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► **To cite this version:**

Alex C. Mcalvay, Anna Dipaola, A. Catherine D'andrea, Morgan L. Ruelle, Marine Mosulishvili, et al.. Cereal species mixtures: an ancient practice with potential for climate resilience. A review. *Agronomy for Sustainable Development*, 2022, 42 (5), pp.100. <10.1007/s13593-022-00832-1>. <hal-04243131>

HAL Id: hal-04243131

<https://hal.science/hal-04243131v1>

Submitted on 16 Oct 2023

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Cereal species mixtures: an ancient practice with potential for climate resilience. A review

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Accepted: 2 September 2022 / Published online: 13 October 2022
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Abstract

Food security depends on the ability of staple crops to tolerate new abiotic and biotic pressures. Wheat, barley, and other small grains face substantial yield losses under all climate change scenarios. Intra-plot diversification is an important strategy for smallholder farmers to mitigate losses due to variable environmental conditions. While this commonly involves sowing polycultures of distinct species from different botanical families in the same field or multiple varieties of the same species (varietal mixtures), mixed plantings of multiple species from the same family are less well known. However, the sowing of maslins, or cereal species mixtures, was formerly widespread in Eurasia and Northern Africa and continues to be employed by smallholder farmers in the Caucasus, Greek Islands, and the Horn of Africa, where they may represent a risk management strategy for climate variability. Here, we review ethnohistorical, agronomic, and ecological literature on maslins with a focus on climate change adaptation, including two case studies from Ethiopian smallholder farmers. The major points are the following: (1) farmers in Ethiopia, Eritrea, and Georgia report that mixtures are a strategy for ensuring some yield under unpredictable precipitation and on marginal soils; (2) experimental trials support these observations, demonstrating increased yield advantage and stability under certain conditions, making maslins a potentially adaptive practice when crops are impacted by new biotic and abiotic conditions due to climate change; (3) maslins may balance trade-offs between interfamilial species plantings and varietal mixtures, and expand the total portfolio of traits available for formulating mixtures from varietal mixtures alone; and (4) they may buffer against the impacts of climate trends through passive shifts in species composition in response to environmental pressures. We demonstrate the potential benefits of maslins as an agroecological intensification and climate adaptation strategy and lay out the next steps and outstanding questions regarding the applicability of these cropping systems.

Keywords Maslin · Cereal species mixture · Varietal mixture · Polyculture · Intercrop · Intercropping · Intensification · Agroecology · Mixed cropping

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1 Introduction

Future food security in a rapidly changing climate will depend heavily on the ability of staple crops to tolerate new abiotic and biotic pressures (Ericksen et al. 2009). Wheat, barley, and other small grains are anticipated to face severe yield losses under even conservative climate change scenarios without farmers adapting their practices (Challinor et al. 2014; Wang et al. 2018; Leng and Hall 2019). Adaptation may involve planting different varieties, changing planting times, or more transformational approaches like novel cropping systems (Rickards and Howden 2012) and increasing on-farm crop species diversity across scales (Renard and Tilman 2019). Low input crops and cropping systems will also likely be important to cope with reduced access to water and fossil fuels as well as reduce greenhouse gas emissions (Pant 2009; Sarkar et al. 2020).

To confront global challenges, many have called for agricultural intensification that integrates ecological principles and farmer knowledge to achieve increased production with the same or less inputs (Wezel et al. 2015; Struik and Kuyper 2017; Milder et al. 2019). For example, the Intergovernmental Panel on Climate Change suggests that traditional knowledge of locally adapted farming strategies is a key resource for climate resilience (IPCC 2022). A number of traditional crop diversification strategies and crops that have decreased in use with the mechanization of agriculture and changing consumer demands are being investigated and revitalized due to low input demands, agroecological services, and/or increased resilience (Finckh et al. 2000; Lin 2011; Hunter et al. 2019; Zanetti et al. 2021).

