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Participatory assessment of minor crops: A situated study on hulled wheats

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Abstract

Expanding crop diversity is essential to address the imminent challenges of agriculture. This is especially true for organic farming, which relies on locally adapted species and varieties. Recently, participatory research approaches have emerged as effective means to support this endeavour. In this study, we collaborated with several stakeholders in the Lyon region, France, to evaluate three minor species related to common wheat (*Triticum aestivum* subsp. *aestivum*): einkorn (*Triticum monococcum* subsp. *monococcum*), emmer (*Triticum turgidum* subsp. *dicoccum*) and spelt (*Triticum aestivum* subsp. *spelta* (L.) Thell). First, we assessed the agronomic characteristics of each species, highlighting a distinction of einkorn that was associated with high tillering, high protein content, a long phenological cycle, small kernels and low relative yields. Second, we compared intra-species variabilities, revealing greater variation in emmer and spelt. Lastly, outcomes of the participatory approach, including testing adaptive methods and fostering collective learning, may interest other participatory research groups.

1. Introduction

Amidst growing concerns about the industrial food system ability to ensure food security and nutrition under climatic and socio-economic threats, organic farming emerges as a compelling alternative (Jouzi et al., 2017). Yet, the dominant seed system severely limits the expansion of organic alternatives. This system, which provides genetically homogeneous varieties bred for conventional farming, has led to a significant decrease in global crop diversity throughout the 20th century (FAO, 2019; Khoury et al., 2022). In contrast, organic agriculture relies on locally rooted and diversified approaches, requiring a wide array of locally adapted varieties (Chable et al., 2020). Hence, the reintroduction of diversity is a critical challenge for agricultural sustainability (Lin, 2011; Mijatović et al., 2013).

Crop diversity can be reintroduced at several levels. This includes increasing species diversity, expanding the number of varieties within each species, enhancing genetic diversity within and between varieties and promoting a balanced spatial distribution of varieties (Bonnin et al., 2014). In France, for example, *in situ* genetic diversity of common wheat decreased by over 50% during the 20th century, despite an increase in the number of available varieties. At the European scale, a lack of diversity among wheat cultivars has been identified as a threat to yield stability in the face of climate variability (Kahiluoto et al., 2019).

Participatory varietal evaluation and participatory plant breeding (PPB) projects have proven effective in locally reintroducing crop diversity (Ceccarelli & Grando, 2019). By involving stakeholders, particularly farmers, in the breeding process, these approaches target their specific needs (Ceccarelli & Grando, 2019; Chable et al., 2020). However, implementing such projects is complex. Achieving alignment with stakeholders' goals requires a careful balance of their preferences with scientific rigor and available resources. In addition, to select varieties adapted to specific regional conditions and farming practices, trials are generally conducted on farms, adding logistical and methodological challenges (Rivière et al., 2013). These factors demand extensive coordination, adaptable methodologies and long timelines (Chable & Berthellot, 2006; Dawson et al., 2011; Demeulenaere & Goldringer, 2017). As such projects remain scarce, sharing experiences is crucial to refining participatory methodologies.

In France, a PPB project on wheat has been ongoing since 2006 (Rivière et al., 2013). This project has mostly focused on the dominant species of wheat, common wheat (*Triticum aestivum* subsp. *aestivum*), with relatively less emphasis on minor wheat species, such as einkorn (*Triticum monococcum* subsp. *monococcum*), emmer (*Triticum turgidum* subsp. *dicoccum*) and spelt (*Triticum aestivum* subsp. *spelta* (L.) Thell.). These minor species can play a crucial role in diversifying agroecosystems (Padulosi, 1996; Padulosi & Hoeschle-Zeledon, 2004).

Einkorn is a diploid wheat (genome AA) while emmer is tetraploid (genome AABB). Emmer is derived from wild emmer (*T. diccocoides*), originating from the hybridization between two diploid wild grasses (Bonjean, 2001). Spelt and common wheat are two hexaploid (genome AABBDD) subspecies of the same species that emerged from a more recent hybridization between tetraploid wheats and *Aegilops tauschii* (genome DD) (Bonjean, 2001). Because their kernels remain enclosed in tough glumes after threshing (Nesbitt & Samuel, 1996), einkorn, emmer and spelt are known as 'hulled wheats'. Hulled wheats were largely replaced by high-yielding and free-threshing species during the first millennium AD (Zaharieva et al., 2010; Zaharieva & Monneveux, 2014). Yet, they are currently regaining interest due to their perceived nutritional quality (Dinu et al., 2018; Shewry, 2018) and potential suitability for organic farming (Cubadda & Marconi, 2002; Zaharieva et al., 2010; Zaharieva & Monneveux, 2014). Several studies have reported valuable agronomic characteristics for hulled wheats, including resistance to pests and diseases (Rouse & Jin, 2011; Singh et al., 2008; Zaharieva & Monneveux, 2014), as well as high protein levels, despite poor fertilization for einkorn (Bencze et al., 2020; Longin et al., 2016; Zaharieva & Monneveux, 2014) and for certain emmer accessions (Bencze et al., 2020; Beteselassie et al., 2007; Longin et al., 2016; Zaharieva et al., 2010). Nevertheless, high variability exists across varieties and environments (Longin et al., 2016; Zaharieva et al., 2010; Zaharieva & Monneveux, 2014), highlighting the need for individual variety evaluations in targeted environments.

This study presents the first outcomes of a participatory research project initiated in 2019 in the Lyon region, France. This project aims at investigating the suitability of einkorn, emmer and spelt for diversified organic farming systems in the Lyon region.

More precisely, this article presents the initial agronomic evaluation of 23 hulled wheat varieties conducted within the framework of the participatory research project (Figure 1a). We addressed two main questions. First, we investigated whether each hulled wheat species (einkorn, emmer and spelt) exhibited specific agronomic characteristics. Second, we compared the intra-species variability across the three species of hulled wheats, hypothesizing high variability, as they did not undergo recent intensive breeding. Lastly, we highlighted the main qualitative outcomes of the participatory process that may be of interest to other groups of researchers and stakeholders.

2. Results

2.1. Characterization of species

Our first aim was to test whether we could distinguish each species according to agronomic characteristics of interest for the stakeholders. We mostly focused on variables related to weed competitiveness, resistance to lodging and yield.

To visually assess differences between species, we conducted a principal component analysis (PCA, Figure 1b,c). For statistical evaluation of such differences, we performed pairwise-comparison tests (Tukey honestly significant difference [HSD] tests) on adjusted means across all quantitative variables. Table 1 presents results of pairwise comparisons, while analysis of variance (ANOVA) results and corresponding p-values are available in Supplemental Material 1.

In the PCA, Principal Component 1 (PC1) explained 43% and PC2 explained 20% of variability within the data (Figure 1b,c). Einkorn was differentiated from the other species along PC1 and was associated with high tillering, late heading, low relative yields, low thousand kernel mass (TKM), spreading posture at the end of April, small height, and high protein contents (Figure 1b,c). This trend was confirmed by pairwise comparisons, as einkorn significantly differed from the three other species for all variables shown in Table 1, except for emergence rate and ground cover. Indeed, at the beginning of March, ground cover was significantly lower for einkorn (16.8% on average) than for emmer (24.4%), but the differences with spelt (22.8%) and common wheat (21.2%) were not significant. However, at the end of April, einkorn had the highest ground cover value (34.6%), even if no significant differences were observed across species.

The distributions of emmer, spelt and common wheat varieties overlapped in the PCA plot of individuals, indicating that they were not discriminated according to agronomic variables (Figure 1c). Notably, these three species displayed lower tillering and higher TKM than einkorn. Pairwise comparisons revealed that TKM was significantly lower for emmer (36.5 g) than for spelt (39.4 g). Furthermore, the final plant height and the total protein content were significantly higher for the three hulled wheat species (71.5 cm and 17.3%dm for einkorn, 78.7 cm and 14.4%dm for emmer and 77.9 cm and 14.1%dm for spelt) than for common wheat (67.9 cm and 12.0%dm) (Table 1).

2.2. Intra-species variability and remarkable traits for individual varieties

Our second objective was to assess intra-species variability, which we estimated through PCA (Figure 1b,c). Given farmers' considerations on cultivating some varieties, we were also interested in evaluating each individual variety (Figure 2).

