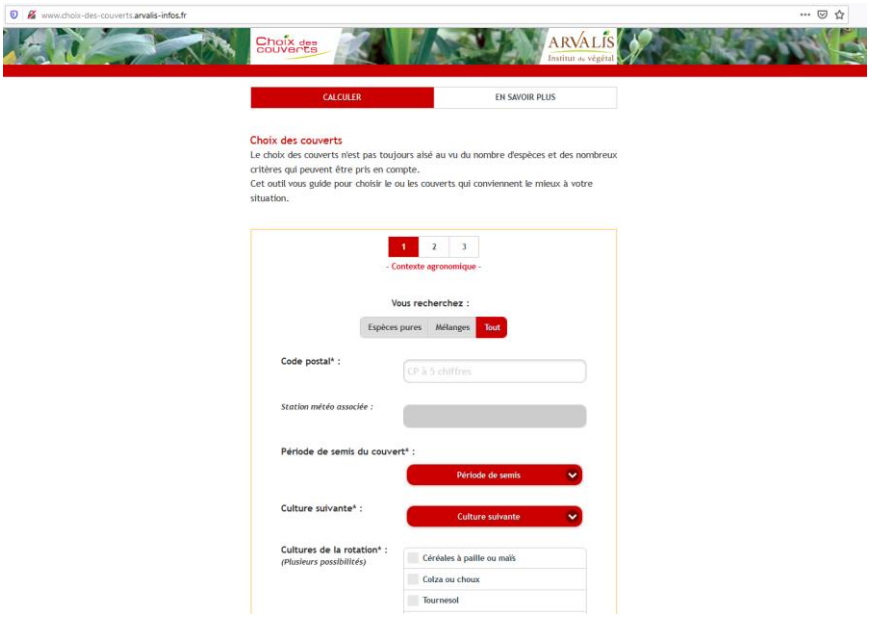
Choosing according to the expected benefits

Many agronomic and environmental benefits can be expected from establishing green cover crops. They depend on which species are sown *(Table 1).* Defining precisely your expectations will help to guide your choice.

Combining species presents the advantage of capitalising on their complementarity and of potentially deriving multiple benefits. Mixtures of non-legumes and legumes are often chosen for those reasons. Non-legumes are better at trapping nitrates and at covering the ground rapidly, while legumes introduce nitrogen into the cropping system through symbiotic fixing. The latter provide more nitrogen to the following crop or produce forage with a higher protein content. Other species can be added to deliver complementary services: for example, a very early-flowering buckwheat will be a source of feed for pollinators.

Choosing a cover crop in a few clicks

A decision-support tool to help you choose the right cover crops has been available since 2016 and has just been updated. It was developed by Arvalis, in partnership with ITB, Terres Inovia, UNILET, Agrifaune Interculture and ITSAP. Freely available at http://www.choix-des-couverts.arvalis-infos.fr/, it guides your choice between 35 single species and 222 mixtures. Once the characteristics have been specified (location, cropping techniques, utilisation, required services), the tool suggests the most suitable cover crops. Some new solutions have been added in recent weeks: non frost resistant or perennial cover crops mixed with oilseed rape, perennial cover crop sown under a crop, utilisation of the cover crop's biomass (energy catch crop)... In addition, technical data sheets are available for single species as well as for mixtures at http://www.fiches.arvalis-infos.fr/.



EXPECTED BENEFITS: increasing their number by combining species

	Nitrate trapping	**Providing nitrogen to subsequent crops**	**Ground cover** (erosion, weeds)	**Carbon storage in the soil**	**Melliferous blossom**	**Utilisation as forage or biomass**
Key characteristics required	Rapid start High biomass level reached before the rainy season	Symbiotic activity Low carbon/ nitrogen ratio*	Rapid ground cover Winter ground cover	High biomass content	Nectar and/or pollen production Early and spread out flowering	Appetence Biomass production Protein content
Most suitable species	Mustards, Radish, Phacelia, Oats…	Legumes	Crucifers, Buckwheat, Winter cereals…	Various possible cover crops	Buckwheat, Phacelia, Egyptian clover, Vetches, Field bean, Sunflower…	Ryegrass, Oats, Rye Legumes (vetches, clovers…) for protein

Table 1

Examples of services provided by green covers and of some species that deliver those services. **If the C/N ratio is low, mineralization is better, and the cover crop supplies nitrogen to the following crop.*

Choosing according to the crop rotation and the following crop

As a general rule, it is best to avoid sowing cover crops from the same family as the following crop (or even as any in the rotation), even when they are grown as part of a mixture of species. However, the level of risk varies greatly depending on the species involved and on the likelihood of increasing the number of bioagressors throughout the rotation *(Table 2)*.

