DIVERSify: Designing InnoVative plant teams for Ecosystem Resilience and agricultural Sustainability

Grant Agreement No.:	727284
Project Acronym:	DIVERSify
Project Title:	Designing Innovative Plant Teams For Ecosystem Resilience And Agricultural Sustainability
Project Co-ordinator:	Dr Alison Karley, JHI
Tel:	+44 (0)1382 568820
Email:	Alison.Karley@hutton.ac.uk

Trouble Shooting Matrix of PAT practical solutions (Report, Public). Deliverable 4.6 (D32)

Deliverable Lead: **STC**

Deliverable Due Date: **30-September-2020**

Actual Submission Date: **28-September-2020**

Version: **1.0**

Work Package: WP 4 In-field validation and demonstration of plant teams

Lead Author: David George (Newcastle University)

Contributing Author(s): Jennifer Banfield-Zanin (STC), Andrew Manfield (Manterra Ltd)

Reviewers: Alison Karley (JHI), Adrian Newton (JHI), Stefano Tavoletti (UNIVPM)

History of Changes		
Version	**Publication Date**	**Change**
0.1	6th July 2020	Initial draft version, sent to co-authors plus Dr Alison Karley and Prof Adrian Newton for comment
0.2	19th August 2020	Final draft version, sent to internal reviewers for comment and approval
0.3	11th September 2020	Revised with internal reviewer comments, version sent to STC for submission
1.0	28th September 2020	Final version

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727284

Table of Contents

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727284

Executive Summary

Multi-species 'plant teams' offer promising opportunities to improve crop yield stability, reduce pest and disease burden and enhance the resilience of agricultural systems to stresses such as climate change and market pressures (as reported under D4.5 'Report on practical restrictions imposed by plant teams'). In consultation with industry stakeholders, however, several barriers have been identified to the commercial adoption of plant teams.

For at least some of these barriers, and particularly those related to the practicalities of drilling, agronomy and harvesting of plant teams, precision agriculture technology (PAT) may offer available or near-market solutions to ease transitions to polycultural cropping, promoting commercial plant team uptake. In order to identify such solutions, discussions with PAT specialists were undertaken and reported under Milestone 38 ('Complete discussions with PAT specialists'). These discussions identified ">40 general and specific PAT solutions to plant team barriers", additionally including machinery and product solutions, through a variety of contact routes. This exercise also began the process of organising these solutions based on their specificity and further designation of the barrier types that each solution could be used to overcome.

To present these data in a more meaningful and usable format, this report presents machinery, product and PAT solutions to plant team barriers formally as a 'Trouble-Shooting Matrix' for farmers and advisors to use when implementing the two broad 'types' of plant teams: i.e.

1) Unstructured teams: e.g. companion/mixed crops and green understories, and
2) Structured teams: e.g. intercrops and strip-tilled living mulches.

Solutions are also presented according to whether they are suited to most operations (being easily 'accessible') or require pre-existing on-farm engagement with at least some elements of PAT and/or high-level investment in machinery (being 'available'). A small number of solutions are included that are theoretically available, but not yet widely accessible, requiring highly specialised equipment (these being included as 'attainable').

Development of trouble shooting matrices of PAT practical solutions to plant team barriers has shown that options to facilitate polycultural practices exist at varying levels of accessibility for use across both unstructured and structured plant team designs. Machinery and product solutions, often but not always linked to PAT, offer additional opportunities to overcome barriers. Overall, engagement with PAT appears likely to facilitate plant team cropping, although it deserves note that some barriers can be addressed through machinery and/or product solutions independently of PAT. Similarly, the results suggest that barriers may be more readily addressed when adopting structured plant team designs, where these better lend themselves to delivery of solutions through PAT placement technologies.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727284

1. Introduction

Species-rich systems often show higher productivity than monocultures, explained by effects resulting from positive plant-plant interactions (Hector *et al*., 2010) that enhance plant resource capture. Moreover, compared to monocultures, diverse vegetation is buffered from environmental fluctuations, increasing resilience to stress. Introducing greater heterogeneity in crop systems through use of plant team polycultures could, therefore, enhance stability, yield and resource-use efficiency (Brooker *et al*., 2015).

'Plant teams' were the foundation of many early agricultural systems (e.g. 'the three sisters', see Burns, 2012), and are still used with great success today in some areas of the globe (e.g. 'push-pull' systems in Kenya, see Cook *et al*., 2007). However, the rise of high-input production systems in 'westernised' cropping cultures has, by design, driven monocultural production models that align themselves to the use of crop-specific agronomic inputs, and harvesting and processing approaches that maximise performance in single species stands. It is therefore unsurprising that, despite the potential of polycultures to deliver multiple benefits to present and future production models, within current farming practices a number of barriers exist that may affect plant team uptake and implementation. These barriers were identified within the DIVERSify project through a participatory approach, working closely with farmers and other stakeholders through 14 workshops across 11 countries, run between 2017 and 2018 (Pearce *et al*., 2018).

The outputs of these international workshops have been used to detail practical barriers to plant teams (Tippin *et al*., 2019a; 2019b), where it was reported that "complexities with harvest, processing and crop management were… broadly identified as barriers to the implementation of plant teams, as was crop-crop competition and yield suppression", with the authors further noting that "This suggests further development and research needs to be undertaken in order to provide approaches and machinery that can be used to help remove complexities in the management of plant teams" (Tippin *et al*., 2019a). Machinery, products and precision agriculture technology (PAT) were subsequently investigated for their potential to overcome physical barriers associated with plant teams (George *et al*., 2020), where > 40 general and specific solutions were identified through a number of interaction routes with industry specialists. As part of this exercise, barriers were further defined at finer resolutions, based on discussions with specialists and the outputs of earlier work, and assigned to barrier codes as follows:

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727284

Drilling barriers:	Multiple seed sizes (DB1)
	Multiple seed rates (DB2)
	Multiple seed depths (DB3)
	Different sowing times (DB4)
Agronomy barriers:	Pest control (AB1)
	Disease control (AB2)
	Weed control (AB3)
	Crop-crop competition (AB4)
	Nutrition complexity (AB5)
Harvest barriers:	Timing (HB1)
	Separation (HB2)
Other barriers:	Barriers not covered above (OB), subsequently redefined here as: 'Plant Team Planning' (PTP)

In this deliverable report, we have refined the above data to create a 'Trouble Shooting Matrix of PAT practical solutions', also including product and machinery approaches that could address barriers to plant team uptake. In order to ensure that this forms an impactful output from the project that could be used by farmers and practitioners to support transitions to plant teams, this single matrix has been expanded to form two independent matrices for each of the major plant team types ('unstructured' and 'structured'), assigning solutions according not only to specific barrier codes, but also to the expected ease with which end-users could engage with them. In this way it is hoped that navigating the matrix will be simplified, ensuring that end-users can quickly access information on barriers/solutions relevant to their business and cropping plans.

2. Methodology

Two separate matrices have been developed, one for unstructured plant teams (Section 3) and the other for structured teams (Section 4). Each matrix is presented in tabulated format, with solutions identified according to barrier codes (George *et al.*, 2020, see above) that are considered by the authors to be:

- 'accessible' (i.e. implementable by most end-users with minimal investment),
- 'available' (i.e. implementable with some prior engagement in PAT or investment in machinery solutions) and
- 'attainable' (i.e. implementable, but only with highly specialised equipment).