In the PCA individuals plot (Figure 1c), einkorn and common wheat formed quite homogeneous groups, suggesting limited intra-species variability compared to emmer and spelt. Notably, the final plant height displayed remarkable uniformity across einkorn varieties, ranging from 64.1 to 77.9 cm (Figure 2j). Among einkorn varieties, einkorn *Noir* stood out for its early heading completion

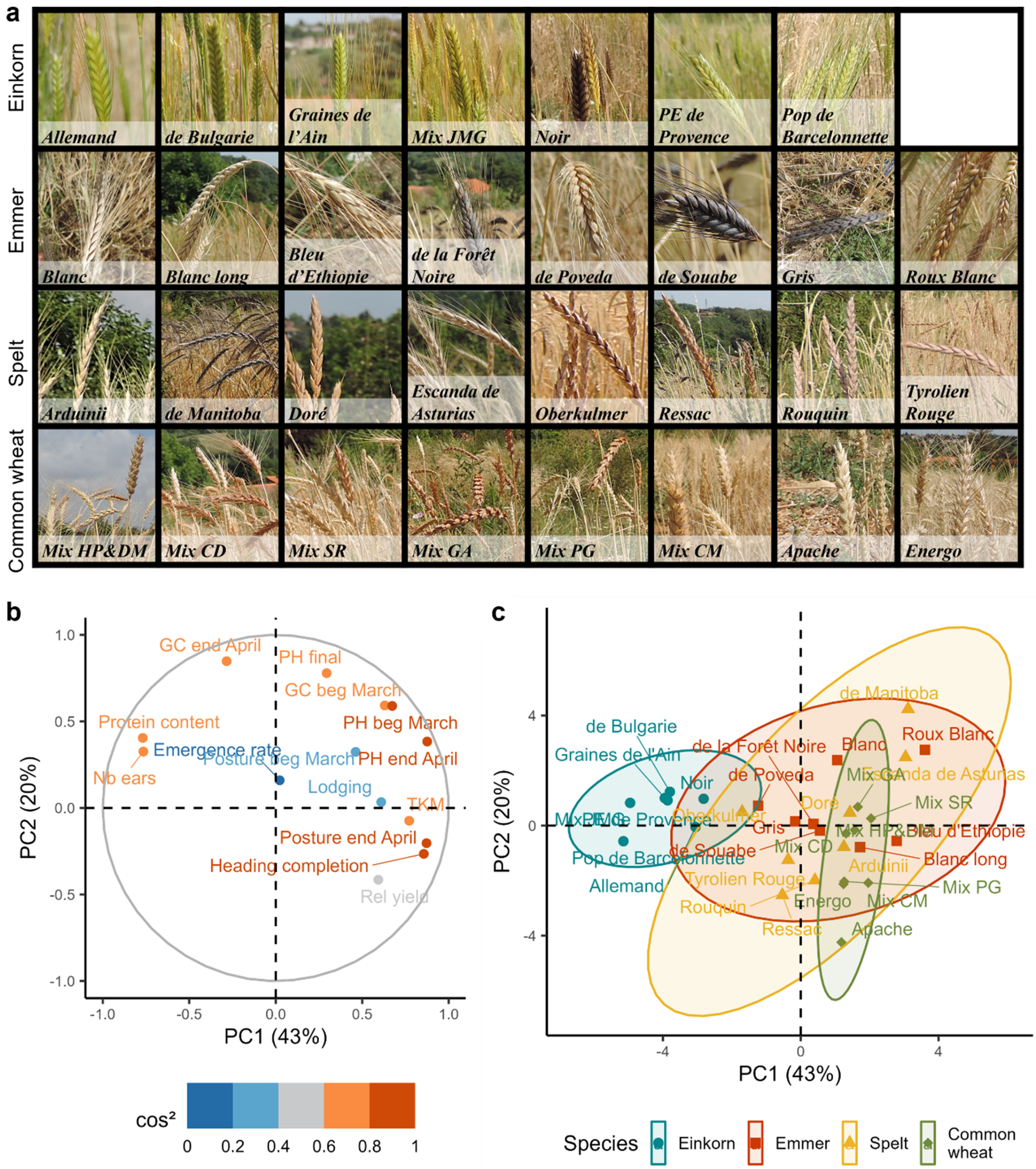

Figure 1. Analysis of agronomic variables of all varieties of einkorn, emmer, spelt and common wheat. (a) Ear morphology of the varieties under study. For mixtures of common wheat, several ears are represented to picture the intra-varietal diversity. (b, c) PCA on agronomic variables. (b) Plot of variables. Colours indicate the quality of representation (cos2) of each variable. Em, emergence; GC, ground cover; PH, plant height; Post, posture; Prot, protein content; Rel, relative. (c) Plot of individuals, with 95% confidence ellipses of the mean point for each species.

(completed on May 25, Figure 2h). Yet, this variety displayed low TKM (33.9 g), relative yield (52%), and protein content (15.7%dm) (Figure 2l–n).

Within emmer varieties, emmer *Bleu d'Ethiopie* distinguished itself for its early maturation, with heading completion on May 13 (Figure 2h), and its short stature (final plant height of 60.4 cm) (Figure 2j). The relatively high lodging score observed for this variety (22.5%, Figure 2k) might be due to the measurement being taken when the plants were completely mature. Lastly, emmer *Roux Blanc* and emmer *Blanc Long* were characterized by very high TKM

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Table 1. Results of pairwise comparisons on adjusted means. For each species, adjusted means and (±) standard errors (SEs) are shown. For each variable, adjusted means with the same letter are not significantly different (*p*-value < 0.05, Tukey's test). Pairwise comparisons were achieved on all quantitative variables for which the ANOVA model was validated by the *Q*–*Q* and residuals versus fitted plots

Variable	Einkorn	Emmer	Spelt	Common wheat
Emergence rate (%)	$82.8^{a} \pm 2.0$	$83.1^{a} \pm 1.8$	$79.6^{a} \pm 1.8$	$77.4^{a} \pm 1.8$
Plant height beg. March (cm)	$5.0^{a} \pm 0.1$	$8.3^{c} \pm 0.1$	$7.8^{c} \pm 0.1$	$6.7^{b} \pm 0.1$
Ground cover beg. March (%)	$16.8^{a} \pm 1.6$	$24.4^{b} \pm 1.5$	$22.8^{ab} \pm 1.5$	$21.2^{ab} \pm 1.5$
Plant height end April (cm)	$16.0^{a} \pm 0.4$	$28.9^{b} \pm 0.4$	$27.7^{b} \pm 0.4$	$27.9^{b} \pm 0.4$
Ground cover end April (%)	$34.6^{a} \pm 2.0$	$29.8^{a} \pm 1.9$	$29.9^{a} \pm 1.9$	$27.3^{a} \pm 1.9$
Nb ears per plant (counts)	$2.2^{b} \pm 0.1$	$1.1^{a} \pm 0.1$	$1.1^{a} \pm 0.1$	$1.1^{a} \pm 0.1$
Plant final height (cm)	$71.5^{b} \pm 0.7$	$78.7^{c} \pm 0.7$	$77.9^{c} \pm 0.7$	$67.9^{a} \pm 0.7$
Relative yield (%)	$59.7^{a} \pm 0.8$	$64.2^{b} \pm 0.8$	$64.8^{b} \pm 0.8$	$73.7^{c} \pm 0.8$
TKM (g)	$23.6^{a} \pm 0.5$	$36.5^{b} \pm 0.5$	$39.4^{c} \pm 0.5$	$38.3^{bc} \pm 0.5$
Protein content (% dm)	$17.3^{c} \pm 0.3$	$14.4^{b} \pm 0.3$	$14.1^{b} \pm 0.3$	$12.0^{a} \pm 0.3$

(54.1 and 46.4 g, respectively) in comparison with the average value for all emmer varieties (36.5 g) (Figure 2l and Table 1). Among all species, the tallest plants were observed for two spelt varieties: spelt *de Manitoba* (98.1 cm) and spelt *Escanda de Asturias* (97.0 cm) (Figure 2j). Spelt *Escanda de Asturias* was also characterized by an elevated TKM (47.4 g). Finally, spelt *Oberkulmer* had exceptionally low relative yield (42.4%) and high protein content (18.1%dm) in comparison with the average values for all spelt varieties (64.8% and 14.1%dm, respectively) (Table 1 and Figure 2m). It is noteworthy that a high rate of seed abortion was observed for this variety, which might explain its distinctive characteristics.

Within common wheat, in the PCA, mixtures of landraces (*Mix GA*, *Mix SR*, *Mix HP&DM* and *Mix CD*) and modern varieties or mixtures of modern varieties (*Energo*, *Apache*, *Mix CM* and *Mix PG*) were differentiated along PC2 (Figure 1c). The latter were characterized by short plants (from 45.0 to 62.9 cm, Figure 2j), earliness (heading completed on May 13, Figure 2h) and high relative yields (from 73.2 to 79.1%, Figure 2m). Finally, a small difference in protein contents was observed between mixtures of landraces, with higher values (from 11.9 to 13.5%dm) than the two modern varieties and the mixture of modern varieties *Mix CM* (from 10.1 to 11.6%dm) (Figure 2n).

2.3. Outcomes from the participatory approach

Beyond the quantitative data on species and varieties, this study also generated qualitative insights into the participatory approach.

