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► To cite this version:

Philippe Debaeke, Rémi Perronne, Nathalie Colbach, Delphine Moreau, Philippe Barre, et al.. Non-chemical weed management: Which crop functions and traits to improve through breeding?. Crop Protection, 2024, Crop Protection, 179, pp.106631. 10.1016/j.cropro.2024.106631 . hal-04506690

HAL Id: hal-04506690

<https://hal.science/hal-04506690v1>

Submitted on 27 Mar 2024

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Non-chemical weed management: which crop functions and traits to improve through breeding?

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Abstract

The agro-ecological transition aims at reducing the anthropogenic impacts of crop production on the environment, for instance by decreasing drastically the applications of pesticides, among which herbicides are the most prevalent. In this review, we focus on management of arable weeds in agro-ecological systems, considering a perspective of steady reduction of synthetic herbicides by fostering the breeding of varieties adapted to non-chemical weed management. Diverse strategies of non-chemical weed management are discussed, taking into account agronomic levers and identifying breeding targets. Weed suppression by enhancing crop competition from cash or cover crops, grown in pure stands or as intercrops, is a key strategy that could be considered together with dense canopies and optimal nitrogen management, also in addition to growing varieties that are tolerant to weed competition and/or characterized by low nitrogen requirements. Then, escaping weed competition could be achieved by shifting sowing dates and/or diversifying crop rotations, particularly by targeting varieties of different maturity groups, more productive spring-sown crops and integrating more frequently minor crops in the rotation. Weeds can be also suppressed by mechanical control that requires varieties tolerant to mechanical weeding. Allelopathy is a less applied strategy that deserves further studies *e.g.* the screening of allochemical composition among varieties of cash and cover crops. For each crop-related agronomic lever contributing to integrated weed management, we identify the functional crop traits to target, *i.e.* the set of morpho-physiological traits associated with an effective weed management, to be screened within the commercial variety panels or to be integrated in a genetic improvement scheme. For all the functional traits and according to the crop species, the potential availability of genetic resources, as well as the ability of varieties to meet the required genetic variability have been explored while, where relevant, the development of appropriate phenotyping methods and trait assessment procedures have been considered. Finally, we propose a set of non-chemical weed management strategies, functional effect traits and agronomic practices associated, as well as their synergies and antagonisms with the other cropping practices for cash and cover crops. We conclude that, to better combine a set of agronomic levers with crop varieties or reinforcing the efficacy of these levers, there is a need to complete classical agronomy and weed science approaches by plant genetics and breeding when designing and evaluating non-chemical weed management strategies.

Key-words : crop competitiveness ; diversification ; integrated weed management ; traits ; plant breeding

43

44 **Introduction**

45 Currently, farmers are experiencing real difficulties to control weeds due to the increasing number of cases
46 of herbicide resistance, the withdrawal of active ingredients not compensated by new authorizations, the
47 costs of mechanical weeding and the hazards due to climate change (Délye *et al.*, 2007; Délye *et al.*, 2016;
48 Birthisel *et al.*, 2021; Storkey *et al.*, 2021; Chauvel *et al.*, 2022). Based on the literature, we assume that the
49 efficient combination of genetic and agronomic levers would make it possible to take advantage of biological
50 regulations within agroecosystems to, at least partially, overcome these difficulties (Petit *et al.*, 2015;
51 Lamichhane *et al.*, 2016; Weisberger *et al.*, 2019). Moreover, this would allow contributing to the
52 conservation of water quality and biodiversity in response to the aspirations of a safer environment by the
53 society and farmers (van der Werf, 1996; Lechenet *et al.*, 2017).

54 For at least three decades, several agronomic levers have been suggested in a context of integrated weed
55 management (IWM) towards the reduction of the dependency on herbicides applied on croplands (Clements
56 *et al.*, 1994; Debaeke *et al.*, 1997; Liebman and Gallandt, 1997; Melander *et al.*, 2005; Nazarko *et al.*, 2005;
57 Blackshaw *et al.*, 2006; O'Donovan *et al.*, 2006; Pannaci *et al.*, 2017 ; Birthisel *et al.*, 2021), notably to control
58 arable weeds in organic farming, which is strictly dependent on non-chemical levers (Bond and Grundy,
59 2001). Now, moving towards agroecological systems, additional levers have been suggested and evaluated
60 for weed control (e.g. crop diversification; Gaba *et al.*, 2014; Weisberger *et al.*, 2019; Riemens *et al.*, 2022).
61 Beyond the steady reduction of herbicides applied, a new aim has also emerged, a pesticide-free agriculture
62 (Jacquet *et al.*, 2022), requiring to substitute systematically the chemical options by a panel of agronomic
63 and genetic levers. The implications of integrated weed management for plant breeding have not been
64 extensively reported so far and crop competitiveness has not been considered as a priority goal for breeders
65 (Pester *et al.*, 1999), except in organic farming (Wolfe *et al.*, 2008 ; Rolland *et al.*, 2017). In this context, the
66 released varieties are characterized by a reduced competitiveness against weeds as compared to ancient
67 varieties (Lever *et al.*, 2022a; Federico *et al.*, 2023).

68 The present review aims to determine the crop functions that should be emphasized for efficient non-
69 chemical weed management and the related traits that should be promoted by breeding. One main avenue
70 is to increase crop diversification in time and space, including the use of major and minor cash and cover
71 crops, either grown as sole crops, intercrops or relay crops, as well as their optimal sequencing in a rotation
72 and the choice of the best varieties. To sustain the competitiveness against weeds, other production-oriented
73 levers such as sowing date, crop density and amounts of nitrogen fertilisation must be optimized to increase
74 the efficiency of weed control. Therefore beyond the traits related to crop competitiveness, this integrated
75 weed management approach aims to highlight a new set of traits for breeding and variety choice.

76 For each crop-related agronomic lever contributing to integrated weed management, we identified the
77 functional crop traits to target, *i.e.* the different traits associated with an effective weed management to be
78 screened within the panels of commercial varieties or to be integrated in a breeding improvement scheme.
79 In the present review, we used the term functional trait in a broad sense, *i.e.* by considering a trait as any
80 morphological, physiological or phenological characteristic measurable at the individual level (Violle *et al.*,
81 2007), but also including other characteristics not measurable at the individual level. In this respect,
82 consideration have been given to the rules to assemble the various agronomic levers. For all the functional
83 traits, the potential availability of genetic resources and sufficient genetic variability have been explored, and
84 the development of appropriate phenotyping methods has been considered. To summarize, we propose to
85 discuss a set of non-chemical weed management strategies, functional traits and associated agronomic

86 practices, as well as their synergies and antagonisms with other weed management strategies for cash and
87 cover crops.

88 These non-chemical levers fell into three categories:

- 89 • The first category is based on the competitive ability of the crop species, and their associated
90 management, grown as sole crops or intercrops, cash crops or cover crops (§ 1-4);
- 91 • The second category is based on several escaping strategies based on the diversification or changes of
92 sowing dates and crop sequences in rotation which offer more opportunities to control weeds and reduce
93 the exposure of the crop to severe flushes of weed emergence (§ 5-6);
- 94 • The third category is based on various weeding techniques such as mechanical destruction of emerging
95 weeds or weed suppression using biocontrol techniques notably allochemicals released by main crops or
96 cover crops, also known as service crops, as living stands or residues (§ 7-8).

97 **1 Crop competitiveness against weeds based on canopy cover capacity**

98 Crop competitiveness against weeds includes two components, *i.e.* the ability of high weed suppression and
99 a high tolerance to weed competition (Lemerle *et al.*, 2001; Zerner *et al.*, 2016). Weed suppression
100 corresponds to a reduction in weed biomass and/or weed seed production by the crop, thus considering
101 consequences on the replenishment of the soil seed bank and seed dispersal (Coleman *et al.*, 2001; Mason
102 *et al.*, 2008; Worthington and Reberg-Horton, 2013; Zerner *et al.*, 2016). Crop tolerance means lower yield
103 loss in the presence of a same weed flora (Lemerle *et al.*, 2006; Zerner *et al.*, 2016). Covering the soil rapidly
104 after sowing and maintaining the canopy cover throughout the season is a strategy for maximizing radiation
105 capture, limiting soil water evaporation and controlling weed development. Canopy cover capacity is a
106 function to be improved genetically in a perspective of integrated weed management (Andrew *et al.* 2015),
107 which is already partially exploited, in particular in organic farming (Wolfe *et al.*, 2008; Fontaine *et al.*, 2009;
108 Rolland *et al.*, 2017; Lever *et al.*, 2022a). So far, most of the studies have been conducted on straw cereals
109 (Lemerle *et al.*, 2001; Mason and Spanner, 2006). However, opportunities exist also for oilseed rape (Sim *et al.*
110 *et al.*, 2007a; Lemerle *et al.*, 2014; Mwendwa *et al.*, 2020a), soybean (Hammer *et al.*, 2018) and grain legumes
111 (*e.g.* lentils, chickpeas, field peas) which severely suffer from competition with weeds during early growth
112 (Tepe *et al.*, 2005; Paolini *et al.*, 2006; Harker *et al.*, 2008; Jacob *et al.*, 2016).

113 In a context of input reduction and climate change, crop competitiveness should necessarily also include
114 competition for soil nutrients and water, which means to consider root system architecture and functioning.
115 However, this section focuses on the special case of canopy cover capacity, related to the architecture of the
116 canopy and its growth over time.

117 **1.1 Associated traits**

118 The canopy cover capacity and the related shading ability depend on the speed of soil cover by leaf area, a
119 criterion combining the architecture of the aboveground parts with their growth rates (Wolfe *et al.*, 2008;
120 Fontaine *et al.*, 2009). The literature mentions a set of traits, usually referred to as early vigour, canopy
121 closure or light interception (Christensen, 1995; Huel and Hucl, 1996; Benaragama *et al.*, 2014; Worthington
122 *et al.*, 2015a; Mwendwa *et al.*, 2020b; Kucek *et al.*, 2021; Aharon *et al.*, 2021; Hendriks *et al.*, 2022). As canopy
123 cover capacity is an integrative criterion, it includes simpler functional traits such as leaf area, leaf habit, plant
124 height, growth habit, growth rate and tillering capacity for cereals (Didon, 2002; Mason *et al.*, 2007a, 2008;
125 Szewczyk, 2013; Hendriks *et al.*, 2022; Lever *et al.*, 2022a). The germination and emergence of weeds may
126 also be affected by crop shading if weed seeds fall and germinate on the soil surface as in no-till systems
127 (Batlla and Benech-Arnold, 2014). In addition, if the crop root system develops fast enough and uses most of

128 the available water, weed seeds will lack water to germinate and emerge successfully. The relative responses
129 of crop and weed plants to shading (quantitative and qualitative changes in radiation) is also a key factor in
130 crop ability to compete with weeds (Holt, 1995; Ballaré and Casal, 2000; Colbach *et al.*, 2019; Kucek *et al.*,
131 2021). The relative time of emergence of weeds and crops will modulate the efficacy of canopy cover for
132 controlling weed survival and growth (Fahad *et al.*, 2015).

133 **1.2 Associated agronomic practices**

134 The date and method of sowing, crop density and row width are associated with agronomic practices to be
135 adapted locally to each crop and type of variety to reinforce the influence of the canopy cover capacity and
136 the competitiveness of the variety, whether the latter should cover the row only (in case of hoeing of inter-
137 rows) or also the interrow (Rasmussen *et al.*, 2004; Hansen *et al.*, 2007; Mason *et al.*, 2007 b; Sim *et al.*,
138 2007b; van der Meulen and Chauhan, 2017; De Vita *et al.*, 2017; Lazzaro *et al.*, 2017; Hammer *et al.*, 2018).
139 As an example, higher crop density and/or reduced row width will enhance the competitive ability of a
140 variety. In early or late spring sowings, starter fertilisation and/or supplementary irrigation may be
141 sometimes necessary to foster crop establishment and soil cover under less favourable conditions
142 (Mohammadi and Amiri, 2011). With climate change, due to the increasing occurrence of drought, these
143 practices could be also relevant for early-sown autumn crops such as oilseed rape in order to promote plant
144 establishment and early vigour.

145 **1.3 Evaluation methods**

146 The canopy cover capacity can be estimated directly by visual assessments using a predefined well-chosen
147 grading scale for the functional trait measured, or indirectly by proxies derived from dynamic measurements
148 of reflectance with on-board (UAV, satellite) or hand-held sensors as the Normalized Difference Vegetation
149 Index (NDVI) (Xie and Yang, 2020). These proxies can estimate the soil cover rate or directly the leaf area
150 index (LAI) at the canopy scale, especially in the absence of early biotic and abiotic stresses (*e.g.* frost damage,
151 early senescence due to leaf disease). They also give access to the potential canopy growth dynamics (Huel
152 and Hucl, 1996; Worthington *et al.*, 2015a; Zerner *et al.*, 2016; Aharon *et al.*, 2020; Milan *et al.*, 2020). The
153 Light Detection and Ranging (LiDAR) technology is a powerful tool for direct 3D measurement of plant
154 structure giving access to canopy height (Omasa *et al.*, 2007). These methods can be easily applied to
155 common plot-based experimental designs used for comparing the performances of a set of varieties under
156 multi-environment trials. Traits should be measured in standard conditions (*e.g.* crop density, nutrients and
157 water availability, either in field or controlled experiments) in order to be used as parameters in process-
158 based models.

159 **2 Crop tolerance to reduced nitrogen supply**

160 Reducing the application of mineral nitrogen fertilizers in crops is required to decrease their negative
161 environmental impacts (Sutton *et al.*, 2011). Several positive effects could also be expected in straw cereals,
162 such as (1) maximising nitrogen use efficiency (Jeuffroy *et al.*, 2013), (2) reducing the development of some
163 foliar diseases (*e.g.* brown rust, septoria, Simon *et al.*, 2003), and (3) limiting the risk of physiological lodging
164 (Wu *et al.*, 2019). In addition, temporary crop nitrogen deficiencies do not systematically lead to crop yield
165 losses, especially in case of early deficiencies (Ravier *et al.*, 2017). Therefore, reducing the use of mineral

166 nitrogen fertilizer under certain circumstances can be both environmentally and economically profitable in
167 cereals (Loyce *et al.*, 2012).

168 For a moderate nitrophilic crops species such as wheat, adjusting nitrogen fertilisation to crop nitrogen
169 requirements or below may theoretically lead to beneficial effects to manage weeds, especially by reducing
170 the growth of nitrophilic weeds that are generally the most problematic ones (Moreau *et al.*, 2014). However,
171 in some field experiments, weed pressure was not lowered when the use of mineral nitrogen fertilizers was
172 reduced. Perthame (2020) indicated that, in most cases, weed pressure even increased, suggesting complex
173 interactions among different factors (crop traits, cropping practices, composition of the weed flora, initial
174 amount of soil nitrogen) and making it difficult to identify general rules. To go further, simulation studies
175 based on a mechanistic model are in progress (Moreau *et al.*, 2021).

176 **2.1 Associated traits**

177 Knowledge is available on which crop traits provide a competitive advantage over arable weeds. In standard
178 situations with soil nitrogen availability, crop plants with a high growth potential, a low root to total biomass
179 ratio, a high efficiency of each root unit to take up nitrogen, and a low nitrogen demand (per unit of leaf
180 biomass) could have a competitive advantage (Moreau *et al.*, 2014; Perthame *et al.*, 2020). In situations of
181 low soil-nitrogen availability, root traits could become more crucial. For instance, a large proportion of fine
182 roots could become useful as fine roots pre-empt the larger part of soil resources (Freschet and Roumet,
183 2017). Also, roots with a large diameter could provide an advantage as they can penetrate through soil layers
184 and elongate faster (Eissenstat, 1992; Pages, 1995), thereby providing access to the deepest soil resources,
185 such as leached nitrate (Chen *et al.*, 2013).

186 **2.2 Associated agronomic practices**

187 Different agronomic practices related to nitrogen fertilisation can be implemented to drive crop-weed
188 competition (Perthame, 2020). Modifying the amount of nitrogen fertilizer was discussed above.
189 Alternatively, modifying the timing of nitrogen application could affect crop-weed competition but,
190 depending on the studies, either weeds or crops may benefit from such modifications (Perthame, 2020).
191 Nitrogen can also be applied locally on the sowing row (rather than broadcasted) in order to make it more
192 directly available to crop plants than to weed plants emerging in the inter-row (Rasmussen *et al.*, 1996). This
193 method proved its effectiveness in promoting crop growth and maintaining crop yield for wide row crops,
194 such as maize or sunflower (Perthame, 2020). To adapt nitrogen fertilisation to each particular production
195 situation (*i.e.* cropping system, weed flora, soil and climate), models and decision support tools that simulate
196 the crop nutritional status and crop-weed interactions can be used (Moreau *et al.*, 2021).

197 **2.3 Evaluation methods**

198 Currently, measurements of the crop traits described above remain complex and time-consuming in field
199 conditions. Other non-destructive methods could be tested based on sensors for determining the plant
200 nutrition status or the change in leaf area resulting from the application of N fertilization (based on canopy
201 reflectance, leaf transmittance, or chlorophyll and polyphenol fluorescence) (Munoz-Huerta *et al.*, 2013; Xie
202 and Yang, 2020). Field experimental designs with monitored soil and plant nitrogen status and sown weeds
203 or natural infestations could be implemented. Differences between varieties in root traits can be more easily
204 analysed in controlled conditions, using high-throughput phenotyping of root structures (Jeudy *et al.*, 2016).

205 **3 Intercropping of annual crops to suppress weeds**

206 The practice of intercropping by combining two annual crops has shown multiple potential benefits (Martin-
207 Guay *et al.*, 2018; Zhang *et al.*, 2019 ; Yan *et al.*, 2024), including weed suppression. In a recent meta-analysis,
208 Gu *et al.* (2021) emphasized that weed biomass was lower in the intercrop than in both crops tested in pure
209 stands in 45% of the cases studied. In addition, weed suppression by intercrops was on average comparable
210 to that of pure stand of the more competitive species in the mixture. These results hide differences due to
211 the composition of intercrop, from maize/soybean to straw cereal/grain legume intercrops, both in terms of
212 experimental designs and geographical areas. The better weed suppressive ability of intercrops seems to
213 mainly originate from the stronger weed suppressive crop component, while the weaker competitive
214 component may also be affected by competition of the most competitive crop, requiring finding a relevant
215 balance between the two crop components (Gu *et al.*, 2021). Weed suppression is related to the increased
216 capture of light resources by the intercrop compared with sole crops (Stomph *et al.*, 2020). The measurement
217 of weed suppressive ability currently considers only the reduction of weed biomass due to the composition
218 of intercrop compared to pure stands, without taking into account the functional traits of the crops. However,
219 some studies suggest relationships between traits chosen and the performance of the intercrop (Demie *et*
220 *al.*, 2022).

221 **3.1 Associated traits**

222 In a recent paper, Kiær *et al.* (2022) defined three categories of traits as breeding targets for cereal/legume
223 intercropping, including complementary traits related to species synergy during the growth period, such as
224 mixing ability. We propose to include the competitiveness of the mixture in this category, knowing that the
225 competitive ability is based probably on a set of traits common to the mixing ability. Breeding for intercrops
226 therefore requires to define the targeted level of interactions between crop species in comparison to the
227 targeted level of weed suppression, for example by increasing the competitive ability of the expected less
228 competitive component of the intercrop (see *e.g.* Annicchiarico *et al.*, 2021). This search for a trade-off
229 between the weed suppression ability and the yield of the least competitive crop components also explains
230 the choice of crop species for intercropping, *e.g.* for lentil-based (Kiær *et al.*, 2022) or soybean-based
231 (Cherière *et al.*, 2020).