Only generic solutions are included within either matrix, though specific solutions (e.g. makes and models of machinery, trade names/active ingredients of products, etc.) with notes on their strengths and weaknesses have been collated in preceding work (George *et al.*, 2020, with the summary table published therein reproduced in Appendix I here for reference). The information presented in these matrices has then been used to make generalised comments on the availability of barrier solutions, comparing and contrasting these across plant team types.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727284

Caveats: It deserves note that in developing the matrices, and in earlier related tasks, only solutions relevant to plant teams that fully overlap in both time and space have been considered. Thus, solutions have not been specifically sought for approaches such as relay cropping (where overlap in time occurs, but not throughout the full crop cycle) or for strip cropping at the scale of full machinery widths (where overlap in space occurs, but only when considered at a coarse scale that, arguably, deviates from the definition of a 'plant team'). It deserves note, however, that such methods do deliver benefits in their own right, and their exclusion here should not be taken to infer that they do not have inherent value. It also deserves note that when classifying plant teams as 'unstructured' or 'structured', strip-tilled living mulches have been assigned to the latter category based on 'structuring' occurring during cultivation, even where this may not necessarily have taken place at sowing (e.g. if mulches were initially established as leys by randomly broadcasting seed). Finally, it should also be kept in mind that in some cases a single machinery/product/PAT solution is applicable to both unstructured and structured plant teams, in which case it will appear in the matrix for each.

3. Unstructured Plant Teams

Unstructured plant teams refer here to those where at least one plant in a team has no set structure to its spatial arrangement; for example where two or more crops are randomly mixed, where companion plants (typically a non-crop species used to deliver a specific benefit, e.g. in pest control) or complete green understories are broadcast to establish at random spacings within the main crop, or where main crops are drilled into existing (full) plant cover. Whilst in theory it should be easier to establish unstructured plant teams, with less reliance on spatial arrangement inferring lower dependence on high-tech machinery or PAT, it could be expected that their unstructured spatial design might present greater challenges to in-season crop management, also posing increased risk to yield suppression through plant competition driven by uncontrolled plant-to-plant proximities.

3.1. PAT and machinery solutions to unstructured plant team barriers

Precision Agriculture Technology (PAT), machinery (Mac) and product (Pro) solutions to barriers for unstructured plant teams are shown below in Matrix 1. In all, 29 individual barriers were noted as being potentially solvable via 18 generic solutions, with at least one 'accessible' solution identified under every barrier code except DB4 ('Different sowing times'). It deserves note, however, that even this barrier may be solvable in unstructured plant teams where certain restrictions are met, or where specific types of plant team are used. Random broadcasting of certain understory species is possible into a growing crop, for example (e.g. using a fertiliser spreader[1]), as is establishment of a full green understory as a ley to be direct drilled with a cash crop species at a later date.

[1] It is worth noting technical limitations of this technique for spinning disc type spreaders, which generally give poor distribution of seeds. Therefore, more expensive boom type spreaders would be required to provide consistent seed distribution.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727284

MATRIX 1: Trouble Shooting Matrix of practical solutions for Unstructured Plant Teams

		BARRIER ADRESSED											
		DB				AB					HB		Other
	PRACTICAL SOLUTION	1	2	3	4	1	2	3	4	5	1	2	PTP
Mac	**Fertiliser spreaders** to apply one seed species, whilst the other is sown through the drill, allowing separation (to a degree) of seed species and sowing depths, though with this being limited to surface sowing through the spreader												
Mac	**Direct drills** can sow through green cover, allowing establishment into unstructured living crop understories, potentially of multiple species simultaneously if fitted with multiple seed tanks. Models developed for pasture may be especially proficient, also drilling different seed at multiple depths (making more diversified designs possible, and making such drills a potential option for structured plant teams also).												
Pro	**Biopesticides** and other 'low risk' products have blanket cross-crop approvals allowing co-application to multiple plant team species												
Pro	**Seed treatments** could be used to manage pest and disease pressure on targeted species within a plant team, or to manipulate competitive interactions in plant teams												
Mac	**Topping mowers** could be used to manage aggressive co-crops when at a height taller than the main crop, though only where compatible with the aims of the plant team. Different co-crops would respond differently to this treatment, so this would need to be considered.												
Mac	**Weed wipers** could be used to target weeds protruding above the plant team canopy level												
Pro	**Herbicides** that are safe across multiple plant team species. These are likely to be few and far between, but for selected plant teams may have been developed for use in alternative sectors (e.g. in enriched pasture). Many herbicides will also have differential effects, supressing growth in some species which can be used to exploit canopy manipulation in plant teams												
Mac	**Selective mowing** technology can be used to target broad leaved weeds in grass-based production systems such as cereals, where this could be used to manage weeds in low growing understories (e.g. clover) or to manage broad-leaved intercrops to suppress them if needed.												
Pro	**Desiccants** could partially overcome issues with varying crop maturity at time of harvest, also offering a means to manage plant team development (e.g. in strip-tilled clover systems)												
Mac	**Crimper Rollers** have been developed for cover crop termination, but could offer a solution for living mulch management – e.g. to 'knock back' green understories ahead of main crop drilling to manage crop-mulch competition during establishment.												
Mac	**UV treatment** of co-crops for plant team-safe pathogen control could be used to overcome potential issues of chemical fungicide crop safety, though remains in its infancy for field crops and may not be universally safe for all plants.												
Mac	**Stripper header** use, or to a lesser extend lifting the combine head, should allow grain harvest from cereal crops whilst avoiding damage to or contamination by lower growing plant teams, also allowing harvest of the latter at a later timing.												
Mac	**In-combine separators** could be reconfigured to seed-sort from certain plant teams, especially where stripper headers are used, and requirements to sort biomass from grain is thus reduced (where less biomass would be harvested by the stripper header than a normal cutter), thus theoretically freeing separation capacity for other tasks.												

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727284

Mac PAT	**Precision harvesters** used in vegetable crops are image based and should be configurable to select out certain harvestable produce from vegetable-based plant teams, regardless of the plant team configuration. Such systems are nevertheless currently limited to certain crops – e.g. heading brassicas.												
Mac	**Low tech seed sorting** technology exists that can separate seed of different sizes, with basic set-ups being possible to construct 'in-house' that separate based on different physical characteristics such as size/weight. These are likely to be more applicable to situations where seed of different species is easily separated (i.e. where it is notably different - e.g. cereal and legume grains)												
Mac	**High tech seed sorting** technology is available that is capable of separating seed based on spectral scanning of traits including quality and species. At present this technology is probably too expensive to be applied to whole crop separation at the farm scale, but in the future would represent a means of separating seeds of identical sizes, based on other traits (e.g. reflectance)												
PAT	**Farm/field profitability software** is now readily available with good uptake and could offer decision support to help to overcome confidence barriers of plant team cropping, also informing on-farm or in-field areas most suitable to plant team approaches, dove-tailing to decision aids being developed in the DIVERSify project												
PAT	**Remote mapping services** could be used to identify fields within a farm, or even areas within a field, where plant team cropping is likely to yield most benefit, which could prove especially useful in the future if coupled to decision tools for plant team selection. On-machine data collection could play an especially key role for plant teams due to the resolution and high accuracy of location it can provide												
	TOTAL ACCESSIBLE SOLUTIONS	1	1	1	0	2	2	3	2	1	2	2	1
	TOTAL AVAILABLE SOLUTIONS	1	1	1	0	0	0	1	1	0	0	1	1
	TOTAL ATTAINABLE SOLUTIONS	0	0	0	0	0	0	0	0	1	1	2	0

Machinery Mac, PAT PAT and Product Pro solutions have been assigned to the matrix according to colour-coded shading of cells, where ▢ = 'accessible' solutions, ▢ = 'available' solutions, and ▢ = 'attainable' solutions. Barrier codes refer to specific challenges identified within the general areas of: Drilling/Establishment Barriers (DB), these being: Multiple seed sizes (DB1), Multiple seed rates (DB2), Multiple seed depths (DB3) and Different sowing times (DB4); Agronomy Barriers (AB), these being: Pest control (AB1), Disease control (AB2), Weed control (AB3), Crop-crop competition (AB4) and Nutrition complexity (AB5); Harvest Barriers (HB), these being: Timing (HB1) and Separation (HB2); and Other Barriers not covered above, grouped here under Plant Team Planning (PTP).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727284

4. Structured Plant Teams

Structured plant teams refer here to in-field arrangements of two or more plant species that are in some way controlled in their spatial arrangement. Examples of structured teams include intercrops and strip-tilled living mulches, where for the purposes of this exercise an intercrop has been defined as alternating rows of one or more plant species where row widths are less than the typical machinery widths used in establishment (e.g. strip-cropping at coarse resolutions, for example > 3m wide strips, is not included). It can be expected that structuring plant teams offers a means of managing plant-to-plant competition to control any interspecies negative competitive interactions, potentially offering further opportunities for delivering species-specific product inputs, particularly through PAT. It could also be expected, however, that in order to structure a plant team, more advanced drilling/cultivation approaches would be needed, with investment in PAT required in most cases to allow implementation of pre-determined high-resolution spatial designs.