To move forward despite the short time for collective discussions, we tested methods based on one-to-one interactions between researchers and individual stakeholders. First, the project was launched through a survey. Meeting stakeholders in their working environments and presenting a highly open project appeared to foster trust and enable the collection of valuable inputs. Throughout the process, we also conducted multiple one-to-one interactions that were prepared in advance. For instance, preliminary results were compiled into documents and discussed individually with each stakeholder before collective discussions. This approach facilitated the gathering of interpretations and enhanced the understanding of analytical methods, further allowing us to better prepare collective meetings. Overall, one-to-one interactions proved valuable for building mutual knowledge and integrating stakeholders' feedback.

Regarding experimental challenges, initial imbalances in the on-farm trials were intensified by climatic events, preventing us from addressing the third question on environmental impacts on agronomic characteristics of hulled wheats. Yet, despite its limited practical value for farmers, we also implemented a larger trial in a single site (the Centre de Ressources de Botanique Appliquée [CRBA]). This approach provided a secure setup for data collection, enabling the production of results that fostered discussions for the future of the project. It is noteworthy that the trial at CRBA was damaged by a hailstorm, which prevented some important data collection.

The process also provided valuable collective learning opportunities. In terms of organization, it shed light on the time required for participating in such projects, on the dependence on funding opportunities and on the critical role of facilitation. It also deepened our understanding of analytical methods and the relationship between the complexity of research questions and their experimental requirements. The multiple species focus introduced an additional layer of analysis (considering species, varieties and environments), significantly increasing the complexity of the experimental design and constraining the methodological choices for data analysis.

This first year of experimentation also generated concrete actions. For instance, some varieties were chosen by the farmers and the CRBA to pursue testing. In some locations, the trials motivated stakeholders to welcome local events on cereal biodiversity. The experimental plots were showcased, raising awareness about hulled wheats, and the broader research project was presented. In addition, the project brought together actors from the same region with shared interests who had not previously connected.

At the beginning of the project, there was limited knowledge about hulled wheats among stakeholders. Therefore, we focused on very broad questions. Through the first year of experimentation and the participatory process, more specific questions emerged. Most of these concerned practical aspects, such as identifying agronomic practices to enhance tillering in hulled wheats (for better ground coverage and lower sowing densities) and examining the effects of different sowing densities and dates on hulled wheat characteristics.

Another qualitative outcome of the project was the motivation among stakeholders to continue the research. We believe this enthusiasm partly stemmed from our success in adapting the project to stakeholders' feedback. For example, the agronomic

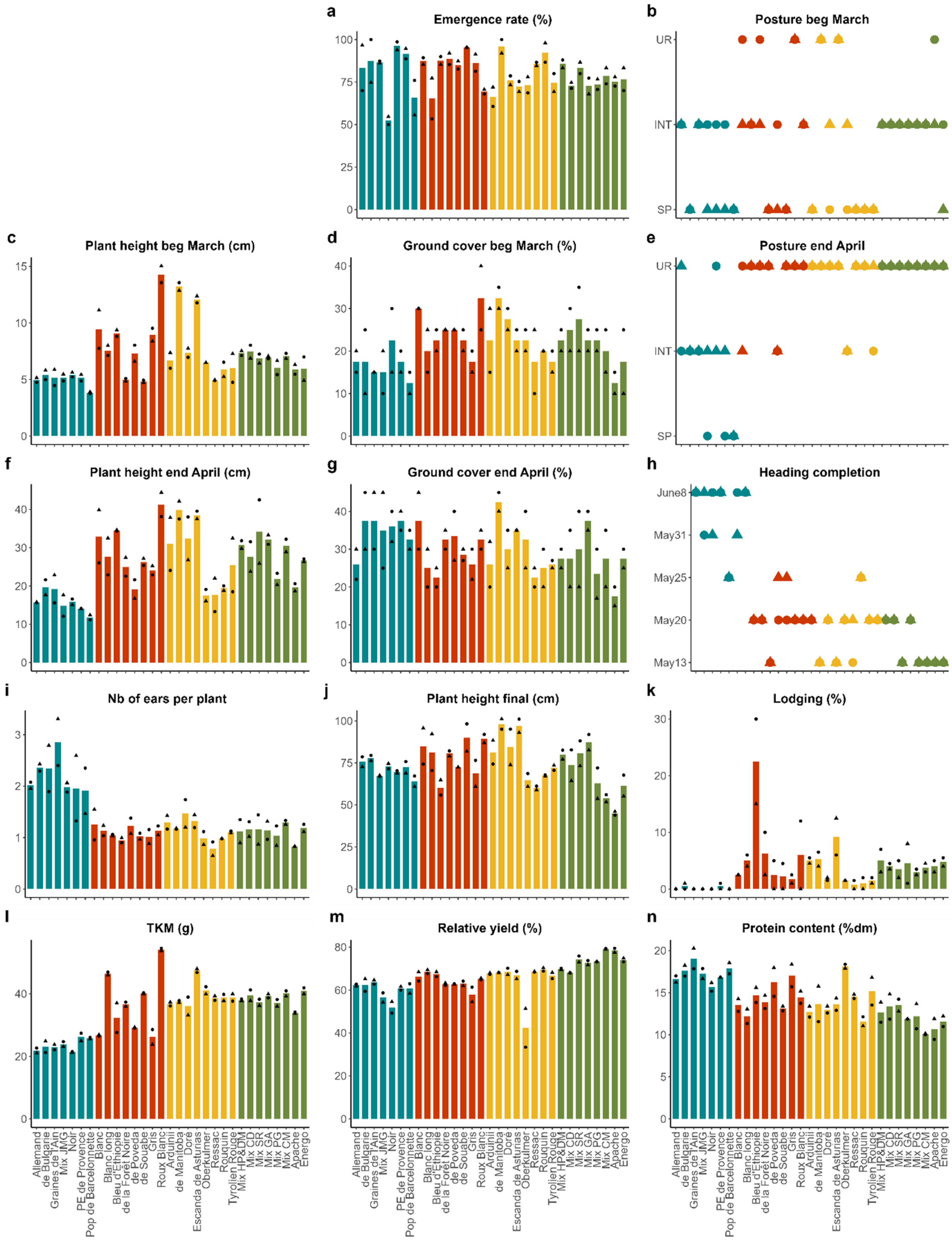

Figure 2. Values of all agronomic variables for all varieties. For quantitative variables, the mean values are represented by histograms. Black dots and triangles indicate the values for each of the two blocks (dots = values for Block 1 and triangles = values for Block 2). For qualitative variables, coloured dots and triangles indicate the values for each of the two blocks (dots = values for Block 1 and triangles = values for Block 2). Each species is represented by a colour: blue for einkorn, red for emmer, yellow for spelt and green for common wheat. In panels b and e, SP: spreading, INT: intermediate and UR: upright.

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management of the trial at the CRBA was closely aligned with farmers' practices, enhancing its relevance. Vernacular knowledge was also integrated at various stages of the project, including the formulation of hypotheses, choice of management practices, selection of assessed characteristics and assessment methods and interpretation of results. At times, we prioritized stakeholder preferences over scientific efficiency, especially regarding the on-farm trials.

3. Discussion

3.1. Distinctive agronomic features for einkorn and high intra-species variability for emmer and spelt

In our study, einkorn stood out from the other species. Einkorn varieties displayed high tillering, high ground cover by late April, elevated protein contents, small kernels and low relative yields (Figure 1 and Table 1). This aligns with previous studies, including those of Longin et al. (2016), which reported small kernels and low relative yields, and Costanzo et al. (2019), which observed high tillering for einkorn. This distinction of einkorn may be due to the lack of a shared genome with tetraploid and hexaploid wheats (Shewry, 2018).

In addition, we observed lower variability within einkorn and common wheat compared to emmer and spelt (Figure 1c). Reduced variability within einkorn may also be due to its diploid genome that supports less variability. However, this contradicts prior studies that have reported high intra-species variability within hulled wheats, including einkorn, in terms of agronomic (Longin et al., 2016; Mondini et al., 2014; Zaharieva et al., 2010; Zaharieva & Monneveux, 2014), kernel chemical (Zaharieva et al., 2010; Zaharieva & Monneveux, 2014) and kernel morphological characteristics (Goriewa-Duba et al., 2018).

Concerning common wheat, this limited variability is likely due to the composition of the studied panel, which primarily includes mixtures of similar varieties. The potentially high intra-varietal variability within these mixtures may further contribute to the overall low variability detected within the species. For the hulled wheat species, the trends identified in this study are also confined to the panels of varieties. To assess species-related agronomic characteristics and intra-species variability on a broader scale, it would be necessary to evaluate a wider range of varieties from diverse origins.