232 **3.2 Associated agronomic practices**

233 Several agronomic practices influence weed suppression in intercrops, including the composition of the
234 intercrop, the plant density (which is higher in additive sowing designs), and the type of row intercropping
235 (with species mixed within the rows being more suppressive than two species sown in alternate rows; Gu *et*

236 *al.*, 2021). Other agronomic practices do not influence weed suppression in intercrops compared to pure
237 stands, such as nitrogen supply rate or relay cropping vs simultaneous intercropping (Gu *et al.*, 2021).

238 **3.3 Evaluation methods**

239 Current issues focus on the definition of breeding schemes adapted to intercropping (Kiær *et al.*, 2022),
240 including the development of efficient experimental designs (Haug *et al.*, 2021; Moutier *et al.*, 2022).

241 Until now, the assessment of mixing ability is generally focused on the yield of the two components in sole
242 crops and in intercrops. Even if herbicides are not applied in intercrops, the resulting weed biomass is not
243 routinely measured to appreciate the efficacy of various cultivar mixtures in suppressing weed growth.

244 **4 Weed suppression using temporary cover crops**

245 Weed growth can be also limited or suppressed by competition with temporary or permanent cover crops,
246 which are not harvested, either sown before (during fallow period) or simultaneously with the harvested
247 crop (Hartwig and Ammon, 2002; Hiltbrunner *et al.*, 2007a-b; Verret *et al.*, 2017 a-b; Vincent-Caboud *et al.*,
248 2019; Bhaskar *et al.*, 2021). In both cases, the term multi-service crop (Justes and Richard, 2017) is now used
249 as these cover crops provide several ecosystem services and benefits for farmers, including weed suppression
250 (Gerhards and Schapper, 2019).

251 Several recent reviews and meta-analyses confirmed that sowing autumn-to-spring cover crops is an efficient
252 method for suppressing weeds and volunteer crops in temperate areas, thus constituting a main component
253 of integrated weed management programs in annual and perennial cropping systems (Osipitan *et al.*, 2018;
254 Osipitan *et al.*, 2019; Gerhards and Schappert, 2019; Kumar *et al.*, 2020; Fernando and Shrestha, 2023).
255 Weed-suppressive cover crop stands can limit seed rain from summer- and winter-annual weed species,
256 reducing weed population growth and ultimately weed pressure in future cash crop stands.

257 In temperate areas, cover cropping is possible between the harvest of winter- or early-spring sown crops and
258 the sowing of spring-sown crops. A vegetation period of at least 6 weeks with favourable growing conditions
259 is required but the vegetation duration could range from 3 to 8 months depending on the termination date
260 (nature of the cover crop, sowing date of subsequent crop, soil type, winter harshness). Cover crops are
261 generally mechanically (e.g. disking, mowing, rolling, undercutting) or chemically destroyed in autumn or
262 early spring, and sometimes frost-killed in some regions (Gerhards and Schappert, 2019). Cover crops can be
263 sown no-till immediately after harvesting the cash crop or 1-2 weeks later after shallow stubble tillage. Rapid
264 emergence and canopy closure of cover crops is crucial for successful suppression of weeds and volunteer
265 crops. The most common winter-killed cover crops are *Sinapis alba*, *Phacelia tanacetifolia*, *Raphanus sativus*
266 and several clover species and grasses. Cover crops more adapted to dry and warm weather conditions
267 include *Avena strigosa*, common buckwheat, *Guizotia abyssinica*, *Vicia sativa*, linseed, sunflower and
268 *Camelina sativa*. Frost-tolerant cover crops also exist such as winter rye and ryegrass species (Gerhards and
269 Schappert, 2019).

270 The effects of cover crops on weed suppression and the underlying mechanisms are not fully understood.
271 However, in the recent literature, cover crops have been reported to suppress weed populations using
272 various mechanisms of plant interactions (Kruidhof *et al.*, 2008; Lemessa and Wakkira, 2015; Kunz *et al.*, 2016;
273 Osipitan *et al.*, 2018; Gerhards and Schappert, 2019; Kumar *et al.*, 2020; Fernando and Shrestha, 2023;
274 Camargo Silva and Bagavathiannan, 2023; McKenzie-Gopsill and Farooque, 2023). First, a direct weed
275 suppression is caused by competition for light, water, nutrients, and space by the cover crop. Second, an
276 indirect reduction of weed density is due to the promotion of granivorous predators. Third, the effect of
277 cover crop residues can act as a physical barrier for germination and emergence (e.g. reduction of light

278 transmittance) and change the seedbed microclimate (soil temperature and moisture) with opposite effects
279 on weed seed germination. Fourth, weed development may be affected by the release of allelochemicals
280 from living and decomposing cover crop tissues.

281 Overall, cover crops would be able to suppress 70% to 95% of weeds and volunteer crops in the autumn-to-
282 spring period between two main crops with an additional suppressive effect of cover crop residues on weed
283 emergence during early development of the following cash crop (Gerhards and Schappert, 2019). The degree
284 of weed suppression by a cover crop depends on the residue persistence, the soil surface coverage, the
285 accumulated biomass and the management practices applied for both cover crop and main crop (Osipitan *et*
286 *al.*, 2019).

287 However, these effects have mainly been assessed in the short term, i.e. during the cover crop growth cycle
288 (Petit *et al.*, 2018). Quantification of the effects over the longer term (i.e. in subsequent crops and at the level
289 of crop rotation) remains rare: few studies seek to determine how this reduction in weed biomass during the
290 fallow period translates into seed production and how the weed seed bank was really impacted in the
291 following years (Hodgdon *et al.*, 2016; Nichols *et al.*, 2020; Adeux *et al.*, 2021; Rouge *et al.*, 2023). However,
292 these studies generally concluded to an insufficient weed control effect in subsequent crops. Even under no-
293 tillage conditions and low herbicide use (tillage and herbicides being major weed management levers that
294 can mask the regulating effects of cover crops as such), the effect of cover crops remains weak.

295 **4.1 Associated traits for the cover crops**

296 The ability of cover crops to suppress weeds depends on their competitiveness, which is related to rapid
297 shoot and root growth (plant vigour), nitrogen acquisition, and canopy closure. This also requires a rapid
298 seedling emergence and good establishment of cover crops soon after harvest of the previous cash crop,
299 sometimes under dry and warm conditions.

300 Among cover crops, grasses and cereals are generally considered more weed suppressive than broadleaf
301 plant species (Baraibar *et al.*, 2018). Osipitan *et al.* (2019) in their meta-analysis showed that there were
302 differences in level of weed suppression at termination among 26 cover crop species. Cereal rye, oat, triticale,
303 wheat, ryegrass and sorghum were the most weed suppressive even with moderate seeding rates; among
304 broadleaves, clovers and vetches were the most suppressive, buckwheat, radish, pea and mustard being the
305 less suppressive according to the literature. Weed suppressive species emerge relatively fast, cover the soil
306 quickly and produce high amounts of shoot and root dry matter. For instance, where cereal rye (*Secale*
307 *cereale* L.) provided weed suppression from 75 to 85%, cover cropping with pea only resulted in 0 to 56 % of
308 suppression (Akemo *et al.*, 2000). Among overwintering cover crops, cereal rye is often appreciated due for
309 its fibrous root system, tolerance to low-fertility soils, high N capture, and soil coverage which makes it
310 extremely weed suppressive as a result of both competitive and non-competitive mechanisms (Kumar *et al.*,
311 2020 ; Camargo Silva and Bagavathiannan, 2023). Therefore, to be effective, low biomass-producing legumes
312 and other broadleaf cover crops may need to be sown in mixtures with productive grass species to improve
313 weed suppression.

314 Based on leaf traits, Tribouillois *et al.* (2015) identified Brassicaceae as highly competitive among 36 cover
315 crops species. All Brassicaceae (except *Camelina sativa*) and *Helianthus annuus* were identified as highly
316 competitive due to their ability to rapidly grow, acquire nitrogen after sowing and occupy the space. Crop
317 growth rate (CGR) and crop nitrogen acquisition rate (CNR) can be used as two indicators of the ability of
318 cover crops to grow and uptake nitrogen. Leaf functional traits as specific leaf area (SLA), leaf dry matter
319 content (LDMC), leaf nitrogen content (LNC) and leaf area (LA) were used to evaluate in a simpler way CGR
320 and CNR.

321 A greater coverage of the soil surface by the residues has also a subsequent negative impact on weed seed
322 germination and seedling emergence due to a physical barrier depending on the nature of the mulch
323 (Teasdale and Mohler, 2000); this lengthens the duration of weed suppression due to competition.

324 Most of the studies compared the suppressive abilities of a range of cover crops but with a difficulty to
325 separate the interactions due to competition and allelopathy (Kunz *et al.*, 2016). Allelopathy that also
326 suppresses weeds after termination of cover crops in the winter and early spring could vary among cover
327 crop species and varieties. The amount of residues and their ability to release sufficient allochemical
328 compounds until the next cash crop could differentiate cover crops in their weed suppressive ability.

329 It would be beneficial to quantify the competitive, physical and biochemical weed control effects of cover
330 crops separately and determine the traits associated to each of these functions. This would help breeders
331 and growers selecting and choosing cover crop species and combining mixtures with multiple weed
332 suppressive abilities and increase the range of ecosystem services that cover crops may provide (Baraibar *et al.*,
333 2018). Competitive species are important for early weed growth suppression while allelopathic species
334 can reduce weed emergence via biochemicals released from living plants and their residues after cover crop
335 termination. The efficacy of cover crop mixtures could be improved by identifying competitive and
336 allelopathic species and combining them appropriately.

337 **4.2 Associated agronomic practices**

338 In their meta-analysis, Osipitan *et al.* (2019) showed that several management decisions could influence the
339 suppressive performance of cover crops, including the choice of species and their assemblages, the sowing
340 date, the seeding rate, the termination date, the delay in main crop sowing after termination of cover crop,
341 and the tillage system. However, very few papers compared the performances of varieties of cover crops for
342 crop biomass and termination effectiveness (Wells *et al.*, 2016).

343 There is not a clear consensus if sowing multispecies cover crop is more successful in producing biomass and
344 residue to suppress weeds than a single species or mixtures of two cover crops. However, based on several
345 experiments, Smith *et al.* (2020) concluded that farmers are more likely to achieve better results sowing the
346 most weed-suppressive cover crop as a monoculture than a mixture. However, mixtures better compensate
347 temporal and spatial variation in sub-optimal growing conditions and fluctuating climatic conditions and thus
348 tend to outperform single species by ensuring that at least some species grow every year at every site (Kumar
349 *et al.*, 2020). Respecting optimal sowing date is crucial for adequate plant establishment and maximum cover
350 crop biomass. Generally, the earlier sowing date resulted in greater weed suppression, but this depends on
351 the species characteristics and weather conditions. For instance, spring- or autumn-seeded cover crops tend
352 to perform better than a late summer-sown cover crop in dry environments because of the available moisture
353 at time of seeding (Kumar *et al.*, 2020). However, in most environments, autumn-sown cover crops provided
354 greater weed suppression than spring-sown cover crops (Osipitan *et al.*, 2019). As was expected, increasing
355 seeding rate of the cover crop species generally increase the biomass production and soil surface cover. A
356 delay in termination date generally results in subsequent greater weed suppression, irrespective of the
357 management of the cover crop residue (either incorporated or left at the soil surface).

358 If biomass of cover crop residue is often reported to be correlated to weed suppression, little research is
359 available regarding the composition of cover crop residue (*i.e.*, carbon, nitrogen, lignin, cellulose, and
360 hemicellulose) and its additional effect on weed suppression. Cover crop residue can act as a mulch that will
361 suppress weeds, but as the residue degrades, weed suppression diminishes. However, if the cover crop
362 biomass has high C:N ratio (e.g. grasses), it will keep the soil covered longer due to reduced decomposition
363 rate as compared to residue with low C:N ratio (e.g. legumes) and consequently it will increase the duration

364 of weed suppression (Pittman *et al.*, 2020). Grass-legume mixtures could be a good compromise between
365 two services offered by cover crops: N release and weed suppression (Muzangwa *et al.*, 2015).

366 4.3 Evaluation methods

367 Classical field experiments comparing the cover crop biomass and effectiveness of termination method could
368 be set up for comparing both species and intraspecific diversity using high throughput phenotyping methods
369 developed for cash crops. To separate the competitive from the allelopathic effects of cover crops,
370 experiments in laboratories, greenhouses, and growth chambers could be useful, although this appears very
371 difficult to implement currently (Mahé *et al.*, 2022). The response of emergence rates of cover crop species
372 and varieties to seedbed temperature and water content could also be tested under controlled conditions
373 and completed by modeling. For instance, the SIMPLE model predicts the emergence duration and rate of
374 crops by considering species and seed characteristics in interaction with seedbed conditions (Constantin *et al.*,
375 2015).

376 5 Weed suppression using living mulch acting as companion crops

377 The term “companion crops” is used when non-harvested species are sown alongside the cash crop either
378 before or at sowing to reinforce weed control, increase beneficial predatory insects and improve soil health
379 (Verret *et al.*, 2017 a-b). When sown simultaneously with the cash crop, cover crops could be considered as
380 intercrops (Malézieux *et al.*, 2009) as seen above. For instance, intercropping frost-sensitive legume crops
381 with winter oilseed rape is now currently used in France in order to reduce weed competition, insect damage,
382 and improve nitrogen use efficiency (Cadoux *et al.*, 2015). Relay cropping consists in sowing one crop into
383 standing second crop prior to its harvest whereby, often, the first crop is cash crop and the second crop is
384 sown either for grain, biomass or cover cropping (Lamichhane *et al.*, 2023). This practice has been shown in
385 several studies to be very effective at helping to manage weeds by suppressing weed emergence (Gesch *et al.*,
386 2023).

387 When the harvested crop is undersown directly in an established companion cover crop, this cover is called
388 “living mulch”. The different species have to coexist within a plot while maintaining the services provided by
389 each of them, *i.e.* grain production for the harvested crop and weed control, reduction of soil water
390 evaporation and sometimes nitrogen fixation for the cover crop. In such a system, there is a need to find a
391 trade-off between maximising the suppression of weed growth and minimising the reduction of cash crop
392 growth (Cougnon *et al.*, 2022). For instance, undersowing wheat with living mulches decreased crop yield in
393 comparison with wheat cropped alone but this was depending on the biomass of the cover crop (Carof *et al.*,
394 2007a). In addition, living mulch can act as a weed if the cover crop starts to reproduce and the seeds fall on
395 the soil becoming a new problem to control. This risk is important to consider when choosing a cover crop:
396 its reproduction cycle should be taken into account regarding the following crops.

397 There is little research on the effects of living mulch on weed and crop emergence. The effect of soil structure
398 on emergence, through a physical barrier effect and an effect on soil hydrothermal conditions, and the effect
399 of mulch on soil properties have been reported as beneficial for the crop (Schlautman *et al.*, 2021). Ryan *et al.*
400 (2021) showed that mulch has no depressive effect on winter wheat emergence.

401 It is therefore essential to understand the interactions between harvested crops and cover crops in order to
402 define which combinations of species and varieties will match. Introducing non-selective herbicides for
403 suppressing poor covers and make easier the establishment of new crops or cover crops is a drawback that
404 has to be balanced with the expected reduction of selective herbicides used for controlling weeds during
405 crop season.

406 As the combinations to explore are numerous, simulation models are essential and should be developed in
407 order to define the relevant associations and then identify the genetic progress to be made as was developed
408 on grassland communities (Faverjon *et al.*, 2019; Louarn *et al.*, 2020).

409 **5.1 Associated traits for both the cover and harvested crops**

410 The choice of cover species and varieties has an effect on weeds (White and Scott, 1991; Petit *et al.*, 2018)
411 but also on cash crop via competition in particular for light, water and nutrients (Bergkvist, 2003; Carof *et al.*,
412 2007b; Cougnon *et al.*, 2022). The establishment of the cover crop should be fast enough to control weeds
413 but then the growth should be reduced during critical development phases of the harvested crop, *i.e.*
414 corresponding to a short prostrate type. Or, once installed, the cover crop should grow preferentially after
415 the harvested crop has become dominant such as winter dormant cover types with winter crops (Carof *et al.*,
416 2007a). This can be achieved by screening different morphologies and/or growth dynamics (phenology)
417 between canopy and harvested crop.

418 Another possibility is to establish the cover crop first, possibly under a previous harvested crop such as
419 sunflower, and then sow a second harvested crop within this cover. For example, a cover of alfalfa could be
420 established in spring and cut in autumn to sow a winter wheat. In that case, the harvested crop should be
421 chosen for having a good establishing potential despite the cover, *i.e.* ability to emerge under a mulch, for
422 example with a large amount of seed reserves allowing a fast autonomous growing. The ability to emerge
423 successfully in such a system is a trait to evaluate among crops and varieties. In addition, traits may be
424 selected in cash or cover crops to facilitate mechanical weed control (residue shredding, harrowing, etc.).

425 It has been observed in organic farming that the most stable harvested crop varieties for yield are often those
426 that have lower nitrogen requirements, knowing that this criterion is often linked to a better efficiency in
427 converting absorbed nitrogen into yield; therefore, this avenue should also be explored. Furthermore, as it
428 is impossible to always ensure optimal growth of both species, the ability to compensate for a low yield
429 component is a trait to be sought and valued for the harvested crop. For example, in cereals, the decrease in
430 a stand of ears can be compensated by ear fertility, *i.e.* by the number of grains/m² or by the unit kernel
431 weight.

432 Traditionally, sown forage species or grassland species including new species to be tested, are a good start
433 for building perennial covers (Hiltbrunner and Liedgens, 2008). However, breeding has created productive
434 varieties that may be too competitive with the harvested crop, such as for alfalfa, whose growth has to be
435 slowed down when combined with cereals (Ilnicki and Enache, 1992; Baresel *et al.*, 2018; Radicetti *et al.*,
436 2018). It might be interesting to screen the genetic resources of these species again with the objective of
437 characterizing ecosystem services such as weed control and nitrogen supply (Cougnon *et al.*, 2022).

438 The species constituting the perennial cover can also present distinct growth dynamics over time. For
439 example, it is possible to combine a species that establishes very quickly to control weeds but has a short
440 lifespan, with a slower-establishing but more persistent species that will take over *e.g.* fenugreek (*Trigonella*
441 *foenum graecum*) in combination with alfalfa or clover.

442 Once the types of both cover and harvested crops have been chosen, it is possible to go further in the
443 selection of co-adapted varieties by breeding directly in mixtures (Sampoux *et al.*, 2020).

444 Various studies conclude that, in order to maintain several species within an ecosystem, intraspecific genetic
445 diversity could be a determining factor by allowing fine local adaptation of each species (Meilhac *et al.*, 2019).
446 However, little is currently known about the optimal ranges of variability and the key traits.

447 5.2 Associated agronomic practices

448 Another way than the choice of varieties to drive the relationship between the harvested and the cover crops
449 is to play with agronomic practices. It would be beneficial to stimulate cash crop growth and resource
450 acquisition in the early phase by increasing its sowing density, reducing row width and choosing varieties
451 with high cover capacity. This also requires genetic resistance to fungal diseases and lodging, both factors
452 favoured by the dense canopy. In the case of a non-N₂-fixing harvested crop such as cereals with a legume
453 cover crop, in the event of early nitrogen deficiency, it would be wise to apply nitrogen earlier in order to
454 favor the growth of the harvested crop and reduce the growth of the permanent cover legume.