Some cover crops encourage pests or diseases that are very harmful to the main crops. This is the case for some legumes that, even in a mixture, can increase the risk of Aphanomyces root rot, a very damaging disease for peas and lentils in particular, and for which there are no control solutions *(insert)*. Cruciferous cover crops (mustard, radish) should not be used in parcels affected by clubroot and are not recommended in rotations that frequently include oilseed rape.

For the same reasons, some crop sequences should be avoided. For example, grasses are not recommended before cereals, especially wheat, in order to limit the risk of take-all or the transmission of viral diseases. Conversely, before wheat, and even more so before wheat after wheat, a cruciferous cover crop may limit the development of take-all due to a biofumigation phenomenon, albeit with varying degrees of success.

In rotations that include beet crops, the most suitable cover crops are nematicide crucifers, as they provide an opportunity to control beet nematode populations: some varieties of white mustard and fodder radish (and more rarely of Indian mustard) trap beet cyst nematodes (*Heteroderaschachtii*). However, stem

nematodes *(Ditylenchus dipsacii*) multiply in cereal, pea and field bean cover crops, so those must be avoided, along with non-nematicide crucifers.

The choice of cover crop according to the rotation or the following crop is not based solely on potential plant health issues. In general, legumes also make nitrogen available to the following crop. Sometimes, but in a less predictable way, they help lift the yield of that crop (this effect was observed in trials with several crops including barley and sunflower).

In addition, the choice of species has an impact on weed control, which is a growing problem in arable farming systems. Some flower rapidly and can produce unwelcome viable seed, turning the cover crop into a weed. This is particularly the case with buckwheat.

The ease of destruction of the cover crop, which varies slightly depending on the mode of destruction, is also important to avoid the risk of volunteers appearing in the following crop. Particular attention should be paid to perennial cover crops such as alfalfa, that can be difficult to destroy, especially if the following crop affords limited means of controlling the cover crop.

The establishment of the following crop must also be taken into account when choosing cover species. For example, when choosing a forage catch crop, cereals are sometimes preferred over Italian ryegrass because they ease the following crop's development (drier soil, nitrogen management, crop establishment).

Aphanomyces: using the rotation to manage risks

As legumes are increasingly used, it is important to manage the plant health risk associated with aphanomyces by choosing species according to their susceptibility to this disease. Field beans, soya, chickpeas, lupin, fenugreek, birdsfoot trefoil, sainfoin, as well as Egyptian and crimson clover are either not hosts or extremely resistant to it. Peas, lentils, alfalfa, beans, grass peas, purple vetch and hairy vetch are sensitive to it. White and red clover's and common vetch's susceptibility varies depending on the variety (see list of susceptible and resistant varieties at www.terresinovia.fr under "Peas > Aphanomyces".

If sensitive species are grown in the rotation, sensitive species or varieties should not be used as cover crops, not even as part of a mixture. If that is not the case, there are no restrictions.

ROTATION AND SUCCESSION: avoid species that attract the same pests as the main crops

	Beneficial effect of the cover
	Moderately beneficial effect of the cover
	No known effect of the cover
	Slight risks generated by the cover
	Risks generated by the cover
	Cover not recommended