4.1. PAT and machinery solutions to structured plant team barriers

Precision Agriculture Technology (PAT), machinery (Mac) and product (Pro) solutions to barriers for structured plant teams are shown in Matrix 2. Fifty-five individual barriers were noted as being potentially solvable via 27 generic solutions. Many solutions that applied to unstructured teams were of equal relevance to structured designs, but with the latter also opening opportunities for further solutions. This was particularly true for overcoming agronomic barriers, primarily as structuring offers opportunities to utilise PAT to deliver targeted application of inputs to single species within a team (see later). It deserves note, however, that whilst engagement with PAT was embedded as a pre-requisite to access many barrier solutions for structured teams, this was not completely universal. Strip-tilling into living mulches, for example, would be achievable without GPS/RTK autosteer (or similar), though gains to crop establishment and development, and the possibility to manage crop-specific inputs later in the season, would all result from accurately placing the strip-till with high repeatability and accuracy.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727284

MATRIX 2: Trouble Shooting Matrix of practical solutions for Structured Plant Teams

	PAT AND/OR MACHINERY SOLUTION	BARRIER ADRESSED											
		DB				AB					HB		Other
		1	2	3	4	1	2	3	4	5	1	2	PTP
Mac, PAT	**Dual-product seeders** can place solid/liquid fertiliser with seed at drilling, allowing starter fertiliser or other product (e.g. biostimulants) to be placed in linear plant team arrangements where this is of benefit (e.g. in cereal-legume mixes, where only the former needs N). This same feature could be used to place additional seed, potentially of different size and at varying depths/rates.	■	■	■						■			
Mac, PAT	**Precision drills** with seed hoppers fitted to each coulter allow multiple species to be sown simultaneously in rows, with depth and metering adjustment of each hopper/coulter permitting seed specific rates and depths to be selected at optimum plant-plant or species-species spacings to minimise competition and maximise facilitation. State of the art systems can also offer facilities such as grid planting. Integrating RTK/autosteer would allow different species to be sown in repeat passes, with precision seeding also facilitating other precision-based operations (see below)	■	■	■					■				
Mac	**Direct drills,** when fitted with multiple seed tanks, can sow multiple species simultaneously, also drilling different seed at multiple depths.	■	■	■									
PAT	**Precision Agriculture Technology** can be used to ensure repeatability and high (e.g. min 2.5 cm with RTK/autosteer) accuracy of seeding and input operations, as required to provide optimal separation of co-crops (see above). This technology would also be key to delivering precision inputs post sowing, such as targeted pest, weed and disease control (chemical or mechanical) or banded application of foliar nutrients.		▒	▒	▒	▒	▒	▒	▒	▒			
Mac	**Strip-till cultivators** can be used to prepare a seedbed within a living understory, allowing staggered sowing/establishment windows for plant teams (e.g. for strip planting cash crops into clover living mulches). Strip till systems in general may also help to suppress weed species, e.g. where they are used to crop into living mulch plant teams or leys, also being of use to manage crop-crop competition in living mulch/ley plant team systems				■			■	■				
Pro	**Biopesticides** and other 'low risk' products have blanket cross-crop approvals allowing co-application to multiple plant team species					▒	▒						
Pro	**Seed treatments** could be used to manage pest and disease pressure on targeted species within a plant team, or, to manipulate competitive interactions in plant teams, biostimulants also being possible post-emergence, with application to individual species in a structured team using precision application technology					▒	▒		▒	▒			
Mac	**Nozzle developments** can help to better direct plant production / protection products, allowing increasingly accurate targeting of single species within mixtures with chemical/biological sprays or liquid fertilisers, assuming that their spatial arrangement is amenable to band/strip spraying					▒	▒			▒			
PAT, Mac	**Precision sprayers** could potentially deliver crop treatments to plant teams, treating individual species separately, assuming that they had been established in bands. This would allow crop protection products to be applied to specific crops within a plant team, and would extend to application of foliar fertilisers					■	■			■			

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727284

Pro	**Herbicides** that are safe across multiple plant team species. These are likely to be few and far between, but for selected plant teams may have been developed for use in alternative sectors (e.g. in enriched pasture). Many herbicides will also have differential effects, supressing growth in some species which can be used to exploit canopy manipulation in plant teams
Mac	**Topping mowers** could be used to manage aggressive co-crops when at a height taller than the main crop, though only where compatible with the aims of the plant team. Different co-crops would respond differently to this treatment, so this would need to be considered.
Mac	**Weed wipers** could be used to target weeds protruding above the plant team canopy level
Mac	**Selective mowing technology** can be used to target broad leaved weeds in grass-based production systems such as cereals, where this could be used to manage weeds in low growing understories (e.g. clover) or to manage broad-leaved intercrops to suppress them if needed.
Mac PAT	**Mechanical inter-row weeders**, if coupled to precision seeding and delivered by RTK autosteer to provide required accuracies, could operate in appropriate structured spatial arrangements of plant teams
Pro	**Desiccants** could partially overcome issues with varying crop maturity at time of harvest, also offering a means to manage plant team development (e.g. in strip-tilled clover systems)
Mac	**Crimper Rollers** have been developed for cover crop termination, but could offer a solution for living mulch management – e.g. to 'knock back' green understories ahead of main crop drilling to manage crop-mulch competition during establishment.
Mac PAT	**Automated robotic weeding systems** can manually weed between individual crop plants, and with future development may be able to weed between plant teams, depending upon the form and spatial arrangement of plant teams, particularly where precision seeding operations have been undertaken.
Mac	**Fertiliser injectors** would permit liquid nutrition, or other products in solution (e.g. biopesticides and biostimulants) to be applied to the roots of individual crops within establishing plant teams, assuming that suitable spatial arrangements were followed (e.g. banding)
Mac	**UV field treatment** of co-crops for plant team-safe pathogen control could be used to overcome potential issues of chemical fungicide crop safety, though remains in its infancy for field crops and may not be universally safe for all plants.
Mac	**Stripper header** use, or to a lesser extend lifting the combine head, should allow grain harvest from cereal crops whilst avoiding damage to or contamination by lower growing plant teams, also allowing harvest of the latter at a later timing.
PAT Mac	**Precision harvesters** used in vegetable crops are image based and should be configurable to select out certain harvestable produce from vegetable-based plant teams, regardless of the plant team configuration. Such systems are nevertheless currently limited to certain crops – e.g. heading brassicas.
Mac	**In-combine separators** could be reconfigured to seed-sort from certain plant teams, especially where stripper headers are used, and requirements to sort biomass from grain is thus reduced (where less biomass would be harvested by the stripper header than a normal cutter), thus theoretically freeing separation capacity for other tasks. Products detecting the quality and attributes of the mass flow of grain in the combine are already becoming available, which could also assist separation into multiple tanks on the harvester.
Mac	**Low tech seed sorting technology** exists that can separate seed of different sizes, with basic set-ups being possible to construct 'in-house' that separate based on different physical characteristics such as size/weight. These are likely to be more applicable to situations where seed of different species is easily separated (i.e. where it is notably different - e.g. cereal and legume grains)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727284