455 The competition of the living mulch with the harvested crop could be reduced mechanically before sowing
456 the harvested crop and during the growing season with specific equipment (Thorsted *et al.*, 2006) or grazing
457 (Jones and Clements, 1993), or chemically with herbicides which could be not environmental-friendly
458 (Bergkvist, 2003; Shili-Touzi *et al.*, 2010).

459 In conclusion, for harvested crops under perennial cover, the choice of varieties to be sown must be
460 considered jointly for all the species in the agro-ecosystem in a given soil and climate context, with given
461 production objectives and a chosen management. This type of agriculture, with limited inputs, renews basic
462 breeding objectives and opens the way for the use of new species.

463 6 Shifted crop sowing dates for escaping weed emergence

464 Depending on the crop species, two opposite strategies (early- vs late sowing) can be considered to reduce
465 weed pressure.

466 Delayed sowing is relevant for autumn-sown crops, especially cereals. Indeed, the most harmful weeds
467 emerge during the optimal sowing period of the crop (Fried *et al.*, 2008; Perronne *et al.*, 2015; Gaba *et al.*,
468 2017). A later sowing date leaves more time to weeds to germinate during the summer fallow, leaving fewer
469 weed seeds in the soil to emerge after sowing (Lutman *et al.*, 2013). This technique is even more efficient by
470 using false seedbed, i.e. triggering additional weed seed germination via repeated shallow stubble tillage in
471 the autumn-to-spring season (Rasmussen, 2004). The first stubble tillage stimulates weed seed germination
472 while subsequent stubble tillage controls the emerged weed seedlings and induces new seeds to germinate.
473 In addition, delaying sowing would reduce the competitive advantage of weeds and the relative growth rate
474 would be in favour of the cereal at least for some autumn-emerging weeds such as blackgrass (Andrew and
475 Storkey, 2017). Delayed sowing requires choosing crop varieties to avoid a reduction in yield resulting from
476 suboptimal soil and climatic conditions and a shorter vegetative phase (Shah *et al.*, 2020). Furthermore, due
477 to climate change, it could be necessary to postpone sowing, *e.g.* for winter wheat requiring vernalization, in
478 order to avoid excessive crop development leading to a higher susceptibility to pathogens and frost damages
479 (Minoli *et al.*, 2022). However, the varietal recommendations already take into account both the pedoclimatic
480 conditions and the preceding crop in order to define optimal sowing and harvest time. In particular cases,
481 spring varieties could even be sown in autumn, but later than winter varieties.

482 Earlier sowing appears as a better strategy for late summer-sown crops such as for oilseed rape, to compete
483 with weeds as fast as possible by targeting a quick canopy closure (Dejoux *et al.*, 2003; Sim *et al.*, 2007b).
484 However, this means that crops and varieties sown can germinate and emerge in relatively dry seedbeds.

485 A significant advance in sowing dates for spring crops has been observed due to climate change, either by
486 sowing early late-maturing varieties to aim a longer crop cycle and higher yields, or by sowing early varieties
487 at conventional or later dates to avoid end-of-cycle abiotic stresses. In the future, maintaining high stable
488 production for crops such as maize and sunflower can only be achieved by sowing significantly earlier (Minoli

489 *et al.*, 2022). For instance, Wang *et al.* (2013) indicate that early sowing in spring can increase the yield of
490 lentils, and can be used as an indirect method of weed control in some organic farming systems. However,
491 sowing early in spring under too cold conditions could lengthen the time necessary for a complete canopy
492 closure and/or result in incomplete soil cover promoting predation. Depending on the differential base
493 temperatures of the crop and the weeds (Gardarin *et al.*, 2016; Brown *et al.*, 2022), some weed species with
494 low temperature requirements could be more competitive under such conditions.

495 **6.1 Associated traits**

496 Cereal varieties adapted to late sowing require a set of traits, especially a crop cycle escaping the main biotic
497 and abiotic stresses. The ability to germinate and emerge in harsher conditions (drought, hydromorphy, cold,
498 more compacted soil) is necessary in this context, as well as a better cold tolerance to avoid the risk of frost
499 damage on seedlings with only little hardening (Castel *et al.*, 2017). This will be crucial with climate change
500 where more frost damage is expected because of less hardening during winter.

501 In straw cereals, the ability to produce leaves more quickly (shorter phyllochron or phyllotherm) may also be
502 relevant to partly escape leaf diseases. Moreover, part of the reduction in potential yield could be offset by
503 an adapted morphogenesis (tillering ability, fertility of the ears, size and weight of the grains), in particular
504 due to a better nitrogen use efficiency (Yin *et al.*, 2019). Cold tolerance and early vigour appear also important
505 for spring varieties sown in autumn or in early spring.

506 However, in some conditions, the earlier sowing of spring crops could increase the weed pressure, justifying
507 to increase also the canopy cover capacity of these varieties and more generally their ability to grow under
508 sub-optimal temperatures (e.g. soybean - Petcu *et al.*, 2023), as well as traits favouring mechanical weeding,
509 sowing under mulch or for relay cropping.

510 **6.2 Associated agronomic practices**

511 Delayed sowing can be combined with previous false seedbed operations in conditions promoting weed
512 emergence. In this case, the conditions of the last pre-sowing tillage should be relevant because, in moist
513 conditions, this may trigger a new flush of weed emergence (Botto *et al.*, 2000; Juroszek *et al.*, 2002; Juroszek
514 *et al.*, 2017). The increase of sowing density due to later sowing associated with a superior risk of seed and
515 seedling losses needs to be modulated according to the region and the type of soil to ensure a non-limiting
516 tillering for cereals.

517 **6.3 Evaluation methods**

518 Laboratory experiments on seed germination and pre-emergence growth to determine hydrothermal
519 requirements and sensitivity to soil compaction are required (Gardarin *et al.*, 2016; Nosratti *et al.*, 2023).
520 Field experiments comparing contrasted sowing dates and detailed observations on phenology, canopy
521 development, yield components for a range of crop genotypes grown under weedy and weed-free conditions
522 could be set up and completed by crop modelling.

523 **7 Increased proportion of spring crops in rotations as a diversification strategy**

524 A greater proportion of spring crops in the commonly grown cereal-based rotations allows alternating more
525 frequently between winter and spring crops. This lever is highly effective for managing weed populations by
526 avoiding the development of a specialised weed flora difficult to control in simplified crop sequences
527 (Anderson, 2005; Anderson, 2015; Adeux *et al.* 2019; San Martin *et al.*, 2019; Weisberger *et al.*, 2019). Beyond
528 the general effect of preventing the increase of this flora in the soil seedbank each year, alternating sowing
529 periods can greatly reduce the soil seedbank of short-lived seeds of certain weed species (e.g. *Bromus spp.*,

530 Blackshaw, 1994). Moreover, alternating spring and autumn sowing periods enables the germination of weed
531 species unable to produce seeds during the crop cycle, such as late-emerging spring weeds in winter cereals
532 or autumn-emerging weeds in spring crops (Chauvel *et al.*, 2001; Gaba *et al.*, 2017). This strategy is expected
533 to be more conducive on weed population changes than delaying or anticipating sowing dates within the
534 same species. To achieve this objective, the performance of spring crops should be improved on a range of
535 criteria whereas their introduction should be combined with other agronomic practices. The range of
536 profitable spring crops should be also extended by significant breeding efforts, especially on minor crops
537 (Peltonen-Sainio *et al.*, 2016).

538 First, diversifying rotations with new crops, beyond new sowing periods, brings many advantages, among
539 which a better management of weeds, animal pests and diseases. Currently, depending on the production
540 situations, crop sequences are more or less diversified, and the expected gain will be greater for the currently
541 most simplified crop sequences (Adeux *et al.*, 2019; Weisberger *et al.*, 2019; Adeux *et al.*, 2022). A set of
542 major or minor crops, eventually in mixtures, can be considered, depending on the production situation (e.g.
543 field pea, sunflower, soybean, buckwheat, flax, camelina), each presenting advantages and disadvantages
544 now and in the future. For weed management, the advantages are based not only on the change in sowing
545 periods, but also on the differences in weeding methods (simplified use of mechanical weeding in crops with
546 wide inter-rows, complementary between active ingredients applied, higher competitiveness of some crop
547 species) (Liebman and Dyck, 1993; Anderson, 2005; Anderson, 2015).

548 Second, yields need to be improved and nitrogen fertilisation reduced for several winter crops to diversify
549 the crop sequences, for instance by including a legume-based cover crop sown in autumn to precede the
550 spring cash crop. Successful improvements have been implemented in spring barley in Western Europe, with
551 gains in yield and protein content associated with a reduction of inputs (Cabeza-Orcel, 2020). However, these
552 modifications have been largely neglected for spring wheat by breeders and farmers, as this crop almost
553 completely disappeared in favour of winter wheat varieties in France. Increasing the proportion of spring
554 wheat would provide the same benefits as barley, but their adoption can only be done in case of genetic
555 improvement.

556 **7.1 Associated traits**

557 Introducing more spring crops in the rotation in a context of increasing water shortage and air temperature
558 will require more drought-tolerant species and genotypes in case of normal sowing date, under rainfed or
559 limited irrigation conditions. As crop adaptation to climate change means avoiding or escaping water and
560 heat stresses by earlier sowings, early vigour and cold tolerance at early developmental stages will be
561 targeted traits for breeding to rapidly cover the soil (Debaeke *et al.*, 2021). The cold tolerance must be
562 improved by reducing the sensitivity to low temperatures, particularly during the floral transition and
563 increasing the ability to produce biomass at suboptimal temperatures (Allinne *et al.*, 2009; Yi *et al.*, 2021).
564 The flowering date must be chosen to be appropriate to the duration of the crop cycle while the harvest
565 index should be improved to increase yield potential without focusing solely on earliness group. Varieties
566 must provide yield gain by increasing fertility of ears and grain weight for spring cereals. Such breeding goals
567 would also make it possible to provide varieties that are probably less water-consuming by escaping the most
568 evaporative periods.

569 **7.2 Associated agronomic practices**

570 The choice of spring crops can be combined with early sowing under mulch or under cover crop, either in
571 permanent cover or in case of relay cropping. Sowing of spring crops can be tied up to a potentially simplified
572 use of mechanical weeding in row crops as well as the use of available herbicides when necessary. In
573 conditions where irrigation is fully available, several spring crops (e.g. soybean, sunflower, sorghum, maize,

574 buckwheat, camelina) could be sown as double crops after early-harvested winter crops (e.g barley, pea,
575 rapeseed) increasing rotation diversity (Pitchers *et al.*, 2023). This will require very early maturing crops in
576 order to complete the cycle and allow autumn harvest in a reasonable time window (Debaeke *et al.*, 2021).

577 **7.3 Evaluation methods**

578 Most of the phenotyping methods have been developed on cereals, mainly wheat and maize, with some
579 applications on oilseed rape, sunflower and pea (Jeudy *et al.*, 2016; Tardieu *et al.*, 2017; Gosseau *et al.*, 2019).
580 Increasing cultivated diversity will require generic tools and protocols for getting information and analysing
581 the traits for a wider range of crop species. This will concern in priority drought, cold and heat tolerance.
582 Field and controlled high-throughput platforms will be completed by ecophysiological modelling and multi-
583 environment trials for evaluating a wide range of genotypes and environments in relation with genotypic
584 data (Araus and Cairns, 2014; Ghanem *et al.*, 2015; Xie and Yang, 2020). For example, the suitability of
585 soybean in Europe and the optimal maturity groups to grow as a function of irrigation availability was
586 explored using ensemble crop modeling and future climatic scenarios (Nendel *et al.*, 2023).

587 **8 Selectivity of mechanical weed control**

588 Mechanical weeding is one of the most important alternatives to chemical weed control, particularly in wide
589 row crops (some annual spring crops, fruit species and vine, Chicouene, 2007; Peruzzi *et al.* 2017; Fogliatto
590 *et al.*, 2018). However, mechanical weeding requires specific equipment depending on the crop, the
591 production situation and the targeted weed flora, and its efficacy is often reduced by inappropriate soil and
592 weather conditions. In order to ensure the widest management window in each production situation and
593 maximize the selectivity, varieties must have traits suitable for mechanical weeding techniques, especially
594 hoeing, harrowing and rotary hoeing, including intra- and inter-row weeding depending on the
595 developmental stages of the crops and the weeds (Fogelberg and Dock Gustavsson, 1998; Rasmussen *et al.*,
596 2004; Osman *et al.*, 2016). Beyond genetic improvement, the implementation of new practices must also be
597 done, such as sowing with wider inter-rows to facilitate hoeing or/and relay cropping to increase competition
598 with weeds (Kolb *et al.*, 2010; Melander *et al.*, 2018; McCollough and Melander, 2022; Gesch *et al.*, 2023).

599 **8.1 Associated traits**

600 A set of traits should be studied and improved to ensure a better selectivity of mechanical weeding
601 operations. To improve weed control efficiency and accuracy over a wider application window, considering
602 a same inter-row distance, an erect growth habit would be more relevant, although appearing potentially
603 antagonistic to a higher canopy cover capacity at early stages of the crop cycle. However, barley varieties
604 with a high seedling density after a pre-emergence harrowing and tall at post-emergence harrowing benefit
605 most from mechanical weeding (Hansen *et al.*, 2007). Currently, it is possible for farmers to choose straw
606 cereal varieties that are either more covering or more upright and characterized by different earliness (Lever
607 *et al.* 2022b), in order to minimize the negative impact of mechanical weeding operations. As an example,
608 concerning harrowing, taller higher-yielding barley genotypes with a high leaf area index (LAI) tend to be less
609 tolerant to post-emergence weed harrowing than shorter and lower-yielding genotypes with a low LAI.
610 However, although being most damaged, these taller high-yielding genotypes remained the highest yielding
611 after weed harrowing (Rasmussen *et al.*, 2004). In case of use of tine harrow or rotary hoe for weeding,
612 varieties could be less sensitive to weeding by improving their root anchorage as well as their earliness and
613 vigour. If the crop is sown deeper, the growth speed and length of the coleoptile or hypocotyl as well as their
614 tolerance to soil compaction must be increased to reduce pre-emergent seedling loss, these traits being
615 correlated to seed reserves and embryo size (Rebetzke *et al.*, 2007; Fayaud *et al.*, 2014; Gardarin *et al.*, 2016).
616 Wider inter-rows, especially in straw cereals, could result in a lower yield, depending on mechanical weeding

617 method and weed pressure (Melander *et al.*, 2003; Rasmussen, 2004; Kolb *et al.*, 2010; Melander *et al.*, 2018;
618 Gerhards *et al.*, 2020; McCollough and Melander, 2022). However, the crop proportion that has been covered
619 by soil due to weed harrowing could also decrease yield in some conditions (Rasmussen *et al.*, 2010; Rueda-
620 Ayala *et al.*, 2011), depending on the straw cereal species (Rasmussen *et al.*, 2009).

621 **8.2 Associated agronomic practices**

622 Several agronomic practices need to be considered to ensure a better selectivity of the mechanical weeding
623 operation in straw cereals. These levers include the timing, the direction and the orientation of the weeding
624 operation, the interrow width, the number of passes and the speed during the operation, as well as the
625 nitrogen rate, fertilizer placement and the moisture conditions during the operation (Rasmussen *et al.*, 1996;
626 Kurstjens *et al.*, 2000; Melander *et al.*, 2003; Rasmussen, 2004; Rasmussen *et al.*, 2008; Rasmussen *et al.*,
627 2010; Fogliatto *et al.*, 2018; Melander *et al.*, 2018). However, these levers have generally not been studied
628 on a range of genotypes. Moreover, only a few studies focused on potential trade-offs between the
629 competitiveness of genotypes, their tolerance to weeding and their impacts on weed development
630 (Rasmussen *et al.*, 2004; Hansen *et al.*, 2007), limiting recommendations on the relevant ideotype (Lever *et*
631 *al.* 2022a).

632 **8.3 Evaluation methods**

633 Several methodologies have been developed to assess the tolerance and selectivity to mechanical weeding,
634 including visual assessments using a predefined grading scale and digital image analysis with an automated
635 procedure, information being obtained prior and just after weeding operation (Hansen *et al.*, 2007).
636 Moreover, mechanical weeding techniques have made significant progress using camera-guided for hoeing
637 in order to reduce the injuries on crop plants (Gerhards *et al.*, 2020).

638 **9 Use of allelopathic crops**

639 The use of crop plants able to produce allelochemicals capable of significantly inhibiting the germination
640 and/or growth of certain weeds is frequently proposed as an additional lever for weed management (Singh,
641 2003; Khamare *et al.*, 2022; Hickman *et al.*, 2023). This capacity has been extensively studied under controlled
642 conditions, but rarely in field conditions (Mahé *et al.*, 2022). Indeed, field trials face a main problem, *i.e.*
643 dissociating allelopathy from other mechanisms. Considering allelopathy by living crops, the main challenge
644 is to discriminate allelopathy from competition, as these two mechanisms occur concomitantly in field
645 conditions (Worthington and Reberg-Horton, 2013; Kunz *et al.*, 2016; Reiss *et al.*, 2018a-b). A systematic
646 review of the literature identified that, in most published field trial studies, the role of crop competition is
647 disregarded or not exhaustively studied (Mahé *et al.*, 2022). Actually, only few articles provide convincing
648 evidence of allelopathy in the field and, even for these studies, a key role of competition could not be totally
649 excluded. Therefore, in spite of strong expectations regarding this mechanism, to which extent allelopathy
650 by living crops can provide a lever to regulate weeds remains an open question.

651 When considering allelopathy by crop residues (used as dead mulch or incorporated into the soil), the
652 difficulty is to dissociate the effects of allelopathy from those of nitrogen immobilization generated by crop
653 residue decomposition. Indeed, immobilization can alter soil nitrogen dynamics, affecting plant nutrition in
654 the following crop and generating potential confounding effects (Doré *et al.*, 2004). Some studies
655 nonetheless provided some field-based evidence of allelopathy by residues on weeds (Petersen *et al.*, 2001).
656 In this situation, care should be taken to avoid adverse allelopathic effects of residues on the growth of the
657 following cash crop or/and cover crop (Mennan *et al.*, 2020). In this context, even though many papers
658 identified allelopathy as a key mechanism to target towards sustainable weed management (*e.g.* Singh *et al.*,

659 2003; Scavo and Mauromicale, 2021), it is necessary to remain cautious given the difficulties to quantify the
660 effects in the field.

661 Another aspect is that the allelopathic capacity of a variety must not adversely affect plants of the same
662 variety or/and companion plants. Such a trade-off was observed in straw cereals, with a negative correlation
663 between allelopathic potential and crop yield (Bertholdsson, 2010). Conversely, other studies found no
664 correlation between allelopathic capacities observed under controlled conditions and competitive ability and
665 grain yield loss in winter wheat in fields (Worthington *et al.*, 2015b). Improving the allelopathic capacity via
666 plant breeding seems to be possible in rice (Kong *et al.*, 2011) but getting information about the key
667 metabolites released and how they are transformed in the rhizosphere seem crucial before investments from
668 breeders (Hussain *et al.*, 2022). Other ways of using allelochemicals could be to introduce or reintroduce
669 crops (known for their allelopathic capacities under controlled conditions) into rotations as cover crops (living
670 or dead mulches) or to incorporate crop residues into the soil (Jabran *et al.*, 2015; Scavo and Mauromicale,
671 2021).

672 **9.1 Associated traits**

673 Crop traits associated to allelopathy mainly refer to the nature and the intensity of emission of
674 allelochemicals (Reiss *et al.*, 2018a-b; Mwendwa *et al.*, 2021). Allelochemicals have been considerably
675 documented for different crop species (Hickman *et al.*, 2023), i.e. either used as cash crops (rice, sorghum,
676 sunflower, wheat, barley) or cover crops (rye, different Brassicaceae). However, the performance of
677 allelopathic crops on weeds can be very variable. Indeed, the emission of allelochemicals is highly dependent
678 on environmental conditions, while the sensitivity of weeds to these allelochemicals also depends on the
679 species and the phenological stage. The extension of the root system should also be important to explain the
680 influence of allelochemicals on weed control.