3.2. Relevance of hulled wheats for organic farming

Organic farming embraces the diversity of environmental conditions and farming practices, recognizing that there is no one-size-fits-all approach (Chable et al., 2020). Instead of seeking standardized characteristics, organic farmers prioritize characteristics well suited to the unique conditions of their farms (Lammerts van Bueren et al., 2011; Rivière et al., 2013). The diversity observed among hulled wheats highlights their potential as a reservoir of crop diversity in a region where they are not traditionally grown.

We collectively identified species and individual varieties meeting the characteristics of interest to the farmers we worked with. For example, weed competitiveness, which is crucial to minimize mechanical weeding in organic farming, led some farmers to prefer early varieties for rapid ground cover, while others favoured late varieties for extended cover. Plant height was another concern as it can cause lodging. Farmers also valued relative yield as a practical indicator, enabling grain yield estimation immediately after harvesting. Moreover, lower relative yield implies increased storage space occupied by glumes, as seeds are generally stored with their hulls. Finally, protein content is crucial for grain quality, affecting both processing and nutrition.

Considering all these factors, einkorn varieties stood out for their suitability for extended ground cover, potential low lodging risk and high protein content, although their storage suitability was less favourable compared to emmer and spelt (Figure 2g,j,m,n). Extended ground cover was likely due to higher tillering (2.5 tillers per plant in average) and spreading form late in the season (Figure 2e–g). These results align with those of Costanzo et al. (2019) who similarly observed better coverage for einkorn than emmer during the phenological stage of stem extension.

In contrast, emmer and spelt varieties demonstrated superior early ground cover and higher relative yields (Figure 2d,m). Particularly, early varieties such as emmer *Bleu d'Ethiopie*, spelt *Arduinii* and spelt *Doré* appeared ideal for quick covering (Figure 2d,h). Remarkably, emmer *Bleu d'Ethiopie* is a free-threshing variety, meaning that it does not require dehulling. In addition, some varieties, including emmer *Bleu d'Ethiopie* and spelt *Ressac*, exhibited comparable or even shorter stature than einkorn varieties (Figure 2j), suggesting a potentially low risk of lodging. Similarly, Longin et al. (2016) observed some emmer varieties that were even shorter than modern common wheat varieties; yet, both species were not grown with the same N levels. Certain emmer varieties also stood out for their high protein levels (Figure 2n). For example, emmer *Gris* had a protein content of 17.0%dm. High protein values for einkorn and certain emmer varieties are consistent with previous studies (Bencze et al., 2020; Castagna et al., 1995; Longin et al., 2016; Mondini et al., 2014), suggesting that these varieties can achieve elevated protein levels despite limited N fertilization.

Low yields of hulled wheats are often pointed out as a limitation, though yield gaps with common wheat might be small in harsh conditions. Similar studies found that spelt, emmer and einkorn had at least 30% lower yields than common wheat, with einkorn and emmer yielding less than spelt (Biel et al., 2016; Longin et al., 2016). However, these studies included only modern common wheat varieties and were conducted in more optimal conditions, sometimes with adjusted N fertilization for each species. Other studies compared hulled wheat yields in harsh conditions but did not include common wheat in the experiments (Bencze et al., 2020; Costanzo et al., 2019).

From a practical perspective, replacing common wheat by hulled wheats, particularly einkorn, may require adjustments in farming practices. These can include modified sowing and harvesting schedules to align with phenological differences, as well as adapted fertilization. Farming practices can also be adjusted to amplify desired characteristics in specific varieties. For instance, according to the farmers we worked with, modifying sowing dates and densities could influence ground cover and lodging risk. Also, hulled wheats appear particularly attractive for low-input farming as the last crop in a rotation (Bencze et al., 2020; Costanzo et al., 2019). This is notably true for einkorn and some emmer varieties, which achieve high protein levels despite no fertilization (Figure 2n). Adapted fertilization can also limit plant growth, reducing the risk of lodging (Costanzo et al., 2019; Longin et al., 2016). Finally, diversification offers increased resilience; for example, growing varieties with differing phenologies can safeguard against stresses or extreme events occurring at the same time of the year, enhancing overall farm stability.

We assessed weed competitiveness, lodging and yields through direct measurements and potentially related variables. However, the relationships between such variables and agronomic characteristics are not always straightforward and require further investigation. For example, the link between plant height and lodging is complex and needs more exploration (Shah et al., 2019). Understanding the correlations between variables could also be useful for further breeding programmes. As noted by Longin et al. (2016) and Castagna et al. (1995), such correlations may vary between species. For example, in einkorn, protein content does not appear to correlate with grain yields. Finally, further research is needed to compare hulled wheat and common wheat yields under various marginal conditions and to better understand the contributions of individual variables to final yields (Bencze et al., 2020).

3.3. Considerations for a one-year, one-environment experiment

Since the complete panel of varieties was evaluated for only one year and at a single location (the CRBA), the trends reported in this article may be strongly influenced by the specific conditions of that year and location. Indeed, according to the stakeholders, heading dates were uncommonly early, likely due to water stress from low precipitation throughout the season (Supplemental Material 2). Water stress, together with other limiting conditions like late sowing and no fertilization, probably also reduced tillering (Allahverdiyev, 2016), plant heights (Allahverdiyev, 2016; Mirbahar et al., 2009), number of grains per ear and TKM (Allahverdiyev, 2016; Gupta et al., 2001; Mirbahar et al., 2009).

On farms with less severe conditions, all varieties were taller (Supplemental Material 3). In addition, on one farm, we observed enhanced tillering for einkorn (reaching 5.6 ears per plant for einkorn *Graines de l'Ain*), indicating the potential to improve tillering for better ground cover. The observed trends in the on-farm trials suggest high variability for most variables, indicating potential effects of the environments and interactions between varieties and environments (Supplemental Material 3).

All trends reported here need confirmation through repeated experiments across multiple years and/or locations to account for the effect of the environment. Such an effect has been reported as important, particularly for grain yield and protein contents (Longin et al., 2016). Conducting trials that allow the assessment of genotype-by-environment interactions would also be valuable, especially in the context of on-farm selection (Dawson et al., 2011; Rivière et al., 2013).

3.4. The initial phase of a participatory project

This study provided an opportunity to reflect on the participatory approach. We tested two methodological adaptations to make progress despite a limited timeframe. First, in terms of organization, one-to-one interactions proved effective in moving forward despite the limited time for participatory workshops. However, this approach required significant coordination efforts, which were managed by the scientific team. Second, to address experimental challenges, establishing a larger trial at the CRBA proved valuable for securing reliable results. In contrast, conducting trials across multiple locations mitigates risks and enhances the overall robustness of the study. Finding a balance between these strategies, adapted to available resources (time, seeds, space, material, etc.) seems essential for further experimentation.

Furthermore, in terms of experimental requirements, a distinctive aspect of this project compared to similar initiatives (e.g. Goldringer et al., 2019) was its focus on multiple species. While this allowed us to address stakeholders' questions, it limited the choice of analytical methods and complicated the generation of meaningful results. This experience will help achieve better alignment between research questions and experimental designs in the next stages of the project.

The enthusiasm expressed by stakeholders, coupled with the emergence of new questions, underscores our ability to fulfill the role typically assigned to researchers in participatory projects: serving as facilitators for the progress of the project and enabling the rise of new questions (Chable & Berthellot, 2006). We attribute this success to the efforts we made in considering stakeholders' feedback and vernacular knowledge, even when it limited scientific efficiency. These choices reveal the flexibility required by such approaches (Dawson et al., 2011) to enhance trust and facilitate collective learning.

Participatory research projects require a significant learning phase to build experience, strengthen communication among stakeholders and define a common goal (Demeulenaere & Goldringer, 2017). The first experimental year presented in this article can be seen as a key part of this phase, as it fostered trust and mutual knowledge between stakeholders while enabling collective learning about the experimental process. We believe the insights gained from this initial phase will facilitate better alignment between questions and available resources as the project moves forward.

4. Materials and methods

4.1. Participatory approach

We collaborated with an array of stakeholders from an area of 80 km around Lyon. The group included six organic farmers, a center of botanical resources (CRBA) and a farmer organization (Association Régionale pour le Développement de l'Emploi Agricole et Rural, ARDEAR).

The group was formed through a survey involving 12 farmers and ARDEAR, during which the main project's objectives – testing marginal cereal species in the Lyon region – were presented, and participation was invited. The survey also enabled an understanding of farmers' unique contexts and challenges, explaining their need for diversification. In addition, it led to a preliminary identification of species of interest, along with an exhaustive list of questions. Finally, it allowed the emergence of feedback from stakeholders on general aspects of the project, including the importance of on-farm trials, the use of common wheat varieties already cultivated as controls and the value of ARDEAR within the group to ensure a better representation of farmers.