Mac **High tech seed sorting technology** is available that is capable of separating seed based on spectral scanning of traits including quality and species, where colour separators are already used commercially to grade potatoes and rootstock. At present this technology is probably too expensive to be applied to whole crop grain/seed separation at the farm scale, but in the future this could represent a means of separating seeds of identical sizes, based on other traits (e.g. reflectance)												
PAT **Farm/field profitability software** is now readily available with good uptake and could offer decision support to help to overcome confidence barriers of plant team cropping, also informing on-farm or in-field areas most suitable to plant team approaches, dove-tailing to decision aids being developed in the DIVERSify project												
PAT **Remote mapping services** could be used to identify fields within a farm, or even areas within a field, where plant team cropping is likely to yield most benefit, which could prove especially useful in the future if coupled to decision tools for plant team selection. On-machine data collection could play an especially key role for plant teams due to the resolution and high accuracy of location it can provide												
PAT **Advanced crop sensing systems** in could be of benefit to overcoming plant team barriers in several areas, though commercial offers remain relatively low resolution, especially when satellite based. Nevertheless, some systems already utilise imaging to drive map creation and inform agronomic inputs at 2-3m resolutions, which could prove useful in some instances for structured plant teams (e.g. strip intercropping), with higher resolutions expected to be a feature of future developments in this sector												
TOTAL ACCESSIBLE SOLUTIONS	**0**	**1**	**1**	**1**	**4**	**4**	**4**	**3**	**3**	**2**	**2**	**1**
TOTAL AVAILABLE SOLUTIONS	**3**	**3**	**3**	**1**	**1**	**1**	**3**	**3**	**3**	**0**	**1**	**2**
TOTAL ATTAINABLE SOLUTIONS	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**1**	**1**	**2**	**0**

Machinery Mac, PAT PAT and Product Pro solutions have been assigned to the matrix according to colour-coded shading of cells, where = 'accessible' solutions, = 'available' solutions, and = 'attainable' solutions. Barrier codes refer to specific challenges identified within the general areas of: Drilling/Establishment Barriers (DB), these being: Multiple seed sizes (DB1), Multiple seed rates (DB2), Multiple seed depths (DB3) and Different sowing times (DB4); Agronomy Barriers (AB), these being: Pest control (AB1), Disease control (AB2), Weed control (AB3), Crop-crop competition (AB4) and Nutrition complexity (AB5); Harvest Barriers (HB), these being: Timing (HB1) and Separation (HB2); and Other Barriers not covered above, grouped here under Plant Team Planning (PTP)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727284

5. Using matrices to draw general conclusions and compare and contrast solutions across plant team types

The compatibility matrices presented above demonstrate that for most barriers to plant team cropping, general potential solutions were identified as part of discussions with PAT specialists (see also George *et al.*, 2020 and Appendix I). The only complete gap identified was for drilling of different seed at different timings in unstructured plant teams, though in specific cases even this would be achievable, as noted above for direct drilling into green understories. This is particularly encouraging, especially given that relatively high proportions of solutions (62% for unstructured and 47% for structured) can be considered as readily 'accessible'; for example, the use of desiccants to manage challenges around crop maturity (HB1), use of blanket-approved low-risk biopesticides to address pest and disease concerns (AB1 and AB2), and the potential to repurpose existing equipment, such as fertiliser spreaders or combi-drills, to establish multiple plant species, including in a single machinery pass (DB1-3).

It deserves note, however, that in certain circumstances solutions that solve plant team barriers present risk elsewhere; for relatively large direct/combi drills that can, for example, simultaneously sow seed from multiple species, at varying rates and depths, possible weight concerns are relevant in heavier soils (due to compaction risk). Nevertheless, this risk may be mitigated where living green understories are present, and/or where compaction concerns are compensated for by the requirement for fewer machinery passes overall. In other cases solutions might only be able to overcome barriers for selected plant team species combinations (e.g. herbicides that are safe to multiple crops are rare, and stripper headers would only help at harvest if cereals were the tallest crop in a team), though in others it could be expected that they would offer broader-brush solutions (e.g. low risk biopesticides). Thus, whilst plant team combinations would dictate and possibly restrict available solutions in some scenarios, there is also opportunity here to pre-select plant teams that are 'solution-friendly' based on their individual and combined traits. It is also the case that many plant teams are selected to deliver specific agronomic benefits (e.g. weed/pest/disease suppression, provision/ mobilisation of crop nutrition) and in these instances it may not be necessary to overcome barriers that the team itself addresses. When deploying a weed suppressive plant team, for example, weed control may be unnecessary and thus no-longer represents a barrier.

Whilst only being subjective, the classification of solutions to plant team barriers described above allows some comment on where bottlenecks exist that could be expected to restrict plant team uptake, particularly when further grouping solutions according to their relative accessibility. In this way it can be seen that relatively few accessible/available generic solutions exist to overcome drilling and, to a lesser extent, harvest barriers (**Figure 1**), with more solutions available to address agronomic barriers, this pattern being consistent regardless of plant team type. This needs to be interpreted with caution, however, as it fails to account for the numbers of specific solutions that exist under a given general solution. Solutions to drilling barriers in unstructured and (particularly) structured plant

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727284

teams, for example, can be addressed by modern direct, dual-purpose and precision seeders (or combinations thereof), with or without initial use of strip-till cultivators. Whilst this presents a limited number of general solutions, discussions with PAT specialists undertaken in preceding work identified six specific drills and five strip tills that could address these barriers to varying degrees (see Appendix I), with this list being far from exhaustive for either implement. In other cases, for example for 'automated robotic weeding systems', far fewer commercially-available options exist within a generic solution (with this entry being based solely on Garford's 'Robocrop' system). Similarly, whereas some solutions are based on relatively configurable systems (such as the example above for drills that can be adjusted and supplemented in various ways, e.g. with additional seed hoppers), others are less flexible in their design, and therefore less able to be customized to address barriers (e.g. combine harvesters, though even here there may be scope to repurpose built-in separators, especially where stripper headers are used to reduce initial cutting and ingress of non-grain material). Thus, whilst it is inappropriate to draw conclusions on the availability of specific solutions based on the data shown in Figure 1, this figure does present a useful visualization of general solutions, their relatively accessibility and their availability across plant team types.