Increased species richness in wild and cultivated plant communities has been associated with broad ecological consequences. For example, in wild plant communities, elevated species richness can be correlated with biomass production, stability of production (Gross et al. 2014), as well as response to disturbance, drought (Grossiord 2020), and elevated

atmospheric CO₂ (Reich et al. 2004). The mechanisms through which species richness may affect ecosystem functioning include facilitation through species changing the physical, chemical, and biotic community composition in a shared environment, as well as resource use diversity and response diversity to biotic and abiotic stressors. Similar patterns have been observed in agricultural systems, where diversity can contribute to resilience and productivity (Lin 2011).

For millennia, farmers have used combinations of multiple crop species and varieties to manage risk and mitigate losses due to uncertain environmental conditions (Maetzumi et al. 2018; Maitra et al. 2021), approaches that may prove useful in confronting contemporary rapid climate change (Mao et al. 2015). In many cases, intercropping of species involves combining crops from distinct plant families such as legumes and grasses with complementary nutritional profiles and functional traits such as nitrogen-fixing beans being combined with maize, which can support climbing legumes (Pleasant and Burt 2010). Mixtures of varieties from the same species are also widely observed and can impart benefits to yield stability, disease resistance, and weed suppression (Kiær et al. 2009; Snyder et al. 2020). However, species mixtures, variety mixtures, and monocultures often involve a suite of tradeoffs between services such as nutritional diversity, ease of mechanization, and yield (Snyder et al. 2020).

A less studied traditional strategy is the mixing of different species from the same botanical family, such as wheat with barley (Woldeamlak et al. 2008a), faba bean with field pea (Sahile et al. 2008), sorghum with maize (Aiyer 1950), or rice with maize (Warburton 1915). These types of mixtures likely possess unique benefits (e.g., Carrubba et al. 2008; Sekine et al. 2021) and tradeoffs, but they are not as well-known as varietal mixtures or multi-family species mixtures. Like varietal mixtures, certain mixtures of functionally similar species may serve to buffer yield instability (Woldeamlak et al. 2008b) or moderate pathogen pressure (Clark 1980). However, because these mixtures tend to be more functionally distinct than intraspecific mixtures, it is possible that some of the benefits observed in varietal mixtures, such as those deriving from niche partitioning or increased nutritional diversity, may be magnified.

In small cereal crops especially, varietal mixtures have shown promising effects on yield advantage, yield stability, and disease tolerance compared to single cultivars (Creissen et al. 2016; Borg et al. 2018), but maslins—mixtures of cereal species such as wheat, barley, rye, or oats—are comparatively little studied. Diversity in maslins mirrors natural grassland ecosystems, representing a traditional example of the “prairie model” (Malézieux 2012) of ecological mimicry. Maslin agriculture was formerly widespread in Eurasia and Africa from the Bronze Age into the early modern period and continues to some extent today on rainfed smallholder farms in the Horn of Africa, Caucasus mountains, and elsewhere (Fig. 1 and 2). In

Fig. 1 A maslin grown by a farmer in Kutaber, Ethiopia, consisting of two bread wheat (*Triticum aestivum*) and two barley (*Hordeum vulgare*) varieties. Photos by Alex McAlvay.



In addition to human food, maslins have been widely used for livestock fodder, as in the case of barley-oat, oat-rye, and oat-wheat mixtures in North America, with the last dating to at least 1889 (Warburton 1915), as well as in parts of Europe (Zajac et al. 2014). While maslins for livestock use are declining in some areas such as North America, the majority of land planted for spring cereals in Poland are still mixtures, especially barley and oats (Szemplinski and Budzynski 2011).

In areas where maslins persist, many smallholder farmers report sowing these mixtures as a strategy to ensure the reliability of staple crops, especially under pest pressure, low soil fertility, inconsistent precipitation, and other challenging conditions (Halstead and Jones 1989; Woldeamlak et al. 2008a; Mosulishvili et al. 2021). Field trials with certain cereal mixtures have shown promising potential for enhanced yield advantage (Prasad et al. 1988; Woldeamlak et al. 2008a), yield stability (Woldeamlak et al. 2008b), weed resistance (O'Donovan et al. 1985; Cousens 1996; Kaut et al. 2008), and pest and pathogen resistance (Clark 1980).