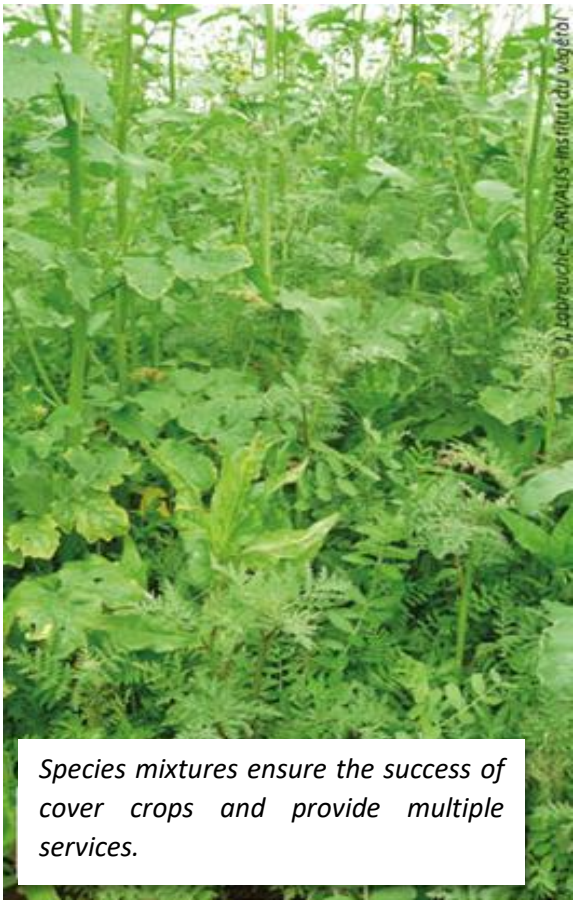
		Nematicide mustards *(nematicides)*	Nematicide fodder radish *(nematicides)*	Other radishes	Oilseed rape	Other crucifers	Phacelia	Flax	Sunflower	Niger	Buckwheat	Rye, Triticale, Canary grass	Cultivated oats, Bristle oats	Foxtail millet, Sorghum	Italian ryegrass	Field bean, lupin	Pea	Fenugreek, EC, CC, Vetches (resistant to aphanomyces)	Other vetches, Lentil, Grass pea	Birdsfoot trefoil, Sainfoin, WC and RC (resistant to Aphanomyces)	Alfalfa, Other WC and RC
IN THE ROTATION	**Pea, Bean, Lentil**										D						A		A		A
	Field bean										D										
	Fibre flax or linseed																				
	Sunflower										D										
	Oilseed rape (if clubroot)																				
	Oilseed rape (no clubroot)																				
IN THE FOLLOWING CROP	**Wheat after wheat**	PE	PE	PE	PE	PE									DN	N	N	N	N	N	N
	Other winter cereals														DN	N	N	N	N	N	N
	Spring barley											t	t	t	tDN	N	N	N	N	NC	NC
	Maize	t	t	t	t	t					D				DNH	N	N	N	N	NC	NC
	Sorghum										D				DNH	N	N	N	N	NC	NC
	Beets (cyst nematodes)	B	B	B	B	B					D				NH	NR	N	N	N	C	C
	Beets (stem nematodes)	B	B	B	B	B					D	B	B		NH	BR	B	N	N	C	C
	Potato										D				NH	N	N	N	N		
	Canning pea Bean	S	S	S	S	S	S	S	S	S	D				H	S	SA	S	SA	CS	CSA
	Protein pea Lentil										D				H		A		A	C	CA
	Field bean, Lupin										D				H					C	C
	Soya, Chickpea								S	S	D				H					C	C
	Sunflower				V			V			D				NH	N	N	N	N		
	Hemp										D				NH	N	N	N	N		
	Fibre flax or linseed				V				V		D	L	L		LNH	LN	LN	LN	LN	C	C

Table 2

Recommended cover species according to the following crop and crop rotation. EC/WC/CC/RC: Egyptian clover/ white clover/ crimson clover/ red clover. **A:** increased risk of Aphanomyces should be considered when deciding on the rotation. White and red clover and common vetch's sensitivity varies between varieties: see varieties list at www.terresinovia.fr, under "Peas > Aphanomyces". **B:** an increase or reduction of the beet cyst nematode or stem nematode impact. **C:** competition from permanent cover crops, difficult to control in spring crops. **D:** risk of poor cover crop control in the following crop, due to volunteers or to the cover crop running to seed. **H:** risk of soil drying out after a catch crop harvested late in the spring. **L:** risk of phytotoxicity of glyphosate applied to a grass cover less than a month before flax sowing. **N:** impact on the following crop's nitrogen nutrition, with an increase or sometimes a reduction in mineralisation. **PE:** possible positive or negative impact on take-all in wheat after wheat. **R:** risk of increased black scurf. **S:** risk of *Sclerotinia* if sclerotia are produced. **t:** potentially negative impact of the cover crop on the following crop, reduced or eradicated by destroying it early enough. V: risk of *Verticillium*. Source: Arvalis, ITB, Terres Inovia and UNILET.