Following the survey, five participatory workshops were held between March 2021 and March 2023. The first workshop finalized the choice of species, research questions and provided feedback on the choice of varieties. Three main questions were chosen for exploration during the first experimental year: (1) What are the main agronomic differences between species? (2) How important is intra-species variability? (3) What is the impact of environmental conditions on the agronomic characteristics of the species? The second workshop focused on variables to measure. To do so, we identified three agronomic characteristics – weed competitiveness, resistance to lodging and yield – of major relevance for the farmers. To evaluate these characteristics, we pinpointed related variables and selected assessment methods, drawing on prior research (Bencze et al., 2020; Costanzo et al., 2019; Goldringer et al., 2019; Longin et al., 2016) and stakeholders' comments. During the second workshop, we also assigned tasks between scientists and farmers. The third workshop, held in March 2022, enabled us to adjust protocols. The last two workshops focused on analysing results,

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Table 2. Einkorn, emmer, spelt and common wheat varieties were included in the trial. Farm names are indicated with initials: CD, CM, GA, HP&DM, JMG, JPC, PG and SR. We define landraces as varieties resulting from on-farm selection, historical varieties as varieties resulting from professional selection between 1850 and 1960 and modern varieties as those resulting from professional selection after 1960. The latter are characterized by highly homogeneous genetic structures (Khan et al., 2020; Khoury et al., 2022). Source of the information contained in the table: Correa et al. (2024))

Variety name	Origin of the seeds	Type of variety	Type of conservation	Harvest year of the seeds	Additional information
		Einkorn (*Triticum monococcum* subsp. *monococcum*)			
Allemand	Association Graines de Noé (Côte d'Or, France)	Probably landrace	Multiplied for at least 15 years in small plots in Côte d'Or (France).	2018	Recovered at the beginning of the year 2000 from a farm in Germany.
de Bulgarie	CRBA (Rhône, France)	Probably landrace	Multiplied during 10 years in small plots in a farm in Isère (France) and once at the CRBA.	2021	Recovered around 2010 from a baker in Bulgary (according to whom the variety grew spontaneously in the fields) and given to the CRBA in 2020.
Graines de l'Ain	Association Graines de l'Ain (Ain, France)	Probably landrace	Cultivated for at least 2 years by a farmer in the Ain (France).	2021	Recovered by a French farmer on a farm in Germany.
Mix JMG	Farm in the Marne (France)	Mixture of landraces	Cultivated for at least 7 years by a farmer in the Marne (France).	2020	Mixture of 5 varieties from different origins: 1 farm in Germany and 4 farms in France (in the regions of Val de Loire, Champagne and Argonne).
Noir	Farm in Haute-Savoie (France)	Probably landrace	Multiplied during at least 7 years in Haute-Savoie (France).	NA	Recovered by a French farmer during farmer seed exchanges.
Petit épeautre de Provence	CRBA (Rhône, France)	Mixture of landraces	Multiplied for 3 years in small plots and then cultivated for 3 years in a farm in the Loire (France). Multiplied once in the CRBA in small plots.	2021	Mixture of two varieties (mostly one recovered from a farmer in the Alpes-de-Haute-Provence (France) and small quantities of another one obtained at farmer seed exchanges).
Pop de Barcelonnette	CRBA (Rhône, France)	Probably landrace	Multiplied once in small plots in the CRBA.	2021	Provided to the CRBA by the association Savors de Terroirs (Ardèche, France).

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Table 2. Continued

Variety name	Origin of the seeds	Type of variety	Type of conservation	Harvest year of the seeds	Additional information
			Emmer (*Triticum turgidum* subsp. *dicoccum*)		
Blanc	CRBA (Rhône, France)	Probably landrace	Multiplied for 5 years in small plots and then cultivated for 4 years in the Loire (France). Multiplied once in the CRBA in small plots.	2021	Recovered by a French farmer in Germany (initially, it was mixed with another emmer variety with black ears).
Blanc long	CRBA (Rhône, France)	Probably landrace	Multiplied once in small plots in the CRBA.	2021	Provided to the CRBA by the association Savoirs de Terroirs (Ardèche, France).
Bleu d'Ethiopie	CRBA (Rhône, France)	Unknown	*Ex situ* conservation (Israel Gene Bank) + 1 year of multiplication in small plots in the CRBA.	2021	Recovered by the CRBA from the Israel Gene Bank (IGB).
de la Forêt Noire	CRBA (Rhône, France)	Probably landrace	Multiplied once in small plots in the CRBA.	2021	Recovered by the CRBA from a French farmer.
de Poveda	Association Graines de Noé (Côte d'Or, France)	Probably landrace	Multiplied once in small plots in the Côte d'Or (France).	2019	Recovered from a Belgian association around 2018.
de Souabe	Association Graines de Noé (Côte d'Or, France)	Probably landrace	Multiplied once in small plots in the Côte d'Or (France).	2020	Recovered from a Belgian association around 2018.
Gris	Association Graines de Noé (Côte d'Or, France)	Probably landrace	*Ex situ* conservation (CRB Clermont-Ferrand) + 10 years of multiplication in small plots in Côte d'Or (France).	2018	Recovered from the INRAE gene bank (CRB) in Clermont-Ferrand (France).
Roux Blanc	Association Graines de Noé (Côte d'Or, France)	Probably landrace	Multiplied during at least 10 years in small plots in Côte d'Or (France).	2018	Recovered by the founder of Graines de Noé in the year 1990 and multiplied for at least 10 years in Côte d'Or (France).

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Table 2. Continued

Variety name	Origin of the seeds	Type of variety	Type of conservation	Harvest year of the seeds	Additional information
			Spelt (*Triticum aestivum* subsp. *spelta* (L.) Thell.)		
Arduinii	INRAE gene bank Centre de Ressources Biologiques Céréales à Paille (CRB) (Clermont-Ferrand, France)	Probably landrace	*Ex situ* conservation (CRB Clermont-Ferrand), with only one multiplication.	2009	Multiplied once in Auvergne (France).
de Manitoba	CRBA (Rhône, France)	Probably landrace	Multiplied during 5 years in small plots in a farm in Isère (France) and once at the CRBA.	2021	Recovered by a French peasant from a farm in Manitoba (Canada).
Doré	Farm in Haute-Savoie (France)	Landrace or historical variety	*Ex situ* conservation (CRB Clermont-Ferrand) + unknown conservation in a monastery + cultivation during several years in Haute-Savoie (France).	2021	Recovered from a monastery (monks had themselves obtained the variety from the CRB in Clermont-Ferrand) by a baker and cultivated for several years (first by the baker and then by a farmer) in Haute-Savoie (France).
Escanda de Asturias	Farm in León (Spain)	Probably landrace	Cultivated for at least 5 years in León (Spain).	2021	Variety from the Asturias region in Spain.
Oberkulmer	Farm in the Marne (France)	Landrace	Cultivated for at least 12 years in Marne (France).	2020	Swiss variety recovered by a French farmer in Germany. This variety is issued from a mass selection of a Swiss landrace. It was released in 1948, registered in the European catalogue of agricultural plant species (https://www.semae.fr/) and used in breeding programmes (Siedler et al., 1994).
Ressac	Graines de Noé association (Côte d'Or, France)	Modern variety	Multiplied during at least 5 years in small plots in Côte d'Or (France).	2015	Belgian variety recovered by the founder of Graines de Noé. This variety was obtained at the Gembloux Agronomic Institute and is a derivative of *Rouquin* (therefore, it has some *Oberkulmer* and common wheat in its pedigree) (Bertin et al., 2001). It is registered in the European catalogue of agricultural plant species (https://www.semae.fr/).
Rouquin	Graines de Noé association (Côte d'Or, France)	Modern variety	Multiplied during at least 5 years in small plots in Côte d'Or (France).	2015	Belgian variety recovered by the founder of Graines de Noé. This variety was obtained at the Gembloux Agronomic Institute, and has some *Oberkulmer* and common wheat in its pedigree (Bertin et al., 2001).
Tyrolien Rouge	Farm in Normandie (France)	Landrace	Multiplied at least once in Normandie (France).	2020	Austrian landrace (Koenig et al., 2015).

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Table 2. Continued

Variety name	Origin of the seeds	Type of variety	Type of conservation	Harvest year of the seeds	Additional information
Common wheat (*Triticum aestivum* subsp. *aestivum*)					
Mix HP&DM	Farm in Rhône (France)	Mixture of landraces	Cultivated for 10 years in Rhône (France). Every year, mass selection was done to favour big kernels.	2021	Mixture of around 100 landraces. Some varieties were obtained from farms CD and SR.
Mix CD	Farm in Isère (France)	Mixture of landraces	Cultivated for at least 5 years in Isère (France). Mass selection only done on Year 1. Small amounts of different varieties were added every 2 years to maintain a high level of genetic diversity.	2021	Mixture of 30 varieties (land varieties and varieties from participatory plant breeding). The varieties were chosen for their adaptation to local pedoclimatic conditions, resistance to lodging and high yields.
Mix SR	Farm in Loire (France)	Mixture of landraces	Cultivated for 3 years in Loire (France). Every year, mass selection was done to favour big kernels.	2021	Mixture of around 10 landraces (*Carossela*, *Cucceta*, *Barbu Milanais*, *Saissette de Provence*, *Touzelles*, *Meunier d'Apt*, *Bardot* and *Bladette*). Some of the varieties came from CD farm. Initially, varieties were chosen for their resistance to lodging, diseases and cold weather.