681 **9.2 Associated agronomic practices**

682 The choice of the crop species and variety has been so far the most studied factor (Scavo and Mauromicale,
683 2021). Other cropping techniques may also be involved, such as seeding rate and date (influencing the
684 intensity and timing of allelochemical emission) and fertilisation (allelochemical production can vary with the
685 nutritional status of the crop). For allelopathy by crop residues, authors recommend that the residues of
686 crops with a high allelopathic activity be incorporated into the soil after their destruction (Mennan *et al.*,
687 2020).

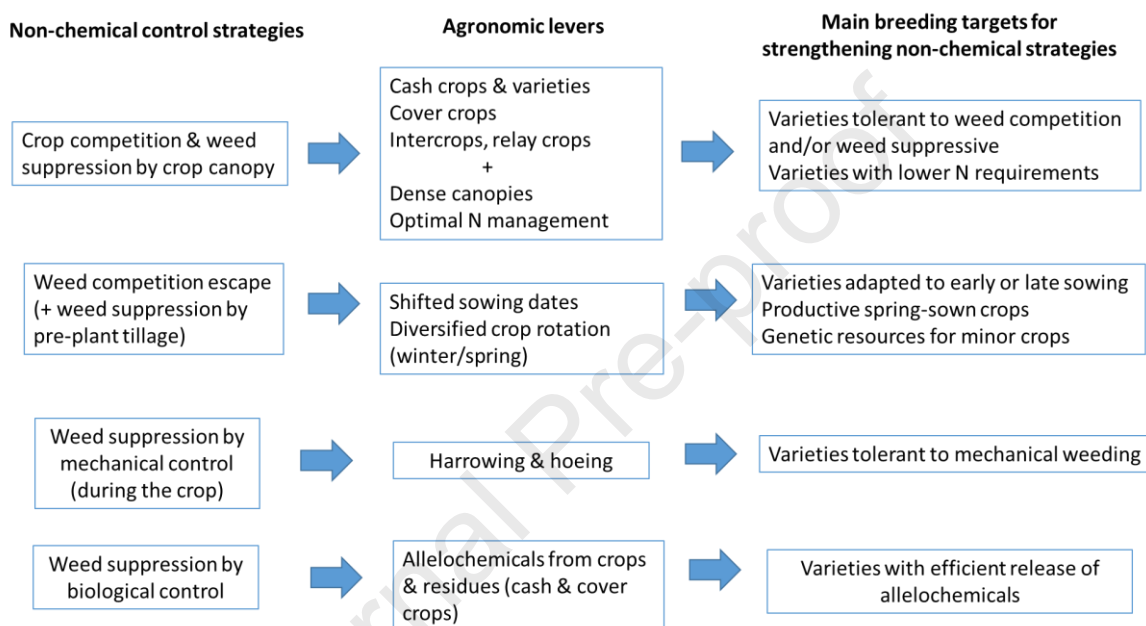
688 **9.3 Evaluation methods**

689 Several methodological devices have been developed under controlled conditions (*e.g.* Wu *et al.*, 2000;
690 Jensen *et al.*, 2008), but so far very few studies rigorously evaluated the effects of allelopathy by living plants
691 of different crop varieties on weeds under field conditions. Indeed, quantifying the effects of allelopathy in
692 the field requires combining several types of experiments on the same varieties (*i.e.* field measurements on
693 weeds and crop varieties, and assessment of allelopathic potential in laboratory), with the measurements of
694 many traits at different stages (to characterise both competition and allelopathy) and relevant statistical
695 methods to cross data (*e.g.* multiple regression) (Mahé *et al.*, 2022). Applying such approaches in crop
696 breeding programs would be particularly tricky, as well as time- and cost-consuming, to improve the
697 allelopathic capability (Hussain *et al.*, 2022), although early results suggest potential for cereal breeding
698 (Reiss *et al.*, 2018a). Even though allelopathic capacity differs among genotypes, substantial research is still
699 needed to develop methods suitable for screening lines in field conditions and breeding procedures to
700 improve genotypes (Worthington and Reberg-Horton, 2013; Scavo and Mauromicale, 2021; Hussain *et al.*,
701 2022; Mahé *et al.*, 2022 ; Rebong *et al.*, 2023).

702 10 Exploration of genetic diversity for non-chemical weed management

703 The assessment of genetic diversity and heritability of targeted traits is a preliminary step in a breeding
 704 program. We identified several priority avenues for the contribution of plant breeding to integrated weed
 705 management and more generally to non-chemical weed control (**Figure 1**). Before being included in a
 706 breeding program, new traits need to be examined on variety trials to identify the most interesting
 707 phenotypes. For instance, varieties with rapid canopy closure could be detected more easily in the near
 708 future with on-board sensors or drones, which are becoming affordable equipments for breeding companies,
 709 technical institutes or examination offices.

710



711

712 **Figure 1** – Non-chemical weed control strategies, agronomic levers and main breeding targets

713

714 10.1 Developing competitive varieties for cash and cover crops

715 In general, choosing competitive genotypes is a low-cost lever for integrated weed management to reduce
 716 the dependence of cropping systems on herbicides. The genetic diversity of the canopy cover capacity is wide
 717 among genotypes as well as between straw cereal species (Huel and Hucl, 1996; Coleman *et al.*, 2001;
 718 Fontaine *et al.*, 2009; Worthington *et al.*, 2015a), but is still underused (Pester *et al.*, 1999; Benaragama
 719 *et al.*, 2014; Rolland *et al.*, 2017; Aharon *et al.*, 2021; Hendriks *et al.*, 2022; Lever *et al.* 2022a). Research and
 720 development projects have identified bread wheat varieties with contrasting canopy cover capacity at
 721 various stages of development (Fontaine *et al.*, 2008; Massot *et al.*, 2018). However, no variety was
 722 characterized by a high canopy cover capacity until flowering so far. Furthermore, traits affecting canopy
 723 cover capacity (early vigour, earliness at various stages, height, leaf growth, leaf area and tillering capacity)
 724 are partially independent or positively correlated. Only a few studies evaluated correlations among traits
 725 until now (*e.g.* Murphy *et al.*, 2008; Fontaine *et al.*, 2009; Hendriks *et al.*, 2022), opening the way to the
 726 selection of new combinations of traits. Indeed, it is possible that two varieties have a similar ability to
 727 compete with weeds due to different combinations of traits (*e.g.* for winter wheat high tillering ability, small
 728 leaves and semi-erect growth habit vs low tillering ability, large leaves and high spreading or creeping
 729 growth), as has also been shown in simulation studies (Colbach *et al.*, 2022). Canopy cover capacity being an

730 integrative trait, it seems more relevant to investigate the genetic determinism of each specific component.
731 However, apart from wheat, very few studies reported such results on other crops although there is probably
732 intraspecific variability to exploit. In oilseed rape, Sim *et al.* (2007a) in UK and Lemerle *et al.* (2014) in Australia
733 reported some evidence of differential competitive tolerance between genotypes. Moreover, developing
734 soybean varieties with rapid canopy closure is now an objective for organic farming in Switzerland (Klaiss *et*
735 *al.*, 2020).

736 **10.2 Developing crop varieties tolerant to mechanical weeding**

737 Developing varieties more tolerant to mechanical weeding represents a potential avenue of research (Osman
738 *et al.*, 2016). Indeed, even if few studies have been conducted until now on a low number of genotypes, there
739 is genetic variability on tolerance to mechanical weeding within straw cereal species (Rasmussen *et al.*, 2004;
740 Hansen *et al.*, 2007), as well as among different species (Rasmussen *et al.*, 2009).

741 **10.3 Developing crop varieties tolerant to N deficiency or with lower N requirement**

742 Developing varieties of cereals tolerant to N deficiency could be a way to disadvantage nitrophilic competitive
743 weeds. Genetic diversity is high in wheat regarding traits allowing lower nitrogen requirements, increased N
744 use efficiency and tolerance to temporary nitrogen deficiencies (Cormier *et al.*, 2016). A large number of
745 QTLs related to the nitrogen status of the plant have been identified in cereals such as wheat (Laperche *et*
746 *al.*, 2007) and rice (Sandhu *et al.*, 2021). This strategy, as a part of integrated weed management, is obviously
747 restricted to cereals and probably oilseed rape, which receive the highest rates of N fertilisation.

748 **10.4 Breeding spring-sown crops adapted to early sowing**

749 The decision to include more spring-sown crops to diversify the crop rotation in the central and northern
750 parts of France and Europe especially depends on the availability of adapted varieties which means early-
751 maturing groups (e.g. sunflower and soybean) as was done for maize in the past decades. Growing summer
752 crops at higher latitudes and sowing earlier with climate change will require cold tolerant varieties expressing
753 a good early vigour for a rapid canopy closure. In recent years, considerable progress has been made in
754 elucidating the mechanisms of maize in response to cold tolerance and large differences in the morphological
755 and physiological changes (seed germination, root phenotypes, shoot photosynthesis) caused by cold stress
756 have been explored among maize varieties highlighting tolerant genotypes (Zhou *et al.*, 2022). Jähne *et al.*
757 (2019) identified a cold tolerance-specific QTL in soybean that is important for increased chilling stress
758 tolerance, especially when flowering occurs.

759 **10.5 Better exploiting the allelopathic properties of crops**

760 The genetic diversity of the allelopathic capacity is high among genotypes in controlled conditions, being
761 however highly dependent on assessment methods and conditions (Wu *et al.*, 2000; Wu *et al.*, 2003;
762 Bertholdsson, 2005; Jensen *et al.*, 2008; Bertholdsson, 2010; Chung *et al.*, 2020; Debaeke *et al.*, 2021).
763 Allelopathic capacity of crop genotypes has been demonstrated as a quantitative trait for wheat and rice in
764 controlled conditions (Wu *et al.*, 2003; Jensen *et al.*, 2008; Vieites-Alvarez *et al.*, 2023). Several works
765 identifying QTLs linked to the allelopathic capacity have highlighted relevant chromosome regions for both
766 wheat (Wu *et al.*, 2003) and rice in these controlled conditions (Jensen *et al.*, 2008; Chung *et al.*, 2020).
767 However, in straw cereals, a negative correlation between the allelopathic capacity and the yield of the
768 variety was found as part of a breeding program (Bertholdsson, 2010). Rye germplasm also exhibits large
769 variability in allelopathic activity, which could be used to breed rye with enhanced weed suppression for
770 cover cropping (Rebong *et al.*, 2023). Moreover, no work has been done on data obtained under field
771 conditions due to the difficulties associated with the evaluation of allelopathy in the field (Mahé *et al.*, 2022).

772 **11 Conclusion**

773 Reducing the reliance of agriculture on synthetic herbicides represents a major challenge to take up in order
774 to successfully achieve the agro-ecological transition. Sustainable and integrated weed management requires
775 the development of combinations of solutions using different levers with cumulative partial effects, usually
776 depending on the production situations (Bond and Grundy, 2001; Hatcher and Melander, 2003; Moss, 2019;
777 Birthisel *et al.*, 2021). Genetic improvement leading to breeding of new genotypes constitutes one of the key
778 lever, both for improving competitiveness against weeds and for enabling the implementation or increasing
779 the efficiency of key agronomic practices (Rasmussen *et al.*, 2004; Osman *et al.*, 2016; Lever *et al.*, 2022a ;
780 Weiner, 2023). Accelerating research on weed competitive crops should lead to more economical, effective
781 and feasible integrated weed management programs for all crops.

782 The relevant functional traits are numerous and characterized by effects that can be additive, synergistic but
783 also antagonistic, furthermore depending on environmental conditions and agronomic practices. Mobilizing
784 genetic resources in absence of sufficient variability in the elite varieties could be necessary, as well as
785 developing and selecting new crops to be introduced in rotations, intercrops and cover crops.

786 The diversity of traits potentially useful for weed management raises the question of the prioritization of
787 their genetic improvement and their inclusion into future breeding schemes. In view of the huge task
788 represented by testing all the relevant functions and the underlying trait combinations for a set of species
789 and production situations, it is clear that modelling and predictive approaches remain to be developed and
790 applied to help breeders identifying the most influential crop traits and the promising ideotypes (Bastiaans
791 *et al.*, 1997; Jeuffroy *et al.*, 2014; Martre *et al.*, 2015; Tao *et al.*, 2017; Colbach *et al.*, 2021, 2022). In addition,
792 there are trade-offs between traits during the breeding process that are important to evaluate through the
793 study of their genetic determinants. This work will be made achievable by the steady improvement of the
794 phenotyping methods for measuring traits and proxies with regard to technological advances in machinery,
795 remote sensing and data science (Tardieu *et al.*, 2017). Current variety assessment (designs and protocols)
796 also needs to be updated to better take account of the diversity of production situations, species and
797 varieties.

798 Furthermore, targeted traits for improving weed control, although important, can only be considered among
799 a set of other traits under selection. Considering together a set of complex traits within a breeding scheme
800 can be a particularly difficult task. Many breeding programs already use traits and QTLs related to vigour and
801 phenology (*e.g.* Hendriks *et al.*, 2022). Focusing specifically on traits for increasing weed control through a
802 pre-breeding program is a time-consuming and complex activity to set up which needs to identify the most
803 relevant traits to target. Highlighting the main traits to target and the relevant evaluation methods requires
804 previous research. Moreover, some species which can be used as cover or companion crops have been
805 neglected by breeders, especially due to their lower profitability. Relaunching breeding programs by
806 increasing the interest in these species should make them more attractive to farmers. For decades, breeding
807 activity was focusing mainly on the genotypes of a crop species, the phenotypic assessments of these multiple
808 genotypes taking place in the same environment, mostly without taking into account other management
809 levers (mechanical weeding, companion crops). Faced with the double challenge of the agro-ecological
810 transition and climate change, breeders would benefit from designing with agronomists and weed scientists
811 more relevant plant ideotypes (Rebong *et al.*, 2023; Weiner, 2023).

812 The objective of weed control must not make us forget the relationship between the cost of the investment
813 and the impact on crop production, with the maintenance of yield and quality that can be valued by the crop
814 markets. A thorough analysis of the benefits and costs of enhancing crop competitiveness is probably needed.
815 The key scientific cooperation between geneticists and agronomists must also encompass other research

816 disciplines and co-innovation with the agricultural sectors, thus conditioning the expression of the expected
 817 agro-ecological functions due to the varieties used. Given the diversity of cropping systems and production
 818 situations that must be preserved and developed as an insurance of resilience in the face of climatic and
 819 economic hazards, the best combinations of levers mentioned in this review cannot be stated *a priori* for a
 820 given year over the entire country. It will have to be assessed on a case-by-case basis by each farmer in
 821 his/her own production system according to the economic and climatic context of the year, his/her technical
 822 possibilities (working time, equipment and weed control solutions available). It is therefore important to
 823 present a wide range of technical combinations that can be tested, sometimes antagonistic, so that farmers
 824 can choose those that should work for them each year. Competitive crops should certainly be more available
 825 in the future as part of a reliable and profitable integrated weed management package for farmers.

826

827 **Acknowledgements**

828 The public-private consortium PlantAlliance has joined forces with the scientific consortium Grandes Cultures
 829 à Hautes Performances Economiques et Environnementales (GIS GC HP2E) to exchange opinions and
 830 approaches between plant geneticists and agronomists. A working group has been set up to combine these
 831 two disciplinary fields for designing sustainable and integrated weed management in new cropping systems.
 832 This document is the result of discussions in a Working Group including the authors and Jean-Pierre Cohan
 833 (Arvalis), Philippe Dufour (RAGT 2n), Philippe Gate (Arvalis), Julie Gombert (GEVES), Fabien Masson (GEVES),
 834 Fabienne Maupas (ITB), Monica Menz (Syngenta France), and Maxime Szambien (PlantAlliance). This work
 835 has been supported by the public-private consortium PlantAlliance.

836 **12 References**

- 837 Adeux, G., Munier-Jolain, N., Meunier, D., Farcy, P., Carlesi, S., Barberi, P., Cordeau S., 2019. Diversified grain-based
 838 cropping systems provide long-term weed control while limiting herbicide use and yield losses. *Agron. Sustain. Dev.*
 839 39, 42, <https://doi.org/10.1007/s13593-019-0587-x>
- 840 Adeux, G., Cordeau, S., Antichi, D., Carlesi, S., Mazzoncini, M., Munier-Jolain, N., Barberi, P., 2021. Cover crops promote
 841 crop productivity but do not enhance weed management in tillage-based cropping systems. *Eur. J. Agron.* 123,
 842 126221, DOI 10.1016/j.eja.2020.126221
- 843 Adeux, G., Yvoz, S., Biju-Duval, L., Cadet, E., Farcy, P., Fried, G., Guillemin, J.-P., Meunier, D., Munier-Jolain, N., Petit, S.,
 844 Cordeau, S., 2022. Cropping system diversification does not always beget weed diversity. *Eur. J. Agron.* 133, 126438,
 845 <https://doi.org/10.1016/j.eja.2021.126438>
- 846 Aharon, S., Peleg, Z., Argaman, E., Ben-David, R., Lati, R.N., 2020. Image-based high-throughput phenotyping of cereals
 847 early vigor and weed-competitiveness traits. *Remote Sens.* 12, 3877, <http://dx.doi.org/10.3390/rs12233877>
- 848 Aharon, S., Fadida-Myers, A., Nashef, K., Ben-David, R., Lati, R. N., Peleg, Z., 2021. Genetic improvement of wheat early
 849 vigor promote weed-competitiveness under Mediterranean climate. *Plant Sci.* 303, 110785, [http://dx.doi.org/](http://dx.doi.org/10.1016/j.plantsci.2020.110785)
 850 [10.1016/j.plantsci.2020.110785](http://dx.doi.org/10.1016/j.plantsci.2020.110785)
- 851 Akemo, M.C., Regnier, E.E., Bennett, M.A., 2000. Weed suppression in spring-sown rye (*Secale cereale*)–pea (*Pisum*
 852 *sativum*) cover crop mixes. *Weed Technol.* 14, 545-549, <https://doi.org/10.1614/0890-037X>
- 853 Allinne, C., Maury, P., Sarrafi, A., Grieu, P., 2009. Genetic control of physiological traits associated to low temperature
 854 growth in sunflower under early sowing conditions. *Plant Sci.* 177, 349-359,
 855 <https://doi.org/10.1016/j.plantsci.2009.07.002>.
- 856 Anderson, R.L., 2005. A multi-tactic approach to manage weed population dynamics in crop rotations. *Agron. J.* 97:1579–
 857 1583, <https://doi.org/10.2134/agronj2005.0194>