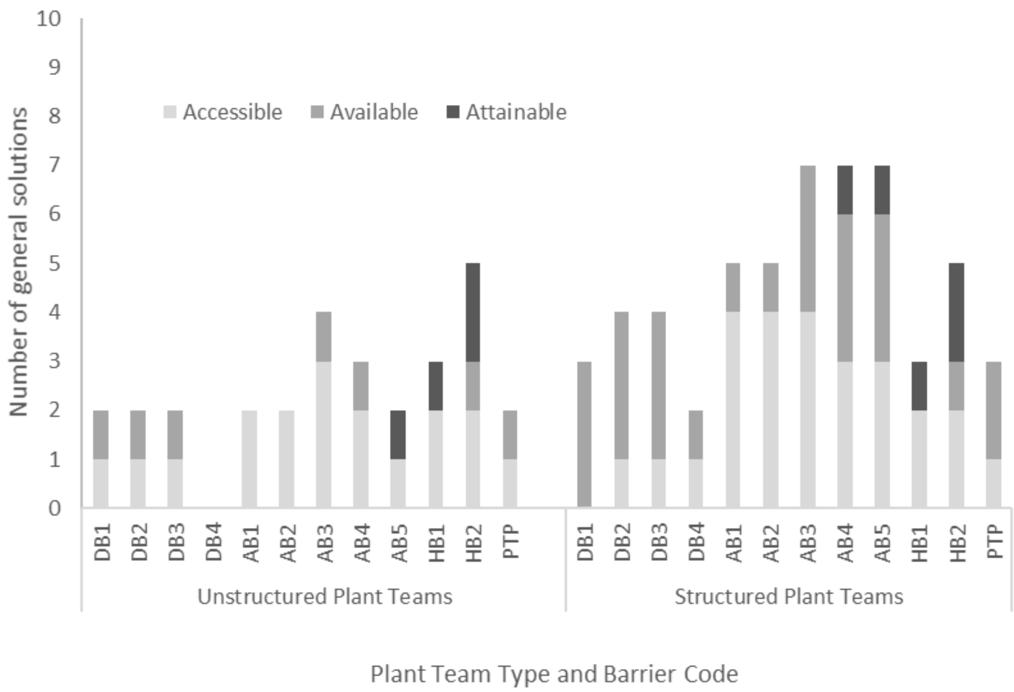

Figure 1. The number of available general PAT/machinery solutions identified to overcome barriers to unstructured and structured plant team cropping. Solutions are shaded according to their expected relative accessibility to end users (as on the 16.06.2020), where ▭ = 'accessible' solutions, ▭ = 'available' solutions, and ▭ = 'attainable' solutions

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727284

When considering differences between plant team types further, it is apparent that more solutions exist for structured vs. unstructured teams (27 vs. 18), and thus, unsurprisingly, more individual barriers can be overcome (55 vs. 29). As can be seen in Figure 1, this difference mainly results from the increased numbers of agronomic barriers that can be overcome in structured teams (31 vs 13), which explains almost 70% of the overall difference. As agronomic barriers relate mainly to crop inputs that are typically species-specific (e.g. plant protection products, that are registered for use on a per-crop basis), it is of little surprise that more of them can be overcome in structured plant team arrangements. Here, by utilising PAT as a solution to direct inputs with potentially high accuracies (i.e. 2.5 cm or less), structural separation at appropriate resolutions allows for different species in a team to still be treated independently, facilitating continued use of species-specific inputs previously developed for use in monocultures. Furthermore, crop-to-crop competition (another agronomic barrier) can also be managed through this PAT-enabled placement technology, permitting precise placement of seed in the same way it enables placement of other inputs, also allowing this seed to be sown at variable rates to further balance competitive interactions (with variable rate application also applying equally to other inputs in structured plant teams). It deserves note, however, that delivery of the highest accuracy and repeatability levels, as would often be required to facilitate PAT-assisted plant team cropping, can require operation at smaller scale; even when fitted with the latest positioning technology, larger machines operating at wider widths will experience increased roll and yaw that will diminish placement/accuracy of any operation. Conversely, smaller, potentially autonomous, machines offer the best potential for high accuracy.

The above suggests that overcoming barriers to plant team cropping is possible when teams are unstructured, but that it can be further facilitated through use of structured cropping designs, particularly when coupled to PAT approaches and modern machinery to take advantage of placement technology and the often adaptable engineering that has evolved to deliver it. This does not imply that unstructured plant teams shouldn't be used, however, and as a higher proportion of solutions for unstructured plant teams are 'accessible' they may represent more suitable entry level systems for those not wanting to invest in less ubiquitous 'available' solutions (although some farmers will already have access to at least some of these – for example if already direct drilling). It does nevertheless support the suggestion that overcoming barriers to plant teams might be easier, or at least less restricted, where structured teams are adopted. To illustrate, pest control on a given species in a unstructured plant team is possible, as shown in Matrix 1, through initial species-specific seed treatment and subsequent use of low-risk, blanket approved biopesticides; if structured, however, additional options become available (e.g. band-spraying of targeted products) as seen in Matrix 2. In either case, it is worth remembering that initial selection of well-matched plant team combinations is critical, with possibilities to pre-empt and overcome barriers even at this stage (e.g. by selecting pest-suppressive plant teams to reduce the likelihood of needing to overcome barriers related to post-emergence pest management). Such overarching principals can also be applied to certain PAT solutions, where, for example, use of ISOBUS systems should make engagement with PAT easier as machines/systems can communicate across platforms, meaning that specific plant team targeted implements will be able to easily integrate into a general 'plant team' approach with other

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727284

machinery/PAT solutions from different manufacturers. In terms of easing pathways to PAT, it is also worth noting that RTK/autosteer, as required to achieve the necessary accuracy and repeatability of operations that could serve as solutions to barriers in structured plant teams, can be retro-fitted to any self-propelled machine, including both hydraulic and electric steered tractors, regardless of age (and thus avoiding the need for large capital investment in new machinery). For further optimisation and improving of accuracy, the same technology can be used to position the implement behind the tractor (e.g. the seed drill or sprayer).

6. Future solutions to Plant Team barriers

In developing the above matrices for plant teams, solutions to barriers have been included that were considered to be 'attainable' (i.e. theoretically available, but not widely accessible at the time of writing). It is worth mentioning, however, that several approaches identified as part of initial discussions with PAT specialists are not featured here as they were considered to be largely unavailable commercially at the time of writing. Specific plant team-friendly crop varieties, for example, would be theoretically achievable through breeding (Kiær *et al*., 2019) and could enhance plant team interactions in the field, or allow barriers such as herbicide application to be overcome. Conviso Smart sugar beet, bred for use with Conviso One broad spectrum herbicide (as it exhibits tolerance to its mode of action – i.e. acetolactate synthase, or ALS, inhibition), for example, is a system that demonstrates the potential of this approach. Current work on crop safeners could deliver similar benefits if introduced to plant team partners. Relatively rapid progress could be possible in this area through genetic modification or gene editing (e.g. CRISPR-CAS9) technologies where these are currently accepted, or permitted through policy change in the future.

Engineering, imaging, data processing/handling and 'Internet of Things' (IoT) developments could deliver similar potential to plant teams in the future as automation and precision are progressed beyond the current state-of-the-art and towards crop management systems that operate increasingly towards the level of a single plant. Small Robot Company, for example, are currently field testing a suite of interconnected and autonomous robots to deliver a 'farming as a service' system designed to manage crop establishment and inputs to very high levels of resolution that could translate well to operations in plant team mixtures. The relatively small sizes of these robots should also lend itself to operations requiring the highest levels of spatial accuracy (see above).

Based on the matrices above, it could be recommended that future solutions be directed to barriers such as DB4 ('Different sowing times') for unstructured teams, where no solutions currently exist; this presenting a market opportunity for any innovations that can fill this gap. As noted earlier, this barrier may be at least partly overcome by random broadcasting of certain understory species into growing crops and/or establishment of a full green understory into which a crop is subsequently direct drilled. Neither of these approaches is currently easily realised without compromising establishment of one or both of the plant team partners, however, this perhaps explaining why such solutions were not identified by PAT specialists in preceding work as potentially addressing this barrier. Taking this as an

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727284

example, it could be expected that opportunity exists here for innovations in areas such as seed treatment (e.g. to increase germination of seed broadcast into standing crops), seed spreading (e.g. to increase penetration of broadcast seed through the existing crop canopy) and advanced direct drilling (e.g. to improve establishment of crops sown directly into leys) to enter the market.

7. Role of other solutions to solving Plant Team barriers

As noted in previous work (Tippin *et al.*, 2019a), "other solutions to solving plant team barriers also need to be identified in addition to machinery and precision agriculture solutions". These are summarised below as previously defined:

- Effective communication between researchers, advisors, policy and farmers to help share experiences and advice when implementing plant teams.
- Increase the advice and guidance available to farmers and advisors, including hosting demonstration events, producing help guides and recommendations.
- Training and education of researchers and farmers to provide them with the skills, knowledge and confidence needed to implement plant teams.
- Initiatives to help with processing and marketing of end products, such as establishment of cooperatives to relieve processing and marketing pressures from individual farmers.
- Cost effective methods to manage plant teams, including case studies, that highlight the cost breakdowns of previous plant team implementation.
- Breeding programmes to ensure the best varieties and seed are available.
- Policy changes to encourage the uptake of plant teams and acknowledge the environmental benefits of plant teams to soil health.