(Continued)

Table 2. Continued

Variety name	Origin of the seeds	Type of variety	Type of conservation	Harvest year of the seeds	Additional information
Mix GA	Farm in Ain (France)	Mixture of landraces and historical varieties	For 5 years, multiplication of each variety separately in the Ain (France). Within each variety, mass selection was done every year to favour adaptation to local climatic conditions, lodging resistance and ground cover. The mixture was composed every year with equal proportions of each variety.	2021	Mixture of 4 landraces (*Rouge de Bordeaux*, *Barbu du mâconnais*, *Autrichien* and *Alauda*). Initially, the varieties were chosen for their adaptation to the pedo-climatic conditions of the Ain department.
Mix PG	Farm in Isère (France)	Mixture of modern varieties	Cultivated for 5 years in Isère (France). Mass selection is done every year to favour weed competitiveness and kernel size.	2021	Mixture of commercial varieties (*Renan*, *Togano*, *Apache*, *Armstrong*, *Pireneo*) and residues of landraces (from the CD farm). Varieties were initially chosen for their adaptability to mountainous weather.
Mix CM	Farm in Loire (France)	Mixture of modern varieties	Cultivated for 2 years in Loire (France).	2021	Mixture of 5 commercial varieties (*Togano*, *Filou*, *Arenzo* and 2 others) and residues of landraces.
Apache	Farm in the Marne (France)	Modern variety	Cultivated for several years in the Marne (France) under conventional practices.	2020	Commercial variety, registered in the French catalogue in 1998 (https://www.semae.fr/).
Energo	Farm in the Marne (France)	Modern variety	Cultivated for several years in the Marne (France) under conventional practices.	2020	Austrian commercial variety, registered in the European catalogue (https://www.semae.fr/).

Table 3. Selected variables to evaluate weed competitiveness, resistance to lodging and yield, along with the corresponding methods of measurement. Plant posture, plant height and ground cover were evaluated from March 2 to March 4 and from April 19 to April 20. Lodging and plant final height were assessed from June 13 to June 16. Emergence rate, ground cover and the number of ears per plant were assessed on a 100 × 60 cm quadrate that included the three central rows of each plot. For all variables measured on individual plants, mean values for each plot were calculated. After harvesting, 60 g of ears (when available) were sampled from each plot and subjected to threshing and dehulling using a laboratory threshing machine. Naked kernels were used for TKM and protein content determinations. Crosses indicate the characteristic(s) to which each variable is related.

Variable	Weed competitiveness	Resistance lodging	Yield	Scale of measurement	Method of measurement
Emergence rate (%)	X		X	Plot (100 × 60 cm quadrate)	Number of single plants divided by the number of germinable seeds.
Posture beg March (spreading, intermediate, upright)	X			Plot	Visual assessment.
Plant height beg March (cm)	X			16 plants per plot	Distance between the soil and the highest point of the plant, without straightening it.
Ground cover beg March (%)	X			Plot (100 × 60 cm quadrate)	Visual assessment.
Posture end April (spreading, intermediate, upright)	X			Plot	Visual assessment.
Plant height end April (cm)	X			16 plants per plot	Distance between the soil and the highest point of the plant, without straightening it.
Ground cover end April (%)	X			Plot (100 × 60 cm quadrate)	Visual assessment.
Nb ears per plant (counts)	X		X	Plot (100 × 60 cm quadrate)	Estimation relatively to single plant densities.
Heading completion (completed, not completed)	X			Plot	Monitoring each week from May 13 to June 8 (5 measurements). The heading is considered completed when more than 50% of the ears have been headed (50% of the ear visible).
Lodging (%)		X		Plot	Visual assessment (estimation of proportions of plants at different angles from the vertical) and calculation of a lodging severity score using the same method as Costanzo et al. (2019) with minor modifications (p.p. = proportion of plants in the given angle range (%).
Plant final height (cm)		X		20 plants per plot	Distance from the soil to the tip of the ear of the main tiller, straightening the plant when necessary.
Relative yield (%)				Plot	Kernel mass after threshing and dehulling divided by the ear mass before threshing and dehulling.
TKM (g)			X	Plot	Estimation on 331 kernels with the technology 'Optoagrimetric' developed by Optomachines (http://optomachines.fr). For each sample, the average surface mass (g/mm^2) was multiplied by the average surface (mm^2) of one kernel (×1000).
Protein content (%dm)				Plot	Measured on 1.5–3 mg flour withdrawn from the milling of 12 g of kernels using a CYCLOTEC 1093 Sample mill (FOSS TECATOR), with a 0.5 mm grid. % N content measured by the Dumas combustion method (with an AE 2000 NC soil analyser, Model Flash Smart 230V AC 50/60 Hz 1400VA, ThermoFisher). Protein content is considered as % N × 5.7 and expressed with respect to dry matter.

sharing feedback on the first experimental year and planning the next steps. One-on-one interactions between workshops further supported trial design, discussions of preliminary results and other adjustments to the process.

4.2. Field trial

Seven einkorn, eight emmer, eight spelt and eight common wheat varieties were evaluated during the growing season 2021/2022 (Table 2). For hulled wheats, we explored different seed sources and selected all varieties with sufficient seed quantity for the trial. For common wheat, we included the six mixtures of varieties cultivated by each of the farmers involved in the project, along with two modern varieties: *Apache* and *Energo*. All varieties were evaluated at the CRBA (Charly, Lat 45.6°N, Long 4.8°E, Alt 242 m) in a complete-randomized block design, with two blocks (Supplemental Material 4). In addition, a subset of these varieties was assessed across the six farms; however, due to design imbalances and cultural accidents, the data from these evaluations are not included in this article (see Supplemental Material 3 for the corresponding experimental designs and data).

At the CRBA, the soil was sampled in April 2022. It was superficial (30 cm depth), had a sandy-loam texture (58% sand, 33% silt and 9% clay) and 20% of stones. The pH was 6.4 with 2% of soil organic carbon content. Consequently, the soil water holding capacity was low (around 1.2 mm/cm of soil). Pre-crops were either a permanent grassland or a permanent grassland followed by one year of diversified vegetable culture. The experiment was sown between November 19 and November 21, 2021, after a superficial tillage at 15 cm depth (Rotovator Kubota RTZ 3011).

Plots were 1 or 4.4 m^2 (depending on the availability of seeds): 1 m width and 1 to 4.4 m length, with either 5 or 22 rows. Seeding rate was adjusted for a density of 250 germinable seeds per m^2. All plots were covered by a forcing sail (P17) for 2 months to prevent seedlings from being eaten by birds. The experiment was conducted according to organic standards. No fertilization was applied, and a single manual weeding was performed in mid-April 2022. Ears were manually harvested from June 22 to July 19, 2022, in accordance with the maturity of each variety.

Daily meteorological data (SAFRAN data from the INRAE (Maury et al., 2021) from 1992 to 2022 were obtained for a 2×2 km^2 mesh including the CRBA. The medium average temperature in the 2021–2022 growing season (from November to July) was 12.0 °C, and the total precipitation was 365 mm (Supplemental Material 2). The season was particularly dry, especially from January to May 2022, with only 114 mm rain.

4.3. Agronomic evaluation

Variables related to weed competitiveness, resistance to lodging and yield were measured (Table 3). Weed competitiveness was assessed through ground cover by crops (itself linked with plant density, plant posture and tillering) and earliness (measured by heading completion and linked with plant height). Given the incidence of lodging being minimal during the growing season, its evaluation mostly relied on plant final height. As for yield determination, we wanted to base it on yield components (emergence rate, number of ears per plant, TKM). Yet, the experiment was damaged by a hailstorm just before harvesting, preventing the determination of number of kernels per ear and, consequently, final yields. Further, we estimated two additional variables of interest for the stakeholders: relative yield and total protein content (Table 3).

4.4. Data analysis

All statistical analyses were performed with R (version 4.3.3). Original data and R scripts are available in Supplemental Material 5.

First, a PCA was performed (package FactoMineR 2.6) on a dataset with the mean values for all variables for each variety. Values of qualitative variables were replaced by quantitative scores to include them in the analysis. All values were scaled to unit variance. The number of dimensions was chosen so that it explained at least 90% of the total variation.