- 858 Anderson, R.L., 2015. Integrating a complex rotation with no-till improves weed management in organic farming. A
859 review. *Agron. Sustain. Dev.* 35, 967–974, <https://doi.org/10.1007/s13593-015-0292-3>
- 860 Andrew, I.K.S, Storkey, J., Sparkes, D.L., 2015. A review of the potential for competitive cereal cultivars as a tool in
861 integrated weed management. *Weed Res.* 55, 239–248, <http://dx.doi.org/>
- 862 Andrew, I.K.S, Storkey, J., 2017. Using simulation models to investigate the cumulative effects of sowing rate, sowing
863 date and cultivar choice on weed competition. *Crop Prot.* 95, 10–115 55, 239–248,
864 <http://dx.doi.org/10.1016/j.cropro.2016.05.002>
- 865 Annicchiarico, P., Nazzicari, N., Notario, T., Monterrubio Martin, C., Romani, M., Ferrari, B., Pecetti, L., 2021. Pea
866 breeding for intercropping with cereals: variation for competitive ability and associated traits, and assessment of
867 phenotypic and genomic selection strategies. *Front. Plant Sci.* 12, 731949, [http://dx.doi.org/](http://dx.doi.org/10.1016/j.cropro.2016.05.002)
868 [10.1016/j.cropro.2016.05.002](http://dx.doi.org/10.1016/j.cropro.2016.05.002)
- 869 Araus, J.L., Cairns, J.E., 2014. Field high-throughput phenotyping: the new crop breeding frontier. *Trends Plant Sci.* 19,
870 52-61, <http://dx.doi.org/10.1016/j.tplants.2013.09.008>
- 871 Bastiaans, L., Kropff, M.J., Kempuchetty, N., Rajan, A., Migo, T.R., 1997. Can simulation models help design rice cultivars
872 that are more competitive against weeds? *Field Crops Res.* 51, 101-111, [http://dx.doi.org/10.1016/S0378-](http://dx.doi.org/10.1016/S0378-4290(96)01046-5)
873 [4290\(96\)01046-5](http://dx.doi.org/10.1016/S0378-4290(96)01046-5)
- 874 Ballaré, C.L., Casal, J.J., 2000. Light signals perceived by crop and weed plants. *Field Crops Res.* 67, 149-160,
875 [http://dx.doi.org/10.1016/S0378-4290\(00\)00090-3](http://dx.doi.org/10.1016/S0378-4290(00)00090-3)
- 876 Baraibar, B, Hunter, M.C., Hamilton, A., Mortensen, D.A., Schipanski, M.E. 2018. Weed suppression in cover crop
877 monocultures and mixtures. *Weed Sci.* 66, 121–133. <http://dx.doi.org/10.1017/wsc.2017.59>
- 878 Baresel, J.P., Nichols, P., Charrois, A., Schmidhalter, U., 2018. Adaptation of ecotypes and cultivars of subterranean
879 clover (*Trifolium subterraneum* L.) to German environmental conditions and its suitability as living mulch. *Genet.*
880 *Resour. Crop Evol* 65, 2057-2068, <http://dx.doi.org/10.1007/s10722-018-0672-z>
- 881 Batlla, D., Benech-Arnold, R.L., 2014. Weed seed germination and the light environment: Implications for weed
882 management. *Weed Biol. Manag.* 14, 77–87. <http://dx.doi.org/10.1111/wbm.12039>
- 883 Bergkvist, G., 2003. Influence of white clover traits on biomass and yield in winter wheat- or winter oilseed rape-clover
884 intercrops. *Biol. Agric. Hortic.* 21, 151-164, <http://dx.doi.org/10.1080/01448765.2003.9755259>
- 885 Benaragama, D., Rosnagel, B.G., Shirtliffe, S.J., 2014. Breeding for competitive and high-yielding crop cultivars. *Crop*
886 *Sci.* 54, 1015-1025, <http://dx.doi.org/10.2135/cropsci2013.04.0223>
- 887 Bertholdsson, N.O., 2005. Early vigour and allelopathy—two useful traits for enhanced barley and wheat competitiveness
888 against weeds. *Weed Res.* 45, 94-102. <http://dx.doi.org/10.1111/j.1365-3180.2009.00754.x>
- 889 Bertholdsson, N.O., 2010. Breeding spring wheat for improved allelopathic potential. *Weed Res.* 50, 49-57,
890 <http://dx.doi.org/10.1111/j.1365-3180.2004.00442.x>
- 891 Bhaskar, V., Westbrook, A.S., Bellinder, R.R., Di Tommaso, A., 2021. Integrated management of living mulches for weed
892 control: A review. *Weed Technol.* 35, 856-868. <https://doi.org/10.1017/wet.2021.52>
- 893 Birtchisel, S.K., Clements, R.S. Gallandt, E.R., 2021. Review: How will climate change impact the ‘many little hammers’ of
894 ecological weed management? *Weed Res.* 61, 327–341. <https://doi.org/10.1111/wre.12497>
- 895 Blackshaw, R.E., 1994. Rotation affects downy brome (*Bromus tectorum*) in winter wheat (*Triticum aestivum*). *Weed*
896 *Technol.* 8, 728-732. <https://doi.org/10.1017/S0890037X00028591>
- 897 Blackshaw, R.E., O’Donovan, J.T., Harper, K.N., Clayton, G.W., Stougaard, R.N., 2006. Reduced herbicide doses in field
898 crops: A review. *Weed Biol. Manag.* 6, 10-17, <http://dx.doi.org/10.1111/j.1445-6664.2006.00190.x>
- 899 Bond, W., Grundy, A.C., 2001. Non-chemical weed management in organic farming systems. *Weed Res.* 41, 383-405.
900 <http://dx.doi.org/10.1046/j.1365-3180.2001.00246.x>

- 901 Botto, J.F., Scopel, A.L., Sanchez, R.A., 2000. Water constraints on the photoinduction of weed seed germination during
902 tillage. *Aust. J. Plant Physiol.* 27, 463-471.
- 903 Brown, B., Gallandt, E.R., DiTommaso, A., Salon, P., Smith, R.G., Ryan, M.R., Cordeau, S., 2022. Improving weed
904 management based on the timing of emergence peaks: a case study of problematic weeds in Northeast United
905 States. *Front. Agron.* 4: 888664. <http://dx.doi.org/10.3389/fagro.2022.888664>
- 906 Cabeza-Orcel, P., 2020. Un couvert de légumineuses peut-il améliorer les performances des cultures ? *Persp. Agric.* 479.
- 907 Cadoux, S., Sauzet, G., Valantin-Morison, M., Pontet, C., Champolivier, L., Robert, C., Lieven, J., Flénet, F., Mangenot, O.,
908 Fauvin, P., Landé, N. 2015. Intercropping frost-sensitive legume crops with winter oilseed rape reduces weed
909 competition, insect damage, and improves nitrogen use efficiency. *OCL* 22, D302,
910 <https://doi.org/10.1051/ocl/2015014>.
- 911 Camargo Silva, G., Bagavathiannan, M., 2023. Mechanisms of weed suppression by cereal rye cover crop: A review.
912 *Agron. J.*, 115, 1571–1585, <https://doi.org/10.1002/agj2.21347>
- 913 Carof, M., de Tourdonnet, S., Saulas, P., Le Floch, D., Roger-Estrade, J., 2007a. Undersowing wheat with different living
914 mulches in a no-till system. I. Yield analysis. *Agron Sustain. Dev.* 27, 347-356, <https://doi.org/10.1051/agro:2007016>
- 915 Carof, M., de Tourdonnet, S., Saulas, P., Le Floch, D., Roger-Estrade, J., 2007a. Undersowing wheat with different living
916 mulches in a no-till system. II. Competition for light and nitrogen. *Agron Sustain. Dev.* 27, 357-365,
917 <https://doi.org/10.1051/agro:2007017>
- 918 Castel, T., Lecomte, C., Richard, Y., Lejeune-Hénaut, I., Larmure, A., 2017. Frost stress evolution and winter pea ideotype
919 in the context of climate warming at a regional scale. *OCL* 24, D106, <https://doi.org/10.1051/ocl/2017002>
- 920 Chauvel, B., Guillemin, J.P., Colbach, N., Gasquez, J., 2001. Evaluation of cropping systems for management of herbicide-
921 resistant populations of blackgrass (*Alopecurus myosuroides* Huds.). *Crop Prot.* 20, 127-137,
922 [http://dx.doi.org/10.1016/S0261-2194\(00\)00065-X](http://dx.doi.org/10.1016/S0261-2194(00)00065-X)
- 923 Chauvel, B., Gauvrit, C., & Guillemin, J.P., 2022. From sea salt to glyphosate salt: a history of herbicide use in France.
924 *Adv. Weed Sci.* 40, e020220015, <http://dx.doi.org/10.51694/AdvWeedSci/2022;40:seventy-five008>
- 925 Chen, Y., Dunbabin, V., Postma, J., Diggle, A., Siddique, K. M., Rengel, Z., 2013. Modelling root plasticity and response of
926 narrow-leaved lupin to heterogeneous phosphorus supply. *Plant Soil* 372, 319-337,
927 <http://dx.doi.org/10.1007/s11104-013-1741-x>
- 928 Cherièrè, T., Lorin, M., Corre-Hellou, G., 2020. Species choice and spatial arrangement in soybean-based intercropping:
929 Levers that drive yield and weed control. *Field Crops Res.* 256, 107923, <http://dx.doi.org/10.1016/j.fcr.2020.107923>
- 930 Chicouene, D., 2007. Mechanical destruction of weeds. A review. *Agron. Sustain. Dev.* 27, 19–27,
931 <http://dx.doi.org/10.1051/agro:2006012>
- 932 Christensen, S., 1995. Weed suppression ability of spring barley varieties. *Weed Res.* 35, 241–247,
933 <https://doi.org/10.1111/j.1365-3180.1995.tb01786.x>
- 934 Chung, I.M., Ham, T.H., Cho, G.W., Kwon, S.W., Lee, Y., Seo, J., An, Y.J., Kim, S.Y., Kim, S.H., Lee, J., 2020. Study of
935 quantitative trait loci (QTLs) associated with allelopathic trait in rice. *Genes* 11, 470, <http://dx.doi.org/10.3390/genes11050470>
- 937 Clements, D., Weise, S., Swanton, C., 1994. Integrated weed management and weed species diversity. *Phytoprotection*
938 75, 1–18, <https://doi.org/10.7202/706048a>
- 939 Colbach, N., Gardarin, A., Moreau, D., 2019. The response of weed and crop species to shading: Which parameters
940 explain weed impacts on crop production? *Field Crops Res.* 238, 45-55, <https://doi.org/10.1016/j.fcr.2019.04.008>
- 941 Colbach, N., Colas, F., Cordeau, S., Maillot, T., Queyrel, W., Villerd, J., Moreau, D. 2021. The FLORSYS crop-weed canopy
942 model, a tool to investigate and promote agroecological weed management. *Field Crops Res.* 261, 108006,
943 <http://dx.doi.org/10.1016/j.fcr.2020.108006>

- 944 Colbach, N., Felten, E., Gée, C., Klein, A., Lannuzel, L., Lecomte, C., Maillot, T., Strbik, F., Villerd, J., Moreau, D., 2022.
945 Tracking ideal varieties and cropping techniques for agroecological weed management: a simulation-based study on
946 pea. *Front. Plant Sci.* 13, 809056, <https://doi.org/10.3389/fpls.2022.809056>
- 947 Coleman, R.D., Gill, G.S., Rebetzke, G.J., 2001. Identification of quantitative trait loci for traits conferring weed
948 competitiveness in wheat (*Triticum aestivum* L.). *Aust. J. Agric. Res.* 52, 1235-1246, [http://dx.doi.org/](http://dx.doi.org/10.1071/AR01055)
949 [10.1071/AR01055](http://dx.doi.org/10.1071/AR01055)
- 950 Cormier, F., Foulkes, J., Hirel, B., Gouache, D., Moenne-Loccoz, Y., Le Gouis, J., 2016. Breeding for increased nitrogen-
951 use efficiency: a review for wheat (*T.aestivum* L.). *Plant Breed.* 135, 255-278, <http://dx.doi.org/10.1111/pbr.12371>
- 952 Constantin, J., Dürr, C., Tribouillois, H., Justes, E., 2015. Catch crop emergence success depends on weather and soil
953 seedbed conditions in interaction with sowing date: A simulation study using the SIMPLE emergence model. *Field*
954 *Crops Res.* 176, 22-33, [10.1016/j.fcr.2015.02.017](https://doi.org/10.1016/j.fcr.2015.02.017)
- 955 Cougnon, M., Durand J.L., Julier, B., Barre, P., Litrico, I., 2022. Using perennial plant varieties for use as living mulch for
956 winter cereals. A review. *Agron. Sustain. Dev.* 42, 110, <http://dx.doi.org/10.1007/s13593-022-00844-x>
- 957 Debaeke, P., 1997. Le désherbage intégré en grande culture: bases de raisonnement et perspectives d'application. *Cah.*
958 *Agric.* 6, 185-194.
- 959 Debaeke, P., Casadebaig, P., Langlade, N., 2021. New challenges for sunflower ideotyping in changing environments and
960 more ecological cropping systems. *OCL* 28, 29, <http://dx.doi.org/10.1051/ocl/2021016>
- 961 Dejoux, J.F., Meynard, J.M., Reau, R., Roche, R., Saulas, P., 2003. Evaluation of environmentally-friendly crop
962 management systems based on very early sowing dates for winter oilseed rape in France. *Agronomie* 23, 725-736,
963 <https://doi.org/10.1051/agro:2003050>
- 964 Délye, C., Menchari, Y., Guillemin, J. P., Matějček, A., Michel, S., Camilleri, C., Chauvel, B., 2007. Status of black grass
965 (*Alopecurus myosuroides*) resistance to acetyl-coenzyme A carboxylase inhibitors in France. *Weed Res.* 47, 95-105,
966 <http://dx.doi.org/10.1111/j.1365-3180.2007.00544.x>
- 967 Délye, C., Causse, R., Michel, S., 2016. Genetic basis, evolutionary origin and spread of resistance to herbicides inhibiting
968 acetolactate synthase in common groundsel (*Senecio vulgaris*). *Pest Manag. Sci.* 72, 89-102, [http://dx.doi.org/](http://dx.doi.org/10.1002/ps.4058)
969 [10.1002/ps.4058](http://dx.doi.org/10.1002/ps.4058)
- 970 Demie, D.T., Döring, T.F., Finckh, M.R., Van der Werf, W., Enjalbert, J., Seidel, S.J., 2022. Mixture × genotype effects in
971 cereal/legume intercropping. *Front. Plant Sci.* 13, 846720, <https://doi.org/10.3389/fpls.2022.846720>
- 972 De Vita, P., Colecchia, S.A., Pecorella, I., Saia, S., 2017. Reduced inter-row distance improves yield and competition
973 against weeds in a semi-dwarf durum wheat variety. *Eur. J. Agron.* 85, 69–77,
974 <http://dx.doi.org/10.1016/j.eja.2017.02.003>
- 975 Didon, U.M.E, 2002. Variation between barley cultivars in early response to weed competition. *J. Agron. Crop Sci.* 188,
976 176-184, <http://dx.doi.org/10.1046/j.1439-037X.2002.00566.x>
- 977 Doré, T., Sène, M., Pellissier, F., Gallet, C., 2004. Approche agronomique de l'allélopathie. *Cah. Agric.* 13, 249-256.
- 978 Eissenstat, D.M., 1992. Costs and benefits of constructing roots of small diameter. *J. Plant Nut.* 15, 763-782,
979 <http://dx.doi.org/10.1080/01904169209364361>
- 980 Fahad, S., Hussain, S., Chauhan, B.S., Saud, S., Wu, C., Hassan, S., Tanveer, M., Jan, A., Huang, J., 2015. Weed growth and
981 crop yield loss in wheat as influenced by row spacing and weed emergence times. *Crop Prot.* 71, 101-108,
982 <https://doi.org/10.1016/j.cropro.2015.02.005>
- 983 Faverjon, L., Escobar-Gutierrez, A., Litrico, I., Julier, B., Louarn, G., 2019. A generic individual-based model can predict
984 yield, nitrogen content, and species abundance in experimental grassland communities. *J. Exp. Bot.* 70, 2491-2504,
985 <http://dx.doi.org/10.1093/jxb/ery323>

- 986 Fayaud, B., Coste, F., Corre-Hellou, G., Gardarin, A., Durr C., 2014. Modelling early growth under different sowing
987 conditions: A tool to predict variations in intercrop early stages. *Eur. J. Agron.* 52, 180-190,
988 <https://doi.org/10.1016/j.eja.2013.09.009>
- 989 Federico, A.A., Pimet, E., Coffin, A., Ducourtieux, C., Queyrel, W., Rolhauser, A.G., Poggio, S.L. Guillemain, J.P., Blouin, M.,
990 2023. Ancient varieties can help control weed density while preserving weed diversity. *Biol. Agric. Hortic.*,
991 <http://dx.doi.org/0.1080/01448765.2023.2270982>
- 992 Fernando, M., Shrestha, A., 2023. The potential of cover crops for weed management: a sole tool or component of an
993 integrated weed management system? *Plants* 12, 752, <https://doi.org/10.3390/plants12040752>
- 994 Fogelberg, F., Dock Gustavsson, A.M., 1998. Resistance against uprooting in carrots (*Daucus carota*) and annual weeds:
995 a basis for selective mechanical weed control. *Weed Res.* 38, 183-190.
- 996 Fogliatto, S., Milan, M., De Palo, F., Ferrero, A., Vidotto, F., 2019. Effectiveness of mechanical weed control on Italian
997 flint varieties of maize. *Renew. Agric. Food Syst.* 34, 447-459, <http://dx.doi.org/10.1017/S1742170517000813>
- 998 Fontaine, L., Rolland, B., Bernicot, M.-H., 2008. Contribution to organic breeding programmes of wheat variety testing
999 in organic farming in France. In: Neuhoff D. *et al.* (Eds.), *Proceedings of Cultivating the Future Based on Science: 2nd*
1000 *Conference of the International Society of Organic Agriculture Research ISO FAR, Modena, Italy*, p. 688-691.
- 1001 Fontaine, L., Bernicot, M.H., Rolland, B., Poiret, L., 2009. Des variétés rustiques concurrentes des adventices pour
1002 l'agriculture durable, en particulier l'agriculture biologique. *Innovations Agronomiques* 4, 115-124.
- 1003 Fontaine L., Coulombel A., Rolland B., 2018. Geny, Grafik, Gwastell : trois variétés de blé tendre inscrites cet hiver au
1004 catalogue français avec la mention AB ! Alter Agri sur <http://itab.asso.fr/publications/varietebletendre.php>
- 1005 Freschet, G.T., Roumet, C., 2017. Sampling roots to capture plant and soil functions. *Funct. Ecol.* 31, 1506-1518,
1006 <http://dx.doi.org/10.1111/1365-2435.12883>
- 1007 Fried, G., Norton, L.R., Reboud, X., 2008. Environmental and management factors determining weed species
1008 composition and diversity in France. *Agric. Ecosys. Environ.* 128, 68-76, <https://doi.org/10.1016/j.agee.2008.05.003>
- 1009 Gaba, S., Fried, G., Kazakou, E., Chauvel, B., Navas, M.-L., 2014. Agroecological weed control using a functional approach:
1010 a review of cropping systems diversity. *Agron. Sustain. Dev.* 34, 103–119, [https://doi.org/10.1007/s13593-013-0166-](https://doi.org/10.1007/s13593-013-0166-5)
1011 5
- 1012 Gaba, S., Perronne, R., Fried, G., Gardarin, A., Bretagnolle, F., Biju-Duval, L., Colbach, N., Cordeau, S., Fernandez-Aparicio,
1013 M., Gauvrit, C., Gibot-Leclerc, S., Guillemain, J.P., Moreau, D., Munier-Jolain, N.G., Strbik, F., Reboud, X., 2017.
1014 Response and effect traits of arable weeds in agro-ecosystems: a review of current knowledge. *Weed Res.* 57, 123-
1015 147. <http://dx.doi.org/10.1111/wre.12245>
- 1016 Gardarin, A., Coste, F., Wagner, M.-H., Dürr C., 2016. How do seed and seedling traits influence germination and
1017 emergence parameters in crop species? A comparative analysis. *Seed Science Res.* 26, 317-331,
1018 <https://doi.org/10.1017/s0960258516000210>
- 1019 Gerhards, R., Schappert, A., 2019. Advancing cover cropping in temperate integrated weed management. *Pest Manag.*
1020 *Sci.* 76, 42-46, <https://doi.org/10.1002/ps.5639>
- 1021 Gerhards, R., Kollenda, B., Machleb, J., Möller, K., Butz, A., Reiser, D., Griegentrog, H.W., 2020. Camera-guided weed
1022 hoeing in winter cereals with narrow row distance. *Gesund. Pflanz.* 72, 403-411. [https://doi.org/10.1007/s10343-](https://doi.org/10.1007/s10343-020-00523-5)
1023 020-00523-5
- 1024 Gesch, R.W., Berti, M.T., Eberle, C.A., Weyers, S.L., 2023. Relay cropping as an adaptive strategy to cope with climate
1025 change. *Agron. J.* 115, 1501–1518, <https://doi.org/10.1002/agj2.21343>
- 1026 Ghanem, M.E., Marrou, H., Sinclair, T.R., 2015. Physiological phenotyping of plants for crop improvement. *Trends Plant*
1027 *Sci.* 20, 139-144, <https://doi.org/10.1016/j.tplants.2014.11.006>.