Experimental, ethnographic, and ecological evidence suggests that they warrant further investigation as possible low-input, climate-resilient cropping systems. However, a relative dearth of research on maslins and limited synthesis between bodies of existing literature due to disciplinary, geographical, and linguistic differences, has limited concerted efforts to evaluate this strategy. To assess the current state of knowledge and the potential for maslins to contribute to agroecological intensification and climate resilience, we consolidate existing research on maslins from agronomy, ethnography, archaeology, history, and ecology, and highlight opportunities for future research, focusing on applications in smallholder systems.

2 Archaeological and ethnographic insights into maslins

Farmers have employed maslin cropping systems spanning significant geographic breadth and temporal depth, often

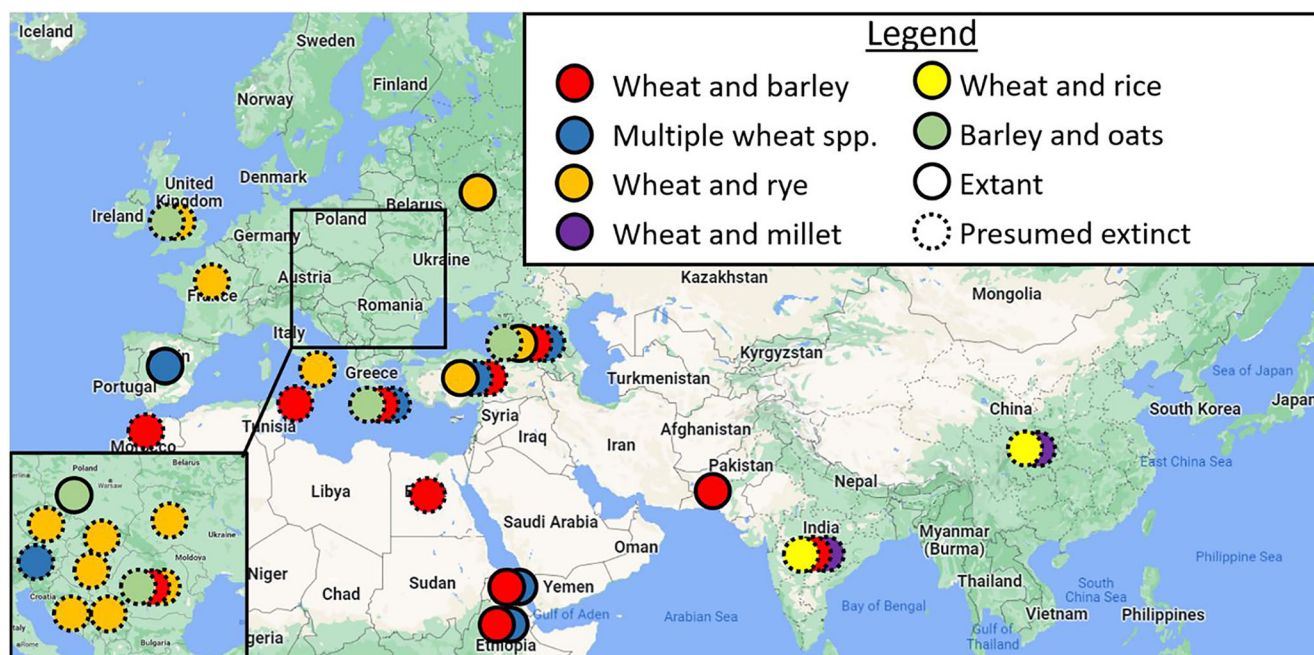


Fig. 2 Historical and contemporary distribution of traditional maslin agriculture. The “presumed extinct” designation was based on either positive reports of their absence or a lack of recent reports of their

presence. Within country boundaries, circles are arbitrarily placed. Not shown: barley-oat maslins grown in Canada for livestock fodder. References in Supp. Table 1.

motivated by risk-reduction. Here, we present archaeological, historical, and ethnographic lines of evidence which suggest that maslins have been used for over 3000 years and in at least 27 countries, and present two case studies from our work in Ethiopia to highlight farmers' perspectives on traditional maslins. These findings suggest potential advantages of maslins over monocrops in terms of tolerance to low and inconsistent precipitation, infertile soils, pests, and other traits of interest for climate-resilient and low-input cropping strategies.