It is worth noting that in one way or another, all of the above solutions could extend to assisting uptake of PAT/product/machinery solutions to plant team barriers. Taking "Effective communication between researchers, advisors, policy and farmers to help share experiences and advice when implementing plant teams" as an example, this could be highly beneficial to sharing best practice with PAT/product/machinery solutions, helping end-users to make decisions on which approaches to plant team cropping would suit their business, and which PAT/machinery investments might be considered most cost-effective for them when transitioning.

8. Conclusions

Trouble shooting matrices of PAT practical solutions to plant team barriers have been developed, demonstrating that such solutions exist at varying levels of accessibility for use across both unstructured and structured plant team designs. In addition to investigating PAT solutions, this work has been extended to consider product and machinery solutions (the latter of which are also being investigated within other European projects such as ReMIX, DiverIMPACTS, Diverfarming, and, albeit

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727284

to a lesser extent, TRUE), identifying opportunities to utilise chemical, biological and engineering solutions both independently of PAT, and when deployed alongside precision placement systems.

Overall it can be concluded that engagement with PAT is likely to facilitate plant team cropping by supporting access to an increased number of solutions, particularly in overcoming agronomic barriers, though it deserves note that some barriers can be addressed independently of PAT uptake, including for machinery solutions. Similarly, it can be concluded that solutions to barriers are more readily realised when adopting structured plant team designs, where these better lend themselves to delivery of solutions through PAT placement technologies. Nevertheless, accessing these additional solutions for structured teams is likely to require increased engagement with more specialist technology, such that the benefits of structuring plant teams must be balanced against the need for investment.

References

Brooker, R.W., Bennett, A.E., Cong, W-F., Daniell, T.J., George, T.S., Hallett, P.D., Hawes, C., Ianetta, P.M., Jines, A.J., Li, L., McKenzie, B.M., Pakeman, R.J., Paterson, E., Schöb, C., Shen, J., Squire, G., Watson, C.A., Zhang, C., Zhang, F., Zhang, J., White, P.J. (2015). Improving intercropping: a synthesis of research in agronomy, plant physiology and ecology. New Phytologist 206: 107-117.

Burns, H. (2012). Concepts in Crop Rotations. In: Alflakpui, G. (Ed), Agricultural Science. Intech, Croatia.

Cook, S.M., Khan, Z.R., Pickett, J.A (2007). The use of push-pull strategies in integrated pest management. Annual Review of Entomology 52: 375-400 .

George, D., Manfield, A., Banfield-Zanin, J. (2020) MILESTONE M38 Report. Complete discussions with PAT specialists. Developed by the EU-H2020 project DIVERSify ('Designing innovative plant teams for ecosystem resilience and agricultural sustainability'), funding by the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement Number 727284.

Hector, A., Hautier, Y., Saner, P., Wacker, L., Bagchi, R., Joshi, J., Scherer-Lorenzen, M., Spehn, E.M., Bazeley-White, E., Weilenmann, M., Caldeira, M.C., Dimitrakopoulos, P.G., Finn, J.A., Huss-Danell, K., Jumpponen, A., Mulde, C.P.H., Palmborg, C., Pereira, J.S., Siamantziouras, A.S.D., Terry, A.C., Troumbis, A.Y., Schmid, B., Loreau, M. (2010). General stabilizing effects of plant diversity on grassland productivity through population asynchrony and overyielding. Ecology 91: 2213–2220.

Kiær, L., Scherber, C., Brandmeier, J., Papagallo, S., Newton, A.C., Karley, A. (2019). Breeding for crop mixtures: Opportunities and challenges. European Conference on Crop Diversification, Sept 18-21 2019, Budapest, Hungary. Book of Abstracts (https://zenodo.org/record/3516329#.XzpEbZ5Kg2w), p362-363.

Pearce, B.D., Bickler, C., Midmer, A., Tippin, L., Schöb, C., Elmquist, H., Rubiales, D., Kiær, L., Tavoletti, S., Vaz Patto, M.C., Adam, E., George, D.R., Banfield-Zanin, J.A., Fustec, J., Bertelsen, I., Olesen, A., Otieno, J., Sbaihat, L., Scherber, C., Barradas, A. (2018) DELIVERABLE 1 (D1.1). Synthesis report on national stakeholder meetings. Developed by the EU-H2020 project DIVERSify ('Designing innovative

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727284

plant teams for ecosystem resilience and agricultural sustainability'), funding by the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement Number 727284.

Tippin, L., Banfield-Zanin, J., Midmer, A., Pearce, B., Bickler, C., Manfield, A., George, D. (2019a) DELIVERABLE 31 (D4.5). Report on practical restrictions imposed by plant teams. Developed by the EU-H2020 project DIVERSify ('Designing innovative plant teams for ecosystem resilience and agricultural sustainability'), funding by the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement Number 727284.

Tippin, L., Banfield-Zanin, J., Midmer, A., Bickler, C., Manfield, A. Karley, A., George, D., Pearce, B. (2019b). The perceived or realised practical restrictions imposed by plant teams. European Conference on Crop Diversification, Sept 18-21 2019, Budapest, Hungary. Book of Abstracts (https://zenodo.org/record/3516329#.XzpEbZ5Kg2w), p284-286.

Copyright

Citation

Please cite this report as follows:

George D.R., Manfield, A., Banfield-Zanin J.A. (2020). D4.6 (D32) – Report on Trouble Shooting Matrix of PAT practical solutions. Developed by the EU-H2020 project DIVERSify ('Designing innovative plant teams for ecosystem resilience and agricultural sustainability'), funded by the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement Number 72728.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727284

Appendix I

Summarised machinery and PAT solutions to plant team barriers as provided through discussions with a range of stakeholders with interests in this area. Columns show: company details; date of engagement; format of engagement (DCF = data capture form, OTO = one-to-one, TI = telephone interview, AE = agricultural event); detail of the solution; general relevance to barrier; and, specific relevance to 'barrier codes' (see text). Rows have been grouped by general relevance to overcoming barriers, but without further sorting (e.g. into generic and specific solutions) which will be undertaken as part of Deliverable 4.6. 'General' solutions are shaded orange, with 'specific' solutions unshaded.

Company	Date	Format	Detail	Relevance to overcoming barriers	Barrier code
Primewest	Feb 2020	TI	CombCut technology can be used to target broad leaved weeds in grass-based production systems such as cereals, where this could well to manage weed in low growing understories (e.g. clover) or to manage broad-leaved intercrops to supress them if needed.	Agronomy of plant teams	AB3
Primewest	Feb 2020	TI	Crimper Rollers have been developed for cover crop termination, but could potentially offer a solution for living mulch management – e.g. to 'knock back' green understories ahead of main crop drilling to manage crop-mulch competition during establishment.	Agronomy of plant teams	AB4
Garford	Jan 2020	AE	Depending upon the form and spatial arrangement of plant teams, automated robotic weeding systems (e.g. Robocrop) may be able to manually weed between individual plants, particularly where precision seeding operations have been undertaken.	Agronomy of plant teams	AB3
Manterra	Mar 2020	OTO	Strip till systems in general may help to supress weed species, e.g. where they are used to crop into living mulch plant teams or leys, also being of use to manage crop-crop competition in living mulch/ley plant team systems	Agronomy of plant teams	AB3 AB4