Species must be suitable for the sowing period and method used

The sowing period is a very important factor when choosing cover species. They all present very different physiological characteristics that determine their suitability or unsuitability for early or late sowing. In the case of very early sowing (July, early August), the best choice is species that require high temperatures and a lot of light, such as those of the composite family (sunflower, niger), polygonaceae (buckwheat), legumes and summer grasses (sorghum, foxtail millet). Consideration must then be given to the earliness of the flowering stage.



Species mixtures ensure the success of cover crops and provide multiple services.

Very early flowering species such as white mustard are not recommended as they may produce limited amounts of biomass and may go to seed. Conversely, late-flowering ones, such as some varieties of radishes, are more suitable.

For late sowing, vigorous species that get established rapidly, such as crucifers, or that tolerate cold temperatures and are able to grow during the winter (cereals, winter legumes…) are advisable.

Seed size determines the type of sowing required and seed positioning in the soil *(Table 3).* Generally, very small seeds must not be buried deeply, however, if they are left too close to the surface, they risk drying out during the germination period. Ideally, they should be covered thinly, either with a mulch, if sowing is carried out before or during the harvest, or with one or two centimetres of soil. Conversely, large seeds may require a greater sowing depth, especially if soil temperature is still low.

The joint sowing of seeds of very different sizes requires two passes, equipment with two distribution mechanisms or a mixture containing many species to reduce the settling effect.

EMERGENCE QUALITY: choose species appropriate for the intended type of establishment and available equipment

SPECIES	1000 seed weight (g)	Optimal depth[1] (cm)	Harvester drill[2]	Tined drill	Direct drilling[3]	Classic cerealdrill	Covered broadcast sowing[4]	Broadcast sowing with stubble plough[5]	Broadcast sowing then rolling
Camelina	1.3	1							
Phacelia	2	1 to 2							
Foxtail millet	2.3	1 to 2							
Italian ryegrass	2.7	1 to 2							
Egyptian clover	3	1 to 2							
Niger	3.2	1 to 2							
Crimson clover	4	1 to 3							
Mustards, oilseed rape, turnip rape	3-7	2 to 4							
Flax	5.4	2 to 4							
Forage and Daikon radish	13	2 to 4							
Lentil, fenugreek	16-20	2 to 5							
Buckwheat	21.5	2 to 4							
Forage sorghum	23	2 to 4							
Rye, triticale, oats	15-48	2 to 5							
Vetches	25-65	2 to 5							
Sunflower	47.3	2 to 5							
Grass pea, pea	175	3 to 10							
Field bean	350-700	3 to 10							

Seed positioning

	Very good
	Good
	Suitable
	Moderately suitable
	Not very suitable
	Absolutely not recommended

Table 3

Choosing cover species that are suited to the intended drilling method when the cover crop is being established after a cereal crop and the straw has been chopped and incorporated. (1) Appropriate depth for level of moisture in the soil. (2) Sowing under the cut or just before harvest. (3) Disc drill on stubble. (4) With pass of stubble plough. (5) Seed deposited level with the roller and covered very thinly.

When a mixture is used, all the species in it must be suitable for the planned sowing date. However, their earliness can vary greatly, especially if the intercrop period is long. This can ensure prolonged soil cover, with vigorous species covering the ground rapidly after their emergence, and others that can withstand frost covering the ground over winter. Seed sizes must be similar in a mixture in order to remain within optimal sowing depth ranges for all of them, unless you accept to sow the different species in two separate passes.■

(1) Choose your cover crop in a few clicks with the "Choix des couverts" DST developed by Arvalis in conjunction with ITB, Terres Inovia, UNILET, Agrifaune Interculture and ITSAP. It is freely available at

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THIS PROJECT HAS RECEIVED FUNDING FROM THE **EUROPEAN UNION'S HORIZON 2020 RESEARCH AND INNOVATION PROGRAMME** UNDER GRANT AGREEMENT N. 727217