2.1 Origins

Many traditional cropping systems imitate unmanaged ecosystems in structure and/or diversity (Winter et al. 2020), and maslins too recapitulate wild plant communities to some degree, with many of their crop wild relatives co-occurring in wild grassland communities. For example, wild einkorn and wild emmer can be found in fields together and with wild barley, wild rye, and/or wild oats (Nevo et al. 1988; Zohary et al. 2012). An extended period of coevolution predating agriculture could have preadapted these species to function together in agricultural mixtures through, for example, the evolution of niche partitioning (Tilman and Downing 1994; Tilman et al. 1996).

While maslins are difficult to identify in archaeological contexts due in part to the potential for postharvest mixing or contamination (Jones and Halstead 1995), they appear to be ancient and possibly arose at the same time as the earliest domestication of cereals. While wild oats and wild rye are thought to have been weeds in wheat or barley fields before being domesticated and could have been domesticated in the context of mixtures (Hancock 2004; Zohary et al. 2012), mixed cultivation may have started with wild grains. A mixture of wild barley (*Hordeum spontaneum*) and wild oat (*Avena sterilis*) was being cultivated at Gilgal in Israel, before either was domesticated (Weiss et al. 2006). The oldest strong archaeological evidence of domesticated maslins includes an emmer-spelt mixture dating to the Bronze Age (Jones et al. 1986), though there is also limited evidence for a Neolithic einkorn-emmer mixture in Southwest Asia (Zohary et al. 2012).

Historically, diverse maslins were grown across an expansive geographic area spanning Eurasia and northern Africa, and later, North America. Our literature review identified traditions of maslins grown in 27 countries (Fig. 2. Supp. Table 1) that include a wide variety of species such as rye, barley, rice, various millets, oats, and multiple species of wheat. Examples of maslin agriculture from Central and South America or Oceania were not recovered. These may be absent due to differences in the timing and nature of the introduction of cereal crops to these regions.

2.2 Farmer perspectives on maslin cropping strategies

While the use of maslins has declined over the last several hundred years, coinciding with changing consumer preferences and increased use of irrigation and chemical fertilizer which may have made the low-input tolerance of maslins a lower-priority trait (Woldeamlak and Struik 2000; Woldeamlak et al. 2001), maslin agriculture persists in several areas. Instances where traditional maslins persisted into the last century or to the present provide more nuanced insights into farmers' activities and motivations for planting maslins. For example, traditional maslins were grown recently, or continue to be grown, in Eritrea (Woldeamlak et al. 2008a), India (Aiyer 1950), Georgia (Bedoshvili et al. 2020), Greece (Halstead and Jones 1989), and Ethiopia (D'Andrea et al. 1999; Ruelle et al. 2019). In several countries, multiple distinct maslins are grown. For example, over twelve distinct maslins involving various combinations of barley, rye, and 9 wheat species are documented in Georgia (Supp. Table 1), and mixtures involving rice, millets, and a variety of other small cereals are documented in India—some including up to four species in a single mixture (Aiyer 1950). Maslins may also contain not only multiple species, but also multiple varieties of one or more of the species included, as in Georgia (Naskidashvili et al. 2013), Eritrea (Woldeamlak et al. 2008a), and Ethiopia (Ruelle 2015). For example, Eritrean and Ethiopian mixtures can contain more than three wheat and four barley varieties (Woldeamlak et al. 2005; Ruelle 2015).

Despite variation in the species involved and their proportions, farmers' agricultural practices involving maslins share a number of commonalities across countries where they have been documented. In most cases, farmers report sowing, harvesting, processing, and consuming the components