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727284

Company	Date	Format	Detail	Relevance to overcoming barriers	Barrier code
Manterra	Mar 2020	OTO	General topping mowers could be used to manage aggressive co-crops when at a height taller than the main crop, though only where compatible with the aims of the plant team. Different co crops would respond differently to this treatment, so this would need to be taken int account.	Agronomy of plant teams	AB3
Manterra	Mar 2020	OTO	Weed wipers could be used to target weeds protruding above the plant team canopy level	Agronomy of plant teams	AB3
Silsoe	Nov 2019	AE	Nozzle developments can help to better direct plant production / protection products, allowing increasingly accurate targeted of single species within mixtures, assuming that their spatial arrangement is amenable to band/strip spraying	Agronomy of plant teams	AB1 AB2 AB5
Manterra	Mar 2020	OTO	Precision sprayers would be able to potentially deliver crop treatments to plant teams, treating species separately assuming that they had been established in bands. This would potentially allow crop protection products to be applied to specific crops within a plant team, and would extend to application of foliar fertiliser	Agronomy of plant teams	AB1 AB2 AB5
Yara/Brandt/ Ilex/ Bionatureuk	Various	AE	A range of foliar nutrient and micronutrient options are available that could be of benefit to provided targeted nutrition to plant team species when delivered through precision sprayers.	Agronomy of plant teams	AB5
DuPort	Mar 2020	OTO*	Fertiliser injectors would permit liquid nutrition to be applied to the roots of individual crops within establishing plant teams, assuming that suitable spatial arrangements were followed (e.g. banding)	Agronomy of plant teams	AB5
CleanLight	Jan 2019	OTO*	UV field treatment of co-crops for plant team safe pathogen control could be used to overcome potential issues of chemical fungicide crop safety, though remains in its infancy for field crops and may not be universally safe for all plants.	Agronomy of plant teams	AB2

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727284

Company	Date	Format	Detail	Relevance to overcoming barriers	Barrier code
EBIC	Nov 2019	AE	Biostimulants could be used to balance competitive interactions in plant teams, encouraging facultative interactions between plant team species	Agronomy of plant teams	AB4 AB5
NuFarm	Nov 2019	AE	Certain herbicides may be 'safe' for multiple species constituting a plant team, allowing some chemical options for weed control. This is likely to be limited, however, with the chances of 'plant team safe' herbicides existing depending upon the specific nature of the plant team (e.g. for green clover understories in cereals some products may be available based on prior development for weed management in enriched pastures systems)	Agronomy of plant teams	AB3
Elsoms	Nov 2019	AE	Seed treatment for P&D on certain species, or to to promote growth of the main crop species and improve completive growth (e.g. by treatment with biostimulants)	Agronomy of plant teams	AB1 AB2 AB4 AB5
Manterra	Mar 2020	OTO	Numerous dual-product seeders (sometimes referred to as combi drills, though this is typically a term given to drills that additionally cultivate) have the capacity to place solid or liquid fertiliser with seed at drilling, allowing starter fertiliser or other product (e.g. biostimulants) to be placed with or near seed and potentially provided variably in linear plant team arrangements where this is of benefit (e.g. in cereal legume mixes, where only the former needs N)	Agronomy of plant teams	AB5
Manterra	Mar 2020	OTO	Highly accurate seed placement through precision seed drills will help to establish either single or multiple crops at optimum plant-plant or species-species spacings to minimise competition and maximise facilitation. Coupling this to RTK/autosteer would further allow seed to be sown at optimal spacings in repeat passes (e.g. if one species was sown in the first pass, and another in the second pass), with precision seeding also facilitating other precision-based operations (e.g. mechanical weeding)	Agronomy of plant teams	AB4
Bednar	Jan 2020	AE	If coupled to precision seeding and delivered by RTK autosteer, appropriate spatial arrangements of plant teams could be compatible with Bednar's range of interrow weeders.	Agronomy of plant teams	AB3

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727284

Company	Date	Format	Detail	Relevance to overcoming barriers	Barrier code
Garford	Jan 2020	AE	If coupled to precision seeding and delivered by RTK autosteer, appropriate spatial arrangements of plant teams could be compatible with Garford's range of interrow weeders.	Agronomy of plant teams	AB3
Monsanto	Feb 2019	OTO	Use of desiccants, such as glyphosate, could partially overcome issues with varying crop maturity at time of harvest, also offering a means to manage plant team development (e.g. in strip-tilled clover systems)	Agronomy of plant teams	AB4
Bayer	June 2019	OTO*	Conviso One herbicide application coupled to Conviso Smart (ALS tolerant) sugar beet is a system that demonstrates the potential of breeding to develop main crop varieties that could be grown alongside plant team partners, whilst retaining the ability to control if latter if needed as insurance as crop-crop competition.	Agronomy of plant teams	AB4
Cotswold Seeds	Nov 2019	OTO*	Certain plant team species can be included that naturally appear to supress weed growth, or deliver gains targeted to pest/disease control	Agronomy of plant teams	AB1 AB2 AB3
OroAgri	Nov 2019	AE	Low-risk plant protection products with blanket approvals are beginning to be developed for outdoor use, and are already widely used in protected cropping, theoretically allowing such products to be applied across crops in plant teams with no labelling issues	Agronomy of plant teams	AB1 AB2
Agrardienstleis-tungen Häfeli	Sept 2019	DCF	Utilisation of fertiliser spreaders to apply one seed species, whilst the other is sown through the drill, allowing separation (to a degree) of seed species and sowing depths, though with this being limited to surface sowing through the spreader	Agronomy of plant teams	DB1 DB2 DB3
John Deere	Sept 2019	OTO	The 750A is a good example of how mainstream operating machinery can be relatively easily adapted to overcome barriers presented by plant team cropping. It contains two separate seed distribution hoppers and can be relatively easily set-up to establish multiple crops in a single pass. An additional seed metering unit could be fitted to one of these hoppers to allow seed to be sown at different rates, and as coulters are independently adjustable seed could be	Establishment of plant teams	DB1 DB2 DB3

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727284

Company	Date	Format	Detail	Relevance to overcoming barriers	Barrier code
			sown for each hopper at species-specific depths. The 750A also benefits from high performance across a wide operating range, including into stubbles or ploughed soils, and is capable of sowing seed ranging from large (e.g. beans) to small (OSR).		
Bednar	Jan 2020	AE	Bednar's Omega series of seed drills offers a flexible and configurable system capable of sowing multiple seed of varying sizes at varying rates/depths in a single pass (up to three species as standard, with addition of one through the fertiliser spreader, or via an additional ALFA seeding unit) and configurable with varying row widths and depth control. Developed with plant team establishment in mind, the Omega system is specifically marketed on the basis of its ability to establish plant teams across a wide range of working conditions, with integration with Bednar's 'chisel plough' (TerraStrip) expanding plant team potential by offering deeper tillage in strips (potentially down to >60cm).	Establishment of plant teams	DB1 DB2 DB3
Horsch	Jan 2020	AE	Horsch's Focus TD range represents a readily available, versatile, flexible and configurable cultivation/seeding/fertiliser placement system that is adaptable to overcoming establishment challenges of plant teams	Establishment of plant teams	DB1 DB2 DB3
Trimble Agriculture	May 2018	OTO	Precision Agriculture Technology can be used to allow different crop species to be drilled in multiple machinery passes, effectively establishing main crop in one pass, and then offsetting to establish co-crop in another (with drill depth adjustment for multiple seed depths possible at this stage). To ensure repeatability and sub-inch accuracy of this operation, as required to provide sufficient separation of co-crops, RTK/autosteer would be required, which can be retro-fitted to any self-propelled machine, including both hydraulic and electric steered tractors, regardless of age and thus avoiding the need for large capital investment in new machinery. For further optimisation and improving of accuracy, the same technology can be used to position the implement behind the tractor (in this case the seed drill).	Establishment of plant teams	DB2 DB3 DB4
Laforge Dynatrac	Oct 2019	OTO*	Side-shifters such as the Dynatrac can be used to deliver high accuracy operations with mounted implements, which could allow levels of precision relevant to overcoming plant team barriers to be realised across a range of operations – e.g. product application to individual species in plant teams arranged in rows.	Agronomy of plant teams	AB1 AB2 AB3 AB4