To statistically test the effect of species, the following ANOVA model was run on all quantitative variables measured at the plot level:

$$y_{i,j,k} = \mu + \alpha_i + \beta_{j \vee i} + \gamma_k + \varepsilon_{i,j,k} \quad (1)$$

In this model, μ was the intercept term, α_i accounted for the fixed effect of the ith species, $\beta_{j \vee i}$ for the fixed effect of the jth variety nested in the ith species, γ_k for the fixed effect of the kth bloc and $\varepsilon_{i,j,k}$ was the random residual. The distribution of the residuals was checked for each variable by visual examination of the *Q*–*Q* and the residuals versus fitted plots (Supplemental Material 5). Adjusted means (estimated marginal means) were then calculated for each species and pairwise comparisons were achieved using Tukey's HSD method with Bonferroni adjustment for *p*-values (packages emmeans 1.8.2 and multcompView 0.1.8*)*. For the variables measured at the plant level, the same model was used, but the residual had an additional source of variability (individual plants).

Supplementary material. The supplementary material for this article can be found at http://doi.org/10.1017/qpb.2025.10010.

Data availability statement. The datasets generated and analysed in the present study are included in this published article (in Supplemental Material 5). All R scripts used for analyses are also available in Supplemental Material 5.

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References

Allahverdiyev, T. (2016). Yield and yield traits of durum wheat (Triticum durum desf.) and bread wheat (*Triticum aestivum* L.) genotypes under drought stress. *Genetika*, **48**(2), 717–727. https://doi.org/10.2298/GENSR1602717A.

Bencze, S., **Makádi, M.**, **Aranyos, T. J.**, **Földi, M.**, **Hertelendy, P.**, **Mikó, P.**, **Bosi, S.**, **Negri, L.**, & **Drexler, D.** (2020). Re-introduction of ancient wheat cultivars into organic agriculture—Emmer and einkorn cultivation experiences under marginal conditions. *Sustainability*, **12**(4), Article 1584. https://doi.org/10.3390/su12041584.

Bertin, P., **Grégoire, D.**, **Massart, S.**, & **de Froidmont, D.** (2001). Genetic diversity among European cultivated spelt revealed by microsatellites. *Theoretical and Applied Genetics*, **102**, 148–156. https://doi.org/10.1007/s001220051630.

Beteselassie, N., **Fininsa, C.**, & **Badebo, A.** (2007). Sources of resistance to stem rust (Puccinia graminis f. Sp. Tritici) in Ethiopian tetraploid wheat accessions. *Genetic Resources and Crop Evolution*, **54**(2), 337–343. https://doi.org/10.1007/s10722-005-5561-6.

Biel, W., **Stankowski, S.**, **Jaroszewska, A.**, **Pużyński, S.**, & **Bośko, P.** (2016). The influence of selected agronomic factors on the chemical composition of spelt wheat (*Triticum aestivum* ssp. Spelta L.) grain. *Journal of Integrative Agriculture*, **15**(8), 1763–1769, Article 8. https://doi.org/10.1016/S2095-3119(15)61211-4

Bonjean, A. (2001). Histoire de la culture des céréales et en particulier de celle du blé tendre (Triticum aestivum L.). *Dossier de l'environnement de l'INRA* **21**, 29–37. http://fdslevigan.free.fr/DOCSHORSITE/ARTICLES/Bonjean2002_Histoire_de_la_culture_des_céréales_et_en_particulier_de_celle_du_blé_tendre.pdf

Bonnin, I., **Bonneuil, C.**, **Goffaux, R.**, **Montalent, P.**, & **Goldringer, I.** (2014). Explaining the decrease in the genetic diversity of wheat in France over the 20th century. *Agriculture, Ecosystems & Environment*, **195**, 183–192. https://doi.org/10.1016/j.agee.2014.06.003.

Castagna, R., **Borghi, B.**, **Di Fonzo, N.**, **Heun, M.**, & **Salamini, F.** (1995). Yield and related traits of einkorn (T. Monococcum ssp. Monococcum) in different environments. *European Journal of Agronomy*, **4**(3), 371–378, Article 3. https://doi.org/10.1016/S1161-0301(14)80038-5

Ceccarelli, S., & **Grando, S.** (2019). Participatory plant breeding: Who did it, who does it and where? *Experimental Agriculture*, **56**(1), 1–11, Article 1. https://doi.org/10.1017/S0014479719000127

Chable, V., & **Berthellot, J.-F.** (2006). La sélection participative en France: Présentation des expériences en cours pour les agricultures biologiques et paysannes. *Dossier de l'environnement de l'INRA*, 30, 129–138. https://www.researchgate.net/publication/228859679_La_selection_participative_en_France_Presentation_des_experiences_en_cours_pour_les_agricultures_biologiques_et_paysannes

Chable, V., **Nuijten, E.**, **Costanzo, A.**, **Goldringer, I.**, **Bocci, R.**, **Oehen, B.**, **Rey, F.**, **Fasoula, D.**, **Feher, J.**, **Keskitalo, M.**, **Koller, B.**, **Omirou, M.**, **Mendes-Moreira, P.**, **van Frank, G.**, **Naino Jika, A. K.**, **Thomas, M.**, & **Rossi, A.** (2020). Embedding cultivated diversity in Society for Agro-Ecological Transition. *Sustainability*, **12**(3), Article 784. https://doi.org/10.3390/su12030784

Correa, S., **Lepagneul, J.**, **Thomas, M.**, **Mayaud, L.**, **Hamant, O.**, **Samson, M.-F.**, & **Charreyre, M.-T.** (2024). Unraveling gluten protein compositions of einkorn, emmer, and spelt grown in the Lyon region in France. *Cereal Chemistry*, **101**(4), 798–816. https://doi.org/10.1002/cche.10781.

Costanzo, A., **Amos, D. C.**, **Dinelli, G.**, **Sferrazza, R. E.**, **Accorsi, G.**, **Negri, L.**, & **Bosi, S.** (2019). Performance and nutritional properties of einkorn, emmer and rivet wheat in response to different rotational position and soil tillage. *Sustainability*, **11**(22), Article 6304. https://doi.org/10.3390/su11226304.

Cubadda, R., & **Marconi, E.** (2002). Spelt wheat. In P. S. Belton & J. R. N. Taylor (eds.), *Pseudocereals and less common cereals: Grain properties and utilization potential* (pp. 153–175). Springer. https://doi.org/10.1007/978-3-662-09544-7_5

Dawson, J. C., **Rivière, P.**, **Berthellot, J.-F.**, **Mercier, F.**, **Kochko, P. de**, **Galic, N.**, **Pin, S.**, **Serpolay, E.**, **Thomas, M.**, **Giuliano, S.**, & **Goldringer, I.** (2011). Collaborative plant breeding for organic agricultural Systems in Developed Countries. *Sustainability*, **3**(8), 1206–1223, Article 8. https://doi.org/10.3390/su3081206

Demeulenaere, É., & **Goldringer, I.** (2017). Semences et transition agroécologique: Initiatives paysannes et sélection participative comme innovations de rupture. *Natures Sciences Sociétés*, **25**, S55–S59. https://doi.org/10.1051/nss/2017045.

Dinu, M., **Whittaker, A.**, **Pagliai, G.**, **Benedettelli, S.**, & **Sofi, F.** (2018). Ancient wheat species and human health: Biochemical and clinical implications. *The Journal of Nutritional Biochemistry*, **52**, 1–9. https://doi.org/10.1016/j.jnutbio.2017.09.001.

FAO. (2019). *The state of the world's biodiversity for food and agriculture*, J. Bélanger & D. Pilling (eds.). FAO Commission on Genetic Resources for Food and Agriculture Assessments. Rome. 572 pp. http://www.fao.org/3/CA3129EN/CA3129EN.pdf

Goldringer, I., **Frank, G. v.**, **d'Yvoire, C. B.**, **Forst, E.**, **Galic, N.**, **Garnault, M.**, **Locqueville, J.**, **Pin, S.**, **Bailly, J.**, **Baltassat, R.**, **Berthellot, J.-F.**, **Caizergues, F.**, **Dalmasso, C.**, **Kochko, P. d.**, **Gascuel, J.-S.**, **Hyacinthe, A.**, **Lacanette, J.**, **Mercier, F.**, **Montaz, H.**, & **Rivière, P.** (2019). Agronomic evaluation of bread wheat varieties from participatory breeding: A combination of performance and robustness. *Sustainability*, **12**(1), 128. https://doi.org/10.3390/su12010128.

Goriewa-Duba, K., **Duba, A.**, **Wachowska, U.**, & **Wiwart, M.** (2018). An evaluation of the variation in the morphometric parameters of grain of six Triticum species with the use of digital image analysis. *Agronomy*, **8**(12), Article 296. https://doi.org/10.3390/agronomy8120296.