- 1028 Gosseau, F., Blanchet, N., Varès, D., Burger, P., Campergue, D., Colombet, C., Gody, L., Liévin, J.-F., Mangin, B., Tison, G.,
1029 Vincourt, P., Casadebaig, P., Langlade, N., 2019. Heliaphen, an outdoor high-throughput phenotyping platform for
1030 genetic studies and crop modeling. *Front. Plant Sci.* 9, 1908, <https://doi.org/10.3389/fpls.2018.01908>
- 1031 Gu, C., Bastiaans, L., Anten, N. P., Makowski, D., van der Werf, W., 2021. Annual intercropping suppresses weeds: A
1032 meta-analysis. *Agric. Ecosyst. Environ.* 322, 107658, <https://doi.org/10.1016/j.agee.2021.107658>
- 1033 Hammer, D.J., Stoltenberg, D.E., Colquhoun, J.B., Conley, S.P., 2018. Has breeding improved soybean competitiveness
1034 with weeds? *Weed Sci.* 66, 57-61, <https://doi.org/10.1017/wsc.2017.60>
- 1035 Hansen, P.K., Rasmussen, I.A., Holst, N., Andreasen, C., 2007. Tolerance of four spring barley (*Hordeum vulgare*) varieties
1036 to weed harrowing. *Weed Res.* 47, 241-251, <https://doi.org/10.1111/j.1365-3180.2007.00560.x>
- 1037 Harker, K.N., Clayton, G.W., Blackshaw, R.E., 2008. Comparison of leafy and semileafless pea for integrated weed
1038 management. *Weed Technol.* 22, 124-131, <https://doi.org/10.1614/WT-07-090.1>
- 1039 Hartwig, N.L., Ammon, H.U. 2002. Cover crops and living mulches. *Weed Sci.* 50, 688-699, [https://doi.org/10.1614/0043-1745\(2002\)050\[0688:AIACCA\]2.0.CO;2](https://doi.org/10.1614/0043-1745(2002)050[0688:AIACCA]2.0.CO;2)
- 1041 Hatcher P.E, Melander, B., 2003. Combining physical, cultural and biological methods: prospects for integrated non-
1042 chemical weed management strategies. *Weed Res.* 43, 303–322. <https://doi.org/10.1046/j.1365-3180.2003.00352.x>
- 1043 Haug, B., Messmer, M. M., Enjalbert, J., Goldringer, I., Forst, E., Flutre, T., Mary-Huard, T., Hohmann, P., 2021. Advances
1044 in breeding for mixed cropping–incomplete factorials and the producer/associate concept. *Front. Plant Sci.* 11,
1045 620400, <https://doi.org/10.3389/fpls.2020.620400>
- 1046 Hendriks, P.W., Gurusinghe, S., Ryan, P.R., Rebetzke, G.J., Weston, L.A. 2022. Competitiveness of early vigour wheat
1047 (*Triticum aestivum* L.) genotypes is established at early growth stages. *Agronomy* 12, 377,
1048 <https://doi.org/10.3390/agronomy12020377>
- 1049 Hickman, D.T., Comont, D., Rasmussen, A., Birkett, M.A., 2023. Novel and holistic approaches are required to realize
1050 allelopathic potential for weed management. *Ecology and Evolution* 13, e10018, <https://doi.org/10.1002/ece3.10018>
- 1052 Hiltbrunner, J., Jeanneret, P., Liedgens, M., Stamp, P., Streit, B., 2007a. Response of weed communities to legume living
1053 mulches in winter wheat. *J. Agron. Crop Sci.* 193, 93–102. <https://doi.org/10.1111/j.1439-037X.2007.00250.x>
- 1054 Hiltbrunner, J., Liedgens, M., Bloch, L., Stamp, P., Streit, B., 2007b. Legume cover crops as living mulches for winter
1055 wheat: components of biomass and the control of weeds. *Eur. J. Agron.* 26:21–29.
1056 <https://doi.org/10.1016/j.eja.2006.08.002>
- 1057 Hiltbrunner, J., Liedgens, M. 2008. Performance of winter wheat varieties in white clover living mulch. *Biol. Agric. Hort.*
1058 26, 85-101. <https://doi.org/10.1080/01448765.2008.9755071>.
- 1059 Hodgdon, E.A., Warren, N.D., Smith, R.G., Sideman, R.G., 2016. In-season and carry-over effects of cover crops on
1060 productivity and weed suppression. *Agron. J.* 108, 1624-1635, <https://doi.org/10.2134/agronj2015.0419>.
- 1061 Holt, J.S., 1995. Plant responses to light: A potential tool for weed management. *Weed Sci.* 43, 474–482,
1062 <https://doi.org/10.1017/S0043174500081509>
- 1063 Huel, D.G., Hucl, P., 1996. Genotypic variation for competitive ability in spring wheat. *Plant Breed.* 115, 325-329,
1064 <https://doi.org/10.1111/j.1439-0523.1996.tb00927.x>
- 1065 Hussain, M.I., Araniti, F., Schulz, M., Baerson, S., Vieites-Álvarez, Y., Rempelos, L., Bilsborrow, P., Chinchilla, N., Macías,
1066 F.A., Weston, L.A., Reigosa, M.J., Sánchez-Moreiras, A.M., 2022. Benzoxazinoids in wheat allelopathy – From
1067 discovery to application for sustainable weed management. *Environ. Exp. Bot.* 202, 104997.
1068 <https://doi.org/10.1016/j.envexpbot.2022.104997>
- 1069 Ilnicki, R.D., Enache, A.J., 1992. Subterranean clover living mulch: an alternative method of weed control. *Agric. Ecosyst.*
1070 *Environ.* 40, 249-264. [https://doi.org/10.1016/0167-8809\(92\)90096-T](https://doi.org/10.1016/0167-8809(92)90096-T)

- 1071 Jabran, K., Mahajan, G., Sardana, V., Chauhan, B.S., 2015. Allelopathy for weed control in agricultural systems. *Crop*
1072 *Prot.* 72, 57-65. <https://doi.org/10.1016/j.cropro.2015.03.004>
- 1073 Jacob, C.E., Johnson, E.N., Dyck, M.F., Willenborg, C.J., 2016. Evaluating the competitive ability of semileafless field pea
1074 cultivars. *Weed Sci.* 64, 137-145, <https://doi.org/10.1614/WS-D-15-00113.1>
- 1075 Jacquet, F., Jeuffroy, M.-H., Jouan, J., Le Cadre, E., Litrico, I., Malausa, T., Reboud, X., Huyghe, C., 2022. Pesticide-free
1076 agriculture as a new paradigm for research. *Agron. Sustain. Dev.* 42, 8, [https://doi.org/10.1007/s13593-021-00742-](https://doi.org/10.1007/s13593-021-00742-8)
1077 8
- 1078 Jähne, F., Balko, C., Hahn, V., Würschum, T., Leiser, W.L., 2019. Cold stress tolerance of soybeans during flowering: QTL
1079 mapping and efficient selection strategies under controlled conditions. *Plant Breed.* 138, 708-720,
1080 [10.1111/pbr.12734](https://doi.org/10.1111/pbr.12734)
- 1081 Jensen, L.B., Courtois, B., Olofsson, M., 2008. Quantitative trait loci analysis of allelopathy in rice. *Crop Sci.* 48, 1459-
1082 1469, <https://doi.org/10.2135/cropsci2007.09.0533>
- 1083 Jeudy, C., Adrian, M., Baussard, C., Bernard, C., Bernaud, E., Bourion, V., Busset, H., Cabrera-Bosquet, L., Cointault, F.,
1084 Han, S. M., Lamboeuf, M., Moreau, D., Pivato, B., Prudent, M., Trouvelot, S., Truong, H. N., Vernoud, V., Voisin, A. S.,
1085 Wipf, D., Salon, C., 2016. RhizoTubes as a new tool for high throughput imaging of plant root development and
1086 architecture: test, comparison with pot grown plants and validation. *Plant Methods* 12, 31, [https://doi.org/10.1186/s13007-](https://doi.org/10.1186/s13007-016-0131-9)
1087 016-0131-9
- 1088 Jeuffroy, M.H., Gate, P., Machet, J.M., Recous, S., 2013. Nitrogen management in arable crops: Can available knowledge
1089 and tools reconcile agronomic and environmental needs? *Cah. Agric.* 22, 249-257, [https://doi.org/](https://doi.org/10.1684/agr.2013.0639)
1090 [10.1684/agr.2013.0639](https://doi.org/10.1684/agr.2013.0639)
- 1091 Jeuffroy, M.H., Casadebaig, P., Debaeke, P., Loyce, C., Meynard, J.M., 2014. Use of agronomic models to predict cultivar
1092 performances in various environments and cropping systems. A review. *Agron. Sustain. Dev.* 34, 121-137,
1093 <https://doi.org/10.1007/s13593-013-0170-9>
- 1094 Jones, L., Clements, R.O., 1993. Development of a low input system for growing wheat (*Triticum vulgare*) in a permanent
1095 understorey of white clover (*Trifolium repens*). *Ann Appl. Biol.* 123, 109-119. [https://doi.org/10.1111/j.1744-](https://doi.org/10.1111/j.1744-7348.1993.tb04078.x)
1096 [7348.1993.tb04078.x](https://doi.org/10.1111/j.1744-7348.1993.tb04078.x)
- 1097 Juroszek, P., Gerhards, R., Kuhbauch W., 2002. Photocontrol of weed germination of arable annual weeds. *Journal of*
1098 *Agronomy and Crop Science* 188, 389-397, <https://doi.org/10.1046/j.1439-037X.2002.00575.x>
- 1099 Juroszek, P., Neuhoff D., Kopke, U., 2017. Night-time tillage revisited: the delayed soil desiccation process in night-time
1100 tilled plots may promote unexpected weed germination. *Weed Res.* 57, 213-217,
1101 <https://doi.org/10.1111/wre.12256>
- 1102 Justes, E., Richard, G., 2017. Contexte, concepts et définition des cultures intermédiaires multi-services. *Innovations*
1103 *Agronomiques* 62, 1-15. <https://doi.org/10.15454/1.5174017785695195E12>
- 1104 Khamare, Y., Chen, J., Marble, S.C., 2022. Allelopathy and its application as a weed management tool: A review. *Front.*
1105 *Plant Sci.*, 13, 1034649, <https://doi.org/10.3389/fpls.2022.103464>
- 1106 Kiær, L P., Weedon, O.D., Bedoussac, L., Bickler, C., Finckh, M.R., Haug, B., Iannetta, P.P.M., Raaphorts-Travaille, G.,
1107 Weih, M., Karley, A.J., 2022. Supply chain perspectives on breeding for legume-cereal intercrops. *Front. Plant Sci.*
1108 459, 844635, <https://doi.org/10.3389/fpls.2022.844635>
- 1109 Klaiss, M., Schmid, N., Betrix, C.A., Baux, A., Charles, R., Messmer, M.M., 2020. Organic soybean production in
1110 Switzerland. *OCL* 27, 64, <https://doi.org/10.1051/ocl/2020059>
- 1111 Kolb, L.N., Gallandt, E.R., Molloy, T., 2010. Improving weed management in organic spring barley: physical weed control
1112 vs. interspecific competition. *Weed Res.* 50, 597-605, <https://doi.org/10.1111/j.1365-3180.2010.00818.x>
- 1113 Kong, C.H., Chen, X.H., Hu, F., Zhang, S.Z., 2011. Breeding of commercially acceptable allelopathic rice cultivars in China.
1114 *Pest Manag. Sci.* 67, 1100-1106. <https://doi.org/10.1002/ps.2154>

- 1115 Kruidhof, H.M., Bastiaans, L., Kropff, M.J., 2008. Ecological weed management by cover cropping: effects on weed
 1116 growth in autumn and weed establishment in spring. *Weed Res.* 48, 492–502, <https://doi.org/10.1111/j.1365->
 1117 3180.2008.00665.x
- 1118 Kucek, L.K., Mallory, E.B., Darby, H.M., Dawson, J.C., Sorrells, M.E., 2021. Breeding wheat for weed-competitive ability:
 1119 I. Correlated traits. *Euphyt.* 217, 1-15, <https://doi.org/10.1007/s10681-021-02930-9>
- 1120 Kumar, V., Obour, A., Jha, P., Liu, R., Manuchehri, M.R., Dille, J.A., Holman, J., Stahlman, P.W., 2020. Integrating cover
 1121 crops for weed management in the semiarid U.S. Great Plains: opportunities and challenges. *Weed Sci.* 68, 311–323.
 1122 <https://doi.org/10.1017/wsc.2020.29>
- 1123 Kunz, C., Sturm, D.J., Varnholt, D., Walker, F., Gerhards, R., 2016. Allelopathic effects and weed suppressive ability of
 1124 cover crops. *Plant Soil Environ.* 62, 60–66, <https://doi.org/10.17221/612/2015-PSE>
- 1125 Kurstjens, D.A.G., Perdok, U.D., Goense, D., 2000. Selective uprooting by weed harrowing on sandy soils. *Weed Res.* 40,
 1126 431-447.
- 1127 Lamichhane, J.R., Dachbrodt-Saaydeh, S., Kudsk, P., Messéan, A., 2016. Toward a reduced reliance on conventional
 1128 pesticides in European Agriculture. *Plant Dis.* 100: 10–24, <https://doi.org/10.1094/PDIS-05-15-0574-FE>
- 1129 Lamichhane, J.R., Alletto, L., Cong, W., Dayoub, E., Maury, P., Plaza-Bonilla, D., Reckling, M., Saia, S., Soltani, E., Tison, G.,
 1130 Debaeke, P., 2023. Relay cropping for sustainable intensification of agriculture across temperate regions: crop
 1131 management challenges and future research priorities. *Field Crops Res.* 291, 108795.
 1132 <https://doi.org/10.1016/j.fcr.2022.108795>
- 1133 Laperche, A., Brancourt-Hulmel, M., Heumez, E., Gardet, O., Hanocq, E., Devienne-Barret, F., Le Gouis, J., 2007. Using
 1134 genotype x nitrogen interaction variables to evaluate the QTL involved in wheat tolerance to nitrogen constraints.
 1135 *Theor. Appl. Genet.* 115, 399-415, <http://dx.doi.org/10.1007/s00122-007-0575>
- 1136 Lazzaro, M., Costanzo, A., Hosam Farag, D., Bàrberi, P., 2017. Grain yield and competitive ability against weeds in
 1137 modern and heritage common wheat cultivars are differently influenced by sowing density. *Ital. J. Agron.* 12, 901,
 1138 <https://doi.org/10.4081/ija.2017.901>
- 1139 Lechenet, M., Dessaint, F., Py, G., Makowski, D., Munier-Jolain, N., 2017. Reducing pesticide use while preserving crop
 1140 productivity and profitability on arable farms. *Nat. Plants* 3, 17008, <https://doi.org/10.1038/nplants.2017.8>
- 1141 Lemerle, D., Gill, G.S., Murphy, C.E., Walker, S.R., Cousens, R.D., Mokhtari, S., Peltzer, S.J., Coleman, R., Lockett, D.J.,
 1142 2001. Genetic improvement and agronomy for enhanced wheat competitiveness with weeds. *Aust. J. Agric. Res.* 52,
 1143 527–548. <https://doi.org/10.1071/AR00056>.
- 1144 Lemerle, D., Smith, A., Verbeek, B., Koetz, E., Lockley, P., Martin, P., 2006. Incremental crop tolerance to weeds: A
 1145 measure for selecting competitive ability in Australian wheats. *Euphyt.* 149, 85-95, <https://doi.org/10.1007/s10681->
 1146 005-9056-5
- 1147 Lemerle, D., Lockett, D.J., Lockley, P., Koetz, E., Wu, H., 2014. Competitive ability of Australian canola (*Brassica napus*)
 1148 genotypes for weed management. *Crop Pasture Sci.* 65, 1300-1310, <https://doi.org/10.1071/CP14125>.
- 1149 Lemessa, F., Wakjira, M., 2015. Cover crops as a means of ecological weed management in agroecosystems. *J. Crop Sci.*
 1150 *Biotechnol.* 18, 123–135, <https://doi.org/10.1007/s12892-014-0085-2>
- 1151 Lever, L., Rolland, B., Chauvel, B., Cordeau, S., Perronne, R., 2022a. Caractères variétaux associés à la compétition des
 1152 génotypes de céréales à paille vis-à-vis des adventices et pistes pour leur sélection : une revue bibliographique.
 1153 *Agronomie, Environnement & Sociétés* 12-1, 201-215, <https://doi.org/10.54800/cgp267>
- 1154 Lever, L., Rolland, B., Chauvel, B., Cordeau, S., Perronne, R., 2022b. Des céréales à paille compétitives vis-à-vis des
 1155 adventices. *Phytoma* 757, 48-52.
- 1156 Liebman, M., Dyck, E., 1993. Crop rotation and intercropping strategies for weed management. *Ecol. Appl.* 3, 92-122,
 1157 <https://doi.org/10.2307/1941795>