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727284

Company	Date	Format	Detail	Relevance to overcoming barriers	Barrier code
					AB5
Weaving	June 2019	AE	Weaving drills are able to sow multiple seed in a single pass, including seed of different sizes (e.g. cereal and bean seed). Addition hoppers can be used to place fertiliser precisely, potentially allowing starter N to be provided to the main crop (e.g. cereal) without application to the co-crop if needed (e.g. if the co-crop were a legume)	Establishment of plant teams	DB1 DB2 DB3
Vaderstad	Mar 2020	OTO*	Dual-product seeder functionality is provided by Vaderstad's 'Biodrill', a mountable small seeder that can be fitted on Väderstad cultivators and seed drills, further improving the functionality/versatility of existing drills to deliver precision seeding of multiple seed species.	Establishment of plant teams	DB1 DB2
Kuhn	Jan 2020	AE	Striger strip-till of potential use for establishing plant teams, particularly living covers, offering flexibility in terms of tillage depth and width settings. Apparently designed for stubbles, where functionality in green covers may be reduced due to increased workload.	Establishment of plant teams	DB4
Baertschi	Mar 2020	OTO	Baertschi's Osakem strip till offers a fixed width strip till design with variable width settings available on different models and options for added seeding/hopper units for single pass cultivating-sowing. Being independently powered via the PTO the Osakem system has a wide working range, and is particularly well suited to strip cultivation operations in living mulches/leys.	Establishment of plant teams	DB4
Bednar	Jan 2020	AE	Bednar's Strip Master EN strip till system is marketed as being able to operate across a wide range of conditions, including heavy stubbles, supporting potential for use in plant team establishment operations where strip cultivation into green understories may be desirable.	Establishment of plant teams	DB4
Manterra	Mar 2020	OTO	Precision drills with seed hoppers fitted to each coulter easily allow multiple species to be sown simultaneously in rows, with depth and metering adjustment of each hopper/coulter permitting seed specific rates and depths to be selected	Establishment of plant teams	DB1 DB2 DB3

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727284

Company	Date	Format	Detail	Relevance to overcoming barriers	Barrier code
Matermacc	May 2018	OTO	Precision drills can potentially sow multiple species in a single pass, also spacing seeds evenly and (if needed) at varying depths to minimise competition and maximise establishment	Establishment of plant teams	DB1 DB2 DB3
JHI	Nov 2019	DCF	Originally developed for pasture systems, the cross slot is a low disturbance drill capable of drilling different seed at multiple depths. It is particularly effective at drilling into leys, though is arguably less versatile than other dual-product seeders with possible weight concerns being relevant in heavier soils (due to compaction risk). One possible advantage of the cross slot is its relatively wide coulter spacings which, with RTK/autosteer, could lend themselves to establishing plant teams in multiple passes, with depths and rates adjusted for each pass depending upon seed requirements	Establishment of plant teams	DB1 DB2 DB3
Claydon	Nov 2019	AE*	Claydon's Hybrid range represents a readily available, versatile, flexible and configurable cultivation/seeding/fertilser placement system that is adaptable to overcoming establishment challenges of plant teams	Establishment of plant teams	DB1 DB2 DB3
MKMartin	Aug 2019	OTO*	StripCat offers a flexible strip till design with variable width settings and options for added seeding units for single pass cultivating sowing. Designed for stubbles, where functionality in green covers may be reduced due to increased workload.	Establishment of plant teams	DB4
SOILKEE	Feb 2020	OTO*	Renovator system adopts a strip-tillage approach targeted to pasture systems, offering PTO powered cultivation to allow working into green covers.	Establishment of plant teams	DB4
JHI	Nov 2019	DCF	Use of desiccants, such as glyphosate, could partially overcome issues with varying crop maturity at time of harvest, where this could be further combined with deployment of NDVI sensing to deliver variable rate application.	Agronomy of plant teams	HB1

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727284

Company	Date	Format	Detail	Relevance to overcoming barriers	Barrier code
Innovative Farmers	July 2019	OTO	Low tech seed sorting technology exists that can separate seed of different sizes, with basic set-ups being possible to construct 'in-house'. These are likely to be more applicable to situations where seed of different species is easily separated (i.e. where it is notably different - e.g. cereal and legume grains)	Harvest of plant teams	HB2
QualySense AG	June 2019	TI	High tech seed sorting technology is available that is capable of separating seed based on spectral scanning of traits including quality and species. At present this technology is probably too expensive to be applied to whole crop separation at the farm scale, but in the future would represent a means of separating seeds of identical sizes, based on other traits (e.g. reflectance)	Harvest of plant teams	HB2
Shellbourne Reynolds	Mar 2020	OTO*	By utilising a stripper header it should be possible to harvest grain from the upper parts of cereal crops whilst avoiding damage to or contamination of harvest by lower growing plant teams, and potentially allowing harvest of these at a different timing. With refinement, it may also be possible to reconfigure separators within combines to seed-sort from certain plant teams where stripper headers are used, this being achievable if separator requirements to sort biomass from grain is reduced (where less biomass would be harvested by the stripper header than a normal cutter), thus theoretically freeing separation capacity for other tasks.	Harvest of plant teams	HB1 HB2
JHI	Nov 2019	DCF	Lifting of the combine head could be used to harvest taller crops in plant teams assuming that other crops were shorter, and minimal lodging was present, where such an approach could work especially well where relay intercropping. Strip cropping could also be amenable to standard combining if strip widths were set to match combine headers (and assuming that this approach would still be within classification parameters of a 'plant team').	Harvest of plant teams	HB1 HB2
ISOBUS	Mar 2020	OTO*	Machine communication protocols driven by ISOBUS systems	Underlying software systems to operate plant team promoting operations	OB

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727284

Company	Date	Format	Detail	Relevance to overcoming barriers	Barrier code
Manterra	Mar 2020	OTO	Crop sensing systems in general could be of benefit to overcoming plant team barriers in several areas, though commercial offers remain relatively low resolution, especially when satellite based. Nevertheless, some systems (e.g. YARA/ISIARI) utilse imaging to drive map creation and inform agronomic inputs at 2-3m resolutions, which could prove useful in some instances (e.g. strip intercropping), with higher resolutions expected to be a feature of future developments in this sector	Plant team planning+	Multiple
Manterra	Mar 2020	OTO	Farm/field profitability software is now readily available with good uptake and could offer decision support to help to overcome confidence barriers of plant team cropping, also informing on-farm or in-field areas most suitable to plant team approaches, dove-tailing to decision support systems being developed in the DIVERSify project	Plant team planning	OB
Hutchinsons	Dec 2019	OTO	Mapping services such as TerraMap/Omnia can be used to prioritise areas/fields to be moved into plant team cropping, helping farmers transition	Plant team planning	OB
DroneAg	Jan 2020	AE	Imaging platforms and remote services could be used to identify fields within a farm, or even areas within a field, where plant team cropping is likely to yield most benefit, which could prove especially useful in the future if coupled to decision tools for plant team selection	Plant team planning	OB
Skippy Scout	Jan 2020	AE	Imaging platforms and remote services could be used to identify fields within a farm, or even areas within a field, where plant team cropping is likely to yield most benefit, which could prove especially useful in the future if coupled to decision tools for plant team selection	Plant team planning	OB
Small Robot Company	Oct 2019	OTO*	Precision/image based ‘farming as a service’ system designed to autonomously manage crop establishment and inputs to high levels of resolution that could translate well to near-single plant operations in plant team mixtures. Currently under development / proof-of-concept, so not currently widely accessible.	Plant team planning+	Multiple

*no direct interaction, but with technology-specific information provided through a third-party during discussion

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 727284