Gupta, N. K., **Gupta, S.**, & **Kumar, A.** (2001). Effect of water stress on physiological attributes and their relationship with growth and yield of wheat cultivars at different stages. *Journal of Agronomy and Crop Science*, **186**(1), 55–62. https://doi.org/10.1007/BF03543302.

Jouzi, Z., **Azadi, H.**, **Taheri, F.**, **Zarafshani, K.**, **Gebrehiwot, K.**, **Van Passel, S.**, & **Lebailly, P.** (2017). Organic farming and small-scale farmers: Main opportunities and challenges. *Ecological Economics*, **132**, 144–154. https://doi.org/10.1016/j.ecolecon.2016.10.016.

Kahiluoto, H., **Kaseva, J.**, **Balek, J.**, **Olesen, J. E.**, **Ruiz-Ramos, M.**, **Gobin, A.**, **Kersebaum, K. C.**, **Takáč, J.**, **Ruget, F.**, & **Ferrise, R.** (2019). Decline in climate resilience of European wheat. *Proceedings of the National Academy of Sciences*, **116**(1), 123–128, Article 1.

Khan, A. R., **Goldringer, I.**, & **Thomas, M.** (2020). Management practices and breeding history of varieties strongly determine the fine genetic structure of crop populations: A case study based on European wheat populations. *Sustainability*, **12**(2), Article 613. https://doi.org/10.3390/su12020613.

Khoury, C. K., **Brush, S.**, **Costich, D. E.**, **Curry, H. A.**, **de Haan, S.**, **Engels, J. M. M.**, **Guarino, L.**, **Hoban, S.**, **Mercer, K. L.**, **Miller, A. J.**, **Nabhan, G. P.**, **Perales, H. R.**, **Richards, C.**, **Riggins, C.**, & **Thormann, I.** (2022). Crop genetic erosion: Understanding and responding to loss of crop diversity. *New Phytologist*, **233**(1), 84–118. https://doi.org/10.1111/nph.17733.

Koenig, A., **Konitzer, K.**, **Wieser, H.**, & **Koehler, P.** (2015). Classification of spelt cultivars based on differences in storage protein compositions from wheat. *Food Chemistry*, **168**, 176–182. https://doi.org/10.1016/j.foodchem.2014.07.040.

Lammerts van Bueren, E. T., **Jones, S. S.**, **Tamm, L.**, **Murphy, K. M.**, **Myers, J. R.**, **Leifert, C.**, & **Messmer, M. M.** (2011). The need to breed crop varieties suitable for organic farming, using wheat, tomato and broccoli as examples: A review. *NJAS – Wageningen Journal of Life Sciences*, **58**(3), 193–205. https://doi.org/10.1016/j.njas.2010.04.001.

Lin, B. B. (2011). Resilience in agriculture through crop diversification: Adaptive management for environmental change. *Bioscience*, **61**(3), 183–193. https://doi.org/10.1525/bio.2011.61.3.4.

Longin, C. F. H., **Ziegler, J.**, **Schweiggert, R.**, **Koehler, P.**, **Carle, R.**, & **Würschum, T.** (2016). Comparative study of hulled (einkorn, emmer, and spelt) and naked Wheats (durum and bread wheat): Agronomic performance and quality traits. *Crop Science*, **56**(1), 302–311, Article 1. https://doi.org/10.2135/cropsci2015.04.0242

Maury, O., **Garcia de Cortazar Atauri, I.**, **Bertuzzi, P.**, **Persyn, B.**, & **Lagier, M.** (2021). *SICLIMA: Système d'information de données climatiques maillées*, https://doi.org/10.15454/HIPDPZ, Recherche Data Gouv, V1.

Mijatović, D., **Oudenhoven, F. V.**, **Eyzaguirre, P.**, & **Hodgkin, T.** (2013). The role of agricultural biodiversity in strengthening resilience to climate change: Towards an analytical framework. *International Journal of Agricultural Sustainability*, **11**(2), 95–107. https://doi.org/10.1080/14735903.2012.691221.

Mirbahar, A. A., **Markhand, G. S.**, **Mahar, A. R.**, & **Abro, S. A.** (2009). Effect of water stress on yield and yield components of wheat (*Triticum aestivum* L.). varieties. *Pakistan Journal of Botany*, **41**(3), 1303–1310.

Mondini, L., **Grausgruber, H.**, & **Pagnotta, M. A.** (2014). Evaluation of European emmer wheat germplasm for agro-morphological, grain quality traits and molecular traits. *Genetic Resources and Crop Evolution*, **61**(1), 69–87. https://doi.org/10.1007/s10722-013-0016-y.

Nesbitt, M., & **Samuel, D.** (1996). From staple crop to extinction? The archaeology and history of the hulled wheats. In S. Padolusi, K. Hammer, J. Heller, (eds.), Hulled wheats. Promoting the conservation and use of underutilized and neglected crops. Proceedings of the First International Workshop on Hulled Wheats, 21-22 July 1995, Castelvecchio Pascoli, Tuscany, Italy. Rome: International Plant Genetic Resources Institute, pp. 40–99. https://www.researchgate.net/profile/Mark-Nesbitt/publication/234003180_From_staple_crop_to_extinction_The_archaeology_and_history_of_the_hulled_wheats/links/548ddee70cf214269f24362a/From-staple-crop-to-extinction-The-archaeology-and-history-ofthe-hulled-wheats.pdf

Padulosi, S., & **Hoeschle-Zeledon, I.** (2004). Underutilized plant species: What are they? *Leisa Magazine*.

Padulosi, S. (1996). International workshop on hulled Wheats, & International Plant Genetic Resources Institute; Leibniz Institute of Plant Genetics and Crop Plant Research; S. Padulosi, K. Hammer, J. Heller, (eds.), Hulled wheat. 262 p. https://cgspace.cgiar.org/items/a8b4a0b6-3ddc-4d3f-9c6c-dd9e2dc1ff56

Rivière, P., **Pin, S.**, **Galic, N.**, **De Oliveira, Y.**, **David, O.**, **Dawson, J.**, **Wanner, A.**, **Heckmann, R.**, **Obbellianne, S.**, & **Ronot, B.** (2013). Mise en place D'une méthodologie de sélection participative Sur le blé tendre en France. *Innovations agronomiques*, **32**, 427–441.

Rouse, M. N., & **Jin, Y.** (2011). Genetics of resistance to race TTKSK of *Puccinia graminis f Sp. Tritici in Triticum monococcum*. *Phytopathology*, **101**(12), 1418–1423. https://doi.org/10.1094/PHYTO-05-11-0133.

Shah, L., **Yahya, M.**, **Shah, S. M. A.**, **Nadeem, M.**, **Ali, A.**, **Ali, A.**, **Wang, J.**, **Riaz, M. W.**, **Rehman, S.**, **Wu, W.**, **Khan, R. M.**, **Abbas, A.**, **Riaz, A.**, **Anis, G. B.**, **Si, H.**, **Jiang, H.**, & **Ma, C.** (2019). Improving lodging resistance: Using wheat and Rice as classical examples. *International Journal of Molecular Sciences*, **20**(17), Article 4211. https://doi.org/10.3390/ijms20174211

Shewry, P. R. (2018). Do ancient types of wheat have health benefits compared with modern bread wheat? *Journal of Cereal Science*, **79**, 469–476. https://doi.org/10.1016/j.jcs.2017.11.010.

Siedler, H., **Messmer, M. M.**, **Schachermayr, G. M.**, **Winzeler, H.**, **Winzeler, M.**, & **Keller, B.** (1994). Genetic diversity in European wheat and spelt breeding material based on RFLP data. *Theoretical and Applied Genetics*, **88**(8), 994–1003. https://doi.org/10.1007/BF00220807.

Singh, K., **Chhuneja, P.**, **Kaur, S.**, **Garg, T.**, **Tiwari, V. K.**, **Rawat, N.**, **Bains, N. S.**, **Dhaliwal, H. S.**, & **Keller, B.** (2008). *Triticum monococcum*: A source of novel genes for improving several traits. In: R. Appels, R. Eastwood, E. Lagudah, P. Langridge, M. M. Lynne (eds.), *Proceedings of the 11th international wheat genetic symposium*. Brisbane, Australia, pp. 295–298.

Zaharieva, M., **Ayana, N. G.**, **Hakimi, A. A.**, **Misra, S. C.**, & **Monneveux, P.** (2010). Cultivated emmer wheat (Triticum dicoccon Schrank), an old crop with promising future: A review. *Genetic Resources and Crop Evolution*, **57**(6), 937–962. https://doi.org/10.1007/s10722-010-9572-6.

Zaharieva, M., & **Monneveux, P.** (2014). Cultivated einkorn wheat (*Triticum monococcum* L. subsp. monococcum): The long life of a founder crop of agriculture. *Genetic Resources and Crop Evolution*, **61**(3), 677–706, Article 3. https://doi.org/10.1007/s10722-014-0084-7