- 1158 Liebman, M., Gallandt, E.R., 1997. Many little hammers: ecological management of crop-weed interactions. In: Ecology
1159 in Agriculture (L. E. Jackson, ed.) Academic Press, San Diego, CA, pp.291-343, [https://doi.org/10.1016/B978-](https://doi.org/10.1016/B978-012378260-1/50010-5)
1160 012378260-1/50010-5
- 1161 Louarn, G., Barillot, R., Combes, D., Escobar-Gutierrez, A., 2020. Towards intercrop ideotypes: non-random trait
1162 assembly can promote overyielding and stability of species proportion in simulated legume-based mixtures. *Ann.*
1163 *Bot.* 126, 671-685, <https://doi.org/10.1093/aob/mcaa014>
- 1164 Loyce, C., Meynard, J.M., Bouchard, C., Rolland, B., Lonnet, P., Bataillon, P., Bernicot, M.H., Bonnefoy, M., Charrier, X.,
1165 Debote, B., Demarquet, T., Duperrier, B., Félix, I., Heddjaj, D., Leblanc, O., Leleu, M., Mangin, P., Meausoone, M.,
1166 Doussinault, G., 2012. Growing winter wheat cultivars under different management intensities in France: A
1167 multicriteria assessment based on economic, energetic and environmental indicators. *Field Crops Res.* 125, 167-178,
1168 <https://doi.org/10.1016/j.fcr.2011.08.007>
- 1169 Lutman, P.J.W., Moss, S.R., Cook, S., Welham, S.J., 2013. A review of the effects of crop agronomy on the management
1170 of *Alopecurus myosuroides*. *Weed Res.* 53, 299-313. <https://doi.org/10.1111/wre.1202453>
- 1171 McCollough, M.R., Melander, B., 2022. Improving upon the interrow hoed cereal system: the effects of crop density and
1172 row spacing on intrarow weeds and crop parameters in spring barley. *Weed Sci.* 70, 341-352,
1173 <https://doi.org/10.1017/wsc.2022.14>
- 1174 McKenzie-Gopsill, A., Farooque, A., 2023. Incorporated cover crop residue suppresses weed seed germination. *Weed*
1175 *Biol. Manag.*, 23, 48–57. <https://doi.org/10.1111/wbm.12267>
- 1176 Mahé, I., Chauvel, B., Colbach, N., Cordeau, S., Gfeller, A., Reiss A., Moreau, D., 2022. Deciphering field-based evidences
1177 for crop allelopathy in weed regulation. A review. *Agron. Sustain. Dev.* 42, 50, [https://doi.org/10.1007/s13593-021-](https://doi.org/10.1007/s13593-021-00749-1)
1178 00749-1
- 1179 Malézieux, E., Crozat, Y., Dupraz, C., Laurans, M., Makowski, D., Ozier-Lafontaine, H., Rapidel, B., De Tourdonnet, S.,
1180 Valantin-Morison, M., 2009. Mixing plant species in cropping systems: concepts, tools and models: a review. *Agron.*
1181 *Sustain. Dev.* 29, 43–62. <https://doi.org/10.1051/agro:2007057>
- 1182 Martin-Guay, M.O., Paquette, A., Dupras, J., Rivest, D., 2018. The new green revolution: sustainable intensification of
1183 agriculture by intercropping. *Sci. Total Environ.* 615, 767-772, <https://doi.org/10.1016/j.scitotenv.2017.10.024>
- 1184 Martre, P., Quilot-Turion, B., Luquet, D., Ould-Sidi, M., Chenu, K., Debaeke, P., 2015. Model assisted phenotyping and
1185 ideotype design. In: Calderini D, Sadras VO (eds), *Crop Physiology. Applications for Genetic Improvement and*
1186 *Agronomy*. 2nd Edition, Academic Press, pp 349-373, <https://doi.org/10.1016/B978-0-12-417104-6.00014-5>
- 1187 Mason, H.E., Spaner, D., 2006. Competitive ability of wheat in conventional and organic management systems: a review
1188 of the literature. *Can. J. Plant Sci.* 86, 333–343. <https://doi.org/10.4141/P05-051>.
- 1189 Mason, H.E., Navabi, A., Frick, B.L., O'Donovan, J.T., Spaner, D.M., 2007a. The weed-competitive ability of Canada
1190 Western red spring wheat cultivars grown under organic management. *Crop Sci.* 47, 1167–1176,
1191 <https://doi.org/10.2135/cropsci2006.09.0566>
- 1192 Mason, H.E., Navabi, A., Frick, B.L., O'Donovan, J.T., Spaner, D.M., 2007b. Cultivar and seeding rate effects on the
1193 competitive ability of spring cereals grown under organic production in northern Canada. *Agron. J.* 99, 1199–1207.
1194 <https://doi.org/10.2134/agronj2006.0262>.
- 1195 Mason, H., Goonewardene, L., Spaner, D., 2008. Competitive traits and the stability of wheat cultivars in differing natural
1196 weed environments on the northern Canadian Prairies. *J. Agric. Sci.* 146, 21–33.
1197 <https://doi.org/10.1017/S0021859607007319>.
- 1198 Massot, H., Le Campion, A., Rolland, B., Sicard, H., Fontaine, L., 2018. Guide de notation de la couverture du sol par le
1199 blé tendre. Document INRA – ITAB, 11 p., http://www.itab.asso.fr/divers/guide_note-couv-sol_2018.pdf
- 1200 Melander, B., Cirujeda, A., Jørgensen, M.H., 2003. Effects of inter-row hoeing and fertilizer placement on weed growth
1201 and yield of winter wheat. *Weed Res.* 43, 428-438, <https://doi.org/10.1046/j.0043-1737.2003.00359.x>

- 1202 Melander, B., Rasmussen, I.E., Bàrberi, P., 2005. Integrating physical and cultural methods of weed control - examples
1203 from European research. *Weed Sci.* 53, 369-381, <https://doi.org/10.1614/WS-04-136R>.
- 1204 Melander, B., Jabran, K., De Notaris, C., Znova, L., Green, O., Olesen, J.E., 2018. Inter-row hoeing for weed control in
1205 organic spring cereals—Influence of inter-row spacing and nitrogen rate. *Eur. J. Agron.* 101, 49-56, <https://doi.org/10.1016/j.eja.2018.08.005>
- 1207 Mennan, H., Jabran, K., Zandstra, B. H., Pala, F., 2020. Non-chemical weed management in vegetables by using cover
1208 crops: a review. *Agronomy-Basel* 10, 16, <https://doi.org/10.3390/agronomy10020257>
- 1209 Milan M., Fogliatto, S., Blandino, M., Vidotto, F., 2020. Are wheat hybrids more affected by weed competition than
1210 conventional cultivars? *Agronomy* 10, 526, <https://doi.org/10.3390/agronomy10040526>
- 1211 Minoli, S., Jägermeyr, J., Asseng, S., Urfels, A., Müller, C., 2022. Global crop yields can be lifted by timely adaptation of
1212 growing periods to climate change. *Nat. Commun.* 13, 7079, <https://doi.org/10.1038/s41467-022-34411-5>.
- 1213 Mohammadi, G.R., Amiri, F., 2011. Critical period of weed control in soybean (*Glycine max*) as influenced by starter
1214 fertilizer. *Aust. J. Crop Sci.* 5, 1350-1355, ISSN 1835-2707.
- 1215 Moreau, D., Busset, H., Matejicek, A., Munier-Jolain, N., 2014. The ecophysiological determinants of nitrophily in annual
1216 weed species. *Weed Res.* 54, 335-346, <https://doi.org/10.1111/wre.12090>
- 1217 Moreau, D., Pointurier, O., Perthame, L., Beaudoin, N., Villerd, J., Colbach, N., 2021. Integrating plant-plant competition
1218 for nitrogen into a 3D individual-based model simulating the effects of cropping systems on weed dynamics. *Field
1219 Crops Res.* 268, 108166, <https://doi.org/10.1016/j.fcr.2021.108166>
- 1220 Moss, S., 2019. Integrated weed management (IWM): why are farmers reluctant to adopt non-chemical alternatives to
1221 herbicides? *Pest Manag. Sci.* 75, 1205–1211, <https://doi.org/10.1002/ps.5267>
- 1222 Moutier, N., Baranger, A., Fall, S., Hanocq, E., Marget, P., Floriot, M., Gauffreteau, A., 2022. Mixing ability of intercropped
1223 wheat varieties: stability across environments and tester legume species. *Front. Plant Sci.* 13, 877791,
1224 <https://doi.org/10.3389/fpls.2022.877791>
- 1225 Munoz-Huerta, R.F., Guevara-Gonzalez, R.G., Contreras-Medina, L.M., Torres-Pacheco, I., Prado-Olivarez, J., Ocampo-
1226 Velazquez, R.V., 2013. A review of methods for sensing the nitrogen status in plants: advantages, disadvantages and
1227 recent advances. *Sensors* 13, 10823-10843, <https://doi.org/10.3390/s130810823>
- 1228 Murphy, K.M., Dawson, J.C., Jones, S.S., 2008. Relationship among phenotypic growth traits, yield and weed suppression
1229 in spring wheat landraces and modern cultivars. *Field Crops Res.* 105, 107-115, <https://doi.org/10.1016/j.fcr.2007.08.004>
- 1231 Muzangwa, L., Chiduza, C., Muchaonyerwa, P., 2015. Bicultures of oat (*Avena sativa*) and grazing vetch (*Vicia dasycarpa*)
1232 regulate residue decomposition, nitrogen and phosphorus dynamics, and weed suppression in maize. *Int. J. Agric.
1233 Biol.* 17, 475-482, <https://doi.org/10.17957/IJAB/17.3.14.233>
- 1234 Mwendwa, J.M., Brown, W.B., Weston, P.A., Shamsul Haque, K.M., Preston, C., Weston, L.A., 2020a. Evaluation of
1235 selected commercial oilseed rape cultivars for early vigour, weed suppression and yield in southern New South
1236 Wales. *Weed Res.* 60, 1-14, <https://doi.org/10.1111/wre.12451>
- 1237 Mwendwa, J.M., Brown, W.B., Weidenhamer, J.D., Weston, P.A., Quinn, J.C., Wu, H., Weston, L.A., 2020b. Evaluation of
1238 commercial wheat cultivars for canopy architecture, early vigour, weed suppression, and yield. *Agronomy* 10, 983,
1239 <https://doi.org/10.3390/agronomy10070983>
- 1240 Mwendwa, J.M., Weston, P.A., Weidenhamer, J.D., Fomsgaard, I.S., Wu, H., Gurusinghe, S., Weston, L.A., 2021.
1241 Metabolic profiling of benzoxazinoids in the roots and rhizosphere of commercial winter wheat genotypes. *Plant Soil*
1242 466, 467-489. <https://doi.org/10.1007/s11104-021-04996-9>
- 1243 Nazarko, O.M., Van Acker, R.C., Entz, M.H., 2005. Strategies and tactics for herbicide use reduction in field crops in
1244 Canada: A review. *Can. J. Plant Sci.* 85, 457-479.

- 1245 Nendel, C., Reckling, M., Debaeke, P., Schultz, M., Berg-Mohnicke, M., Constantin, J., Fronzek, S., Hoffmann, M.P., Jaksik,
1246 S., Kersebaum, K.C., Klimek-Kopyra, A., Raynal, C., Schoving, C., Stella, T., Battisti, R., 2023. Future area expansion
1247 outweighs increasing drought risk for soybean in Europe. *Glob. Change Biol.* 29, 1340-1358.
1248 <https://doi.org/10.1016/10.1111/gcb.16562>
- 1249 Nichols, V., English, L., Carlson, S., Gailans, S., Liebman, M., 2020. Effects of long-term cover cropping on weed
1250 seedbanks, *Front. Agron.* 2, 591091, <https://doi.org/10.3389/fagro.2020.591091>
- 1251 **Nosratti, I., Korres, N.E., Cordeau, S., 2023. Knowledge of cover crop seed traits and treatments to enhance weed
1252 suppression: A narrative review. *Agronomy*, 13, 1683, <https://doi.org/10.3390/agronomy13071683>**
- 1253 O'Donovan, J.T., Blackshaw, R.E., Harke, K.N., Clayton, G.W., Moyer, J.R., Dossdall, L.M., Maurice, D.C., Turkington, T.K.,
1254 2006. Integrated approaches to managing weeds in spring-sown crops in western Canada. *Crop Prot.* 26, 390–398,
1255 <https://doi.org/10.1016/j.cropro.2005.09.018>
- 1256 Omasa, K., Hosoi, F., Konishi, A., 2007. 3D lidar imaging for detecting and understanding plant responses and canopy
1257 structure. *J. Exp. Bot.* 58, 881+898, <https://doi.org/10.1093/jxb/erl142>
- 1258 Osipitan, O.A., Dille, J.A., Assefa, Y., Knezevic, S.Z., 2018. Cover crop for early season weed suppression in crops:
1259 systematic review and meta-Analysis. *Agron. J.* 110, 2211-2221, <https://doi.org/10.2134/agronj2017.12.0752>
- 1260 Osipitan, O.A., Dille, J.A., Assefa, Y., Radicetti, E., Ayeni, A., Knezevic, S.Z., 2019. Impact of cover crop management on
1261 level of weed suppression: a meta-analysis. *Crop Sci.* 59, 833-842, <https://doi.org/10.2135/cropsci2018.09.0589>
- 1262 Osman, A.M., Almekinders, C.J.M., Struik, P.C., van Bueren, E.L., 2016. Adapting spring wheat breeding to the needs of
1263 the organic sector. *NJAS Wageningen J. Life Sci.* 76, 55-63, <https://doi.org/10.1016/j.njas.2015.11.004>
- 1264 Pagès, L., 1995. Growth-patterns of the lateral roots of young oak (*Quercus robur*) tree seedlings - Relationship with
1265 apical diameter. *New Phytol.* 130, 503-509, <https://doi.org/10.1111/j.1469-8137.1995.tb04327.x>
- 1266 Pannaci, E., Lattanzi, B., Tei, F., 2017. Non-chemical weed management strategies in minor crops: A review. *Crop Prot.*
1267 96, 44-58, <https://doi.org/10.1016/j.cropro.2017.01.012>
- 1268 Paolini, R., Faustini, F., Saccardo, F., Crino, P., 2006. Competitive interactions between chickpea genotypes and weeds.
1269 *Weed Res.* 46, 335–344, <https://doi.org/10.1111/j.1365-3180.2006.00513.x>
- 1270 Parent, B., Leclere, M., Lacube, S., Semenov, M. A., Welcker, C., Martre, P., Tardieu, F., 2018. Maize yields over Europe
1271 may increase in spite of climate change, with an appropriate use of the genetic variability of flowering
1272 time. *Proceedings of the National Academy of Sciences of the United States of America*, 115, 10642–
1273 10647. <https://doi.org/10.1073/pnas.1720716115>
- 1274 Peltonen-Sinio, P., Jauhainen, L., Lehtonen, H., 2016. Land use, yield and quality changes of minor field crops: is there
1275 superseded potential to be reinvented in Northern Europe? *Plos One* 11, e0166403,
1276 <https://doi.org/10.1371/journal.pone.0166403>
- 1277 Perronne, R., Le Corre, V., Bretagnolle, V., Gaba, S., 2015. Stochastic processes and crop types shape weed community
1278 assembly in arable fields. *J. Veget. Sci.* 26, 348-359, <https://doi.org/10.1111/jvs.12238>
- 1279 Perthame, L., 2020. Analyse et modélisation du rôle de la compétition pour l'azote dans la régulation des adventices.
1280 Université de Bourgogne Franche-Comté, Dijon, France.
- 1281 Perthame, L., Colbach, N., Brunel-Muguet, S., Busset, H., Lilley, J. M., Matejcek, A., Moreau, D., 2020. Quantifying the
1282 nitrogen demand of individual plants in heterogeneous canopies: a case study with crop and weed species. *Eur. J.*
1283 *Agron.* 119, <https://doi.org/10.1016/j.eja.2020.126102>
- 1284 Peruzzi, A., Martelloni, L., Frascioni, C., Fontanelli, M., Pirchio, M., Raffaelli, M., 2017. Machines for non-chemical intra-
1285 row weed control in narrow and wide-row crops: a review. *J. Agric. Eng.* 583, 57-70,
1286 <https://doi.org/10.4081/jae.2017.583>
- 1287 Pester, T.A., Burnside, O.C., Orf, J.H., 1999. Increasing crop competitiveness to weeds through crop breeding. *J. Crop*
1288 *Prod.* 2, 31-58, <https://doi.org/10.1300/9785531>

- 1289 Petcu, V., Barbieru, A., Popa, M., Lazar, C., Ciornei, L., Strateanu, A.G., Todirica, I.C., 2023. Early sowing on some soybean
1290 genotypes under organic farming conditions. *Plants* 12, 2295. <https://doi.org/10.3390/plants12122295>
- 1291 Petersen, J., Belz, R., Walker, F., Hurle, K., 2001. Weed suppression by release of isothiocyanates from turnip-rape mulch.
1292 *Agron. J.* 93, 37-43, <https://doi.org/10.2134/agronj2001.93137x>
- 1293 Petit, S., Munier-Jolain, N., Bretagnolle, V., Bockstaller, C., Gaba, S., Cordeau, S., Lechenet, M., Mézière, D., Colbach, N.,
1294 2015. Ecological intensification through pesticide reduction: weed control, weed biodiversity and sustainability in
1295 arable farming. *Environ. Manag.* 56, 1078–1090, <https://doi.org/10.1007/s00267-015-0554-5>
- 1296 Petit, S., Cordeau, S., Chauvel, B., Bohan, D., Guillemin, J.P., Steinberg, C., 2018. Biodiversity-based options for arable
1297 weed management. A review. *Agron. Sust. Dev.* 38, 48, <https://doi.org/10.1007/s13593-018-0525-3>
- 1298 Pitchers, J., Ferrand, N., Pull, M., Minette, S., Abella, M., Debaeke, P., 2023. Opportunities and risks of double cropping
1299 in southwestern France with a focus on soybean and sunflower crops. *OCL, Oilseeds & fats Crops and Lipids* 30, 16,
1300 <https://doi.org/10.1051/ocl/2023016>
- 1301 Pittman, K.B., Barney, J.N., Flessner, M.L., 2020. Cover crop residue components and their effect on summer annual
1302 weed suppression in corn and soybean. *Weed Sci.* 68, 301-310, <https://doi.org/10.1017/wsc.2020.16>
- 1303 Radicetti, E., Baresel, J.P., El-Haddoury, E.J., Finckh, M., Mancinelli, R., Schmidt, J.H., Thami-Alami, I., Udupa, S., Van der
1304 Heijden M.G.A, Wittwer, R., Campiglia, E., 2018. Wheat performance with subclover living mulch in different agro-
1305 environmental conditions depends on crop management. *Eur. J. Agron.* 94, 36-45,
1306 <https://doi.org/10.1016/j.eja.2018.01.011>
- 1307 Rasmussen, I.A., 2004. The effect of sowing date, stale seedbed, row width and mechanical weed control on weeds and
1308 yields of organic winter wheat. *Weed Res.* 44, 12-20, <https://doi.org/10.1046/j.1365-3180.2003.00367.x>
- 1309 Rasmussen, J., Kurtzmann, J.I., Jensen, A., 2004. Tolerance of competitive spring barley cultivars to weed harrowing.
1310 *Weed Res.* 44, 446–452, <https://doi.org/10.1111/j.1365-3180.2004.00419.x>
- 1311 Rasmussen, J., Bibby, B.M., Schou, A.P., 2008. Investigating the selectivity of weed harrowing with new methods. *Weed*
1312 *Res.* 48, 523-532, <https://doi.org/10.1111/j.1365-3180.2008.00661.x>
- 1313 Rasmussen, J., Nielsen, H.H., Gundersen, H., 2009. Tolerance and selectivity of cereal species and cultivars to
1314 postemergence weed harrowing. *Weed Sci.* 57, 338-345, <https://doi.org/10.1614/WS-08-109.1>
- 1315 Rasmussen, J., Mathiasen, H., Bibby, B.M., 2010. Timing of post-emergence weed harrowing. *Weed Res.* 50, 436-446,
1316 <https://doi.org/10.1111/j.1365-3180.2010.00799.x>
- 1317 Rasmussen K., Rasmussen, J., Petersen, J., 1996. Effects of fertilizer placement on weeds in weed harrowed spring
1318 barley. *Acta Agric. Scand. B Soil Plat Sci.* 46, 192-196, <https://doi.org/10.1080/09064719609413133>
- 1319 Ravier, C., Meynard, J.-M., Cohan, J.-P., Gate, P., Jeuffroy, M.-H., 2017. Early nitrogen deficiencies favour high yield,
1320 grain protein content and N use efficiency in wheat. *Eur. J. Agron.* 89, 16-24,
1321 <https://doi.org/10.1016/j.eja.2017.06.002>
- 1322 Rebetzke, G.J., Richards, R.A., Fettell, N.A., Long, M., Condon, A.G., Forrester, R.I., Botwright, T.L., 2007, Genotypic
1323 increases in coleoptile length improves stand establishment, vigour and grain yield of deep-sown wheat. *Field Crops*
1324 *Res.* 100, 10-23, <https://doi.org/doi:10.1016/j.fcr.2006.05.001>
- 1325 Rebetzke, G., Ingvordsen, C., Newman, P., Weston, L.A., French, B., Gill, G., 2018. Delivering weed-competitive, wheat
1326 breeding lines to growers. [https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-
1327 update-papers/2018/02/delivering-weed-competitive-wheat-breeding-lines-to-growers](https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2018/02/delivering-weed-competitive-wheat-breeding-lines-to-growers). Accessed 01/12/2023
- 1328 Rebong, D., Inoa, S.H., Moore, V.M., Reberg-Horton, S.C., Mirsky, S., Murphy, J.P., Leon, R.G., 2023. Breeding allelopathy
1329 in cereal rye for weed suppression. *Weed Sci.*, <https://doi.org/10.1017/wsc.2023.64>.
- 1330 Reiss, A., Fomsgaard, I. S., Mathiassen, S.K., Stuart, R.M., Kudsk, P., 2018a. Weed suppression by winter cereals: relative
1331 contribution of competition for resources and allelopathy. *Chemoecol.* 28, 109-121,
1332 <https://doi.org/10.1007/s00049-018-0262-8>

- 1333 Reiss, A., Fomsgaard, I.S., Mathiassen, S.K., Randhawa, H.S., Kudsk, P., 2018b. Weed suppression by Canadian spring
1334 cereals: relative contribution of competition for resources and allelopathy. *Chemoecol.* 28, 183-187, [https://doi.org/](https://doi.org/10.1007/s00049-018-0267-3)
1335 <https://doi.org/10.1007/s00049-018-0267-3>
- 1336 Riemens, M., Sønderskov, M., Moonen, A.C., Storkey, J., Kudsk, P., 2022. An Integrated Weed Management framework:
1337 A pan-European perspective. *Eur. J. Agron.* 133, 126443, <https://doi.org/10.1016/j.eja.2021.126443>
- 1338 Rolland, B., Fontaine, L., Mailliard, A., Gardet, O., Heumez, E., Walczak, P., Le Campion A., Oury, F.X., 2017. From selection
1339 to cultivation with the support of all stakeholders: the first registration in France of two winter bread wheat varieties
1340 after value for cultivation and use evaluation in organic farming systems. *Organic Agric.* 7, 73-81,
1341 <https://doi.org/10.1007/s13165-015-0140-4>
- 1342 Rouge, A., Adeux, G., Busset, H., Hugard, R., Martin, J., Matejicek, A., Moreau, D., Guillemin, J.-P., Cordeau, S., 2023.
1343 Carry-over effects of cover crops on weeds and crop productivity in no-till systems. *Field Crops Res.* 295, 108899,
1344 <https://doi.org/10.1016/j.fcr.2023.108899>
- 1345 Rueda-Ayala, V.P., Rasmussen, J., Gerhards, R., Fournaise, N.E., 2011. The influence of post-emergence weed harrowing
1346 on selectivity, crop recovery and crop yield in different growth stages of winter wheat. *Weed Res.* 51, 478-488,
1347 <https://doi.org/10.1111/j.1365-3180.2011.00873.x>
- 1348 Ryan, M.R., Wayman, S., Pelzer, C.J., Peterson, C.A., Menalled, U.D., Rose, T.J., 2021. Winter wheat (*Triticum aestivum* L.)
1349 tolerance to mulch. *Plants* 10, 2047. <https://doi.org/10.3390/plants10102047>
- 1350 Sampoux, J.-P., Giraud, H., Litrico, I., 2020. Which recurrent selection scheme to improve mixtures of crop species?
1351 Theoretical expectations. *G3-Genes Genom Genet* 10, 89–107. <https://doi.org/10.1534/g3.119.400809>
- 1352 Sandhu, N., Pruthi, G., Prakash Raigar, O., Singh, M.P., Phagna, K., Kumar, A., Sethi, M., Singh, J., Ade, P.A., Saini, D.K.,
1353 2021. Meta-QTL Analysis in rice and cross-genome talk of the genomic regions controlling nitrogen use efficiency in
1354 cereal crops revealing phylogenetic relationship. *Front. Genet.* 12, 807210,
1355 <http://dx.doi.org/10.3389/fgene.2021.807210>
- 1356 San Martin, C., Long, D.S., Gourlie, J.A., Barroso, J., 2019. Spring crops in three-year rotations reduce weed pressure in
1357 winter wheat. *Field Crops Res.* 233, 12-20, <https://doi.org/10.1016/j.fcr.2018.12.017>
- 1358 Scavo, A., Mauromicale, G., 2021. Crop allelopathy for sustainable weed management in agroecosystems: Knowing the
1359 present with a view to the future. *Agronomy* 11, 2104, <https://doi.org/10.3390/agronomy11112104>
- 1360 Schlautman, B., Barte, C., Diaz-Garcia, L., Fei, S., Flynn, S., Haramoto, E., Moore, K., Raman, D.R., 2021. Perennial
1361 groundcovers: an emerging technology for soil conservation and the sustainable intensification of agriculture. *Emerg*
1362 *Top Life Sci.* 5, 337-347, <https://doi.org/10.1042/ETLS20200318>. PMID: 33973632; PMCID: PMC8166338.
- 1363 Shah, F., Coulter, J.A., Ye, C., Wu, W., 2020. Yield penalty due to delayed sowing of winter wheat and the mitigatory role
1364 of increased seeding rate. *Eur. J. Agron.* 119, 126120, <https://doi.org/10.1016/j.eja.2020.126120>
- 1365 Shili-Touzi, I., De Tourdonnet, S., Launay, M., Doré, T., 2010. Does intercropping winter wheat (*Triticum aestivum*) with
1366 red fescue (*Festuca rubra*) as a cover crop improve agronomic and environmental performance? A modeling
1367 approach. *Field Crops Res.* 116, 218-229, <https://doi.org/10.1016/j.fcr.2009.11.007>
- 1368 Sim, L.C., Froud-Williams, R.J., Gooding, M.J., 2007a. The influence of winter oilseed rape (*Brassica napus* ssp. *oleifera*
1369 var. *biennis*) cultivar and grass genotype on the competitive balance between crop and grass weeds. *J. Agric. Sci.*
1370 145, 329-342, <https://doi.org/10.1017/S0021859607006764>
- 1371 Sim, L.C., Froud-Williams, R.J., Gooding, M.J., 2007b. The influence of winter oilseed rape (*Brassica napus* ssp. *oleifera*
1372 var. *biennis*) canopy size on grass weed growth and grass weed seed return. *J. Agric. Sci.* 145, 313–327,
1373 <https://doi.org/10.1017/S0021859606006721>
- 1374 Simon, M.R., Cordo, C.A., Perello, A.E., Struik, P.C., 2003. Influence of nitrogen supply on the susceptibility of wheat to
1375 *Septoria tritici*. *J. Phytopathol.* 151, 283-289, <https://doi.org/10.1046/j.1439-0434.2003.00720.x>

- 1376 Singh, H.P., Batish, D.R., Kohli, R.K., 2003. Allelopathic interactions and allelochemicals: new possibilities for sustainable
1377 weed management. *Crit. Rev. Plant Sci.* 22, 239-311, <https://doi.org/10.1080/713610858>
- 1378 Smith, R.G., Warren, N.D., Cordeau, S., 2020. Are cover crop mixtures better at suppressing weeds than cover crop
1379 monocultures? *Weed Sci.* 68, 186-194, <https://doi.org/10.1017/wsc.2020.12>
- 1380 Stomph, T., Dordas, C., Baranger, A., de Rijk, J., Dong, B., Evers, J., Gu, C., Li, L., Simon, J., Jensen, E.S., Wang, Q., Wang
1381 Y., Wang Z., Xu, H., Zhang, C., Zhang, L., Zhang, W.P., Bédoussac, L., van der Werf, W., 2020. Designing intercrops for
1382 high yield, yield stability and efficient use of resources: Are there principles. *Adv. Agron.* 160, 1-50,
1383 <https://doi.org/10.1016/bs.agron.2019.10.002>
- 1384 Storkey, J., Mead, A., Addy, J., MacDonald, A.J., 2021. Agricultural intensification and climate change have increased the
1385 threat from weeds. *Glob. Change Biol.* 27, 2416-2425, <https://doi.org/10.1111/gcb.15585>
- 1386 Sutton, M.A., Oenema, O., Erisman, J. W., Leip, A., van Grinsven, H., Winiwarter, W., 2011. Too much of a good thing.
1387 *Nature* 472, 159-161, <https://doi.org/10.1038/472159a>
- 1388 Szewczyk, B.F., 2013. The influence of morphological features of spelt wheat (*Triticum aestivum* ssp. *spelta*) and
1389 common wheat (*Triticum aestivum* ssp. *vulgare*) varieties on the competitiveness against weeds in organic farming
1390 system. *J. Food Agric. Environ.* 11, 416-421.
- 1391 Tao, F., Rötter, R.P., Palosuo, T., Díaz-Ambrona, C.G.H., Mínguez, M.I., Semenov, M.A., Schulman, A.H., 2017. Designing
1392 barley ideotypes using a crop model ensemble. *Eur. J. Agron.* 82, 144-162, <https://doi.org/10.1016/j.eja.2016.10.012>
- 1393 Tardieu, F., Cabrera-Bosquet, L., Pridmore, T., Bennett, M., 2017. Plant phenomics, from sensors to knowledge. *Curr.*
1394 *Biol.* 27, R770-R783, <https://doi.org/10.1016/j.cub.2017.05.055>.
- 1395 Teasdale, J.R., Mohler, C.L., 2000. The quantitative relationship between weed emergence and the physical properties
1396 of mulches. *Weed Sci.* 48, 385-392, [https://doi.org/10.1614/0043-1745\(2000\)048\[0385:TQRBWE\]2.0.CO;2](https://doi.org/10.1614/0043-1745(2000)048[0385:TQRBWE]2.0.CO;2)
- 1397 Tepe, I., Erman, M., Yazlik, A., Levent, R., Ipek, K., 2005. Comparison of some winter lentil cultivars in weed-crop
1398 competition. *Crop Prot.* 24, 585-589, <https://doi.org/10.1016/j.cropro.2004.10.006>
- 1399 Thorsted, M.D., Olesen, J.E., Weiner, J., 2006. Mechanical control of clover improves nitrogen supply and growth of
1400 wheat in winter wheat/white clover intercropping. *Eur. J. Agron.* 24, 149-155,
1401 <https://doi.org/10.1016/j.eja.2005.07.004>
- 1402 Tribouillois, H., Fort, F., Cruz, P., Charles, R., Flores, O., Garnier, E., Justes, E., 2015. A functional characterisation of a
1403 wide range of cover crop species: growth and nitrogen acquisition rates, leaf traits and ecological strategies. *PLoS*
1404 *ONE* 10, e0122156, <https://doi.org/10.1371/journal.pone.0122156>
- 1405 van der Meulen, A., Chauhan, B.S., 2017. A review of weed management in wheat using crop competition. *Crop Prot.*
1406 95, 38-44, <https://doi.org/10.1016/j.cropro.2016.08.004>
- 1407 van der Werf, H.M.G., 1996. Assessing the impact of pesticides on the environment. *Agric. Ecosys. Environ.* 60, 81-96,
1408 [https://doi.org/10.1016/S0167-8809\(96\)01096-1](https://doi.org/10.1016/S0167-8809(96)01096-1)
- 1409 Verret, V., Gardarin, A., Makowski, D., Lorin, M., Cadoux, S., Butier, A., Valantin-Morison, M., 2017a. Assessment of the
1410 benefits of frost-sensitive companion plants in winter rapeseed. *Eur. J. Agron.* 91, 93-103,
1411 <https://doi.org/10.1016/j.eja.2017.09.006>
- 1412 Verret, V., Gardarin, A., Pelzer, E., Mediène, S., Makowski, D., Morison, M., 2017b. Can legume companion plants control
1413 weeds without decreasing crop yield ? A meta-analysis. *Field Crops Res.* 204, 158-168, <https://doi.org/10.1016/j.fcr.2017.01.010>
- 1415 Vieites-Álvarez, Y., Otero, P., Prieto, M.A., Simal-Gandara, J., Reigosa, M.J., Sánchez-Moreiras, A.M., Hussain, M.I., 2023.
1416 Testing the role of allelochemicals in different wheat cultivars to sustainably manage weeds. *Pest Manag. Sci.* 79,
1417 2625-2638, <https://doi.org/10.1002/ps.7444>

- 1418 Vincent-Caboud, L., Casagrande, M., David, C., Ryan, M.R., Silva, E.M., Peigné, J., 2019. Using mulch from cover crops to
1419 facilitate organic no-till soybean and maize production. A review. *Agron. Sustain. Dev.* 39, 45,
1420 <https://doi.org/10.1007/s13593-019-0590-2>
- 1421 Violle, C., Navas, M. L., Vile, D., Kazakou, E., Fortunel, C., Hummel, I., Garnier, E., 2007. Let the concept of trait be
1422 functional ! *Oikos* 116, 882-892, <https://doi.org/10.1111/j.0030-1299.2007.15559.x>
- 1423 Wang, L., Gruber, S., Claupein, W., 2013. Effect of sowing date and variety on yield and weed populations in a lentil-
1424 barley mixture. *J. Agric. Sci.* 151, 672-681, <https://doi.org/10.1017/S0021859612000895>
- 1425 Weiner, J., 2023. Weed suppression by cereals: Beyond 'competitive ability'. *Weed Res.* 63, 133-138,
1426 <https://doi.org/10.1111/wre.12572>
- 1427 Weisberger, D., Nichols, V., Liebman, M., 2019. Does diversifying crop rotations suppress weeds? A meta-analysis. *PLOS*
1428 *ONE* 14, e0219847, <https://doi.org/10.1371/journal.pone.0219847>
- 1429 Wells, M.S., Brinton, C.M., Reberg-Horton, S.C., 2016. Weed suppression and soybean yield in a no-till cover-crop
1430 mulched system as influenced by six rye cultivars. *Renew. Agric. Food Syst.* 31, 429-440,
1431 <https://doi.org/10.1017/S1742170515000344>
- 1432 White, J.G., Scott, T.W., 1991. Effects of perennial forage-legume living mulches on no-till winter wheat and rye. *Field*
1433 *Crops Res.* 28, 135-148, [https://doi.org/10.1016/0378-4290\(91\)90079-B](https://doi.org/10.1016/0378-4290(91)90079-B)
- 1434 Wolfe, M.S., Baresel, J.P., Desclaux, D., Goldringer, I., Hoad, S., Kovacs, G., Löschenberger, F., Miedaner, T., Ostergard,
1435 H., Lammerts van Bueren, E.T., 2008. Developments in breeding cereals for organic agriculture. *Euphyt.* 163, 323-
1436 346, <https://doi.org/10.1007/s10681-008-9690-9>.
- 1437 Worthington, M., Reberg-Horton, S.C., 2013. Breeding cereal crops for enhanced weed suppression: optimizing
1438 allelopathy and competitive ability. *J. Chem. Ecol.* 39, 213-231, <https://doi.org/10.1007/s10886-013-0247-6>
- 1439 Worthington, M., Reberg-Horton, S.C., Brown-Guedira, G., Jordan, D., Weisz, R., Murphy, J.P., 2015a. Morphological
1440 traits associated with weed-suppressive ability of winter wheat against Italian ryegrass. *Crop Sci.* 55, 50-56,
1441 <https://doi.org/10.2135/cropsci2014.02.0149>
- 1442 Worthington, M., Reberg-Horton, S.C., Brown-Guedira, G., Jordan, D., Weisz, R., Murphy, J.P., 2015b. Relative
1443 contributions of allelopathy and competitive traits to the weed suppressive ability of winter wheat lines against
1444 Italian ryegrass. *Crop Sci.* 55, 57-64, <https://doi.org/10.2135/cropsci2014.02.0150>
- 1445 Wu, H., Pratley, J., Lemerle, D., Haig, T., 2000. Evaluation of seedling allelopathy in 453 wheat (*Triticum aestivum*)
1446 accessions against annual ryegrass (*Lolium rigidum*) by the equal-compartment-agar method. *Aust. J. Agric. Res.* 51,
1447 937-944, <https://doi.org/10.1071/AR00017>
- 1448 Wu, H., Pratley, J., Ma, W., Haig, T., 2003. Quantitative trait loci and molecular markers associated with wheat
1449 allelopathy. *Theor. Appl. Genet.* 107, 1477-1481, <https://doi.org/10.1007/s00122-003-1394-x>
- 1450 Wu, W., Ma, B.L., Fan, J.J., Su, M., Yi, Y., Guo, W.S., Voldeng, H.D., 2019. Management of nitrogen fertilization to balance
1451 reducing lodging risk and increasing yield and protein content in spring wheat. *Field Crops Res.* 241, 107584,
1452 <https://doi.org/10.1016/j.fcr.2019.107584>.
- 1453 Xie, C., Yang, C., 2020. A review on plant high-throughput phenotyping traits using UAV-based. *Comput. Electron. Agric.*
1454 178, 105731, <https://doi.org/10.1016/j.compag.2020.105731>
- 1455 Yan, E., Munier-Jolain, N., Martin, P., Carozzi, M., 2024. Intercropping on French farms: Reducing pesticide and N
1456 fertiliser use while maintaining gross margins. *Eur. J. Agron.* 152, 127036, <https://doi.org/10.1016/j.eja.2023.127036>
- 1457 Yi, Q., Álvarez-Iglesias, L., Malvar, R.A., Romay, M.C., Revilla P., 2021. A worldwide maize panel revealed new genetic
1458 variation for cold tolerance. *Theor. Appl. Genet.* 134, 1083–1094, <https://doi.org/10.1007/s00122-020-03753-3>
- 1459 Yin, L., Xu, H., Dong, S.X., Chu, J.P., Dai, X.L., He, M.R., 2019. Optimised nitrogen allocation favours improvement in
1460 canopy photosynthetic nitrogen-use efficiency: Evidence from late-sown winter wheat. *Environ. Exp. Bot.* 159, 75-
1461 86, <https://doi.org/10.1016/j.envexpbot.2018.12.013>

- 1462 Zerner, M.C., Rebetzke, G.J., Gill, G.S., 2016. Genotypic stability of weed competitive ability for bread wheat (*Triticum*
1463 *aestivum*) genotypes in multiple environments. *Crop Pasture Sci.* 67, 695-702, <https://doi.org/10.1071/CP15198>
- 1464 Zhang, C., Dong, Y., Tang, L., Zheng, Y., Makowski, D., Yu, Y., Zhang, F., van der Werf, W., 2019. Intercropping cereals
1465 with faba bean reduces plant disease incidence regardless of fertilizer input: a meta-analysis. *Eur. J. Plant Pathol.*
1466 154, 931-942, <https://doi.org/10.1007/s10658-019-01711-4>
- 1467 Zhou, X., Muhammad, I., Lan, H., Xia, C., 2022. Recent advances in the analysis of cold tolerance in maize. *Front. Plant*
1468 *Sci.* 13, 866034, [10.3389/fpls.2022.866034](https://doi.org/10.3389/fpls.2022.866034)
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Highlights

- Herbicides could be substituted partially by non-chemical management
- Weed escaping, weed growth reduction and weed burial are three ways to control weeds
- Weed suppression by enhancing crop competition is a key strategy
- New traits have to be considered for breeding genotypes substituting to chemicals
- Agronomy, weed science and plant breeding are required for non-chemical management

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Declaration of Interest Statement

The authors declare to have no financial interests/personal relationships which may be considered as potential competing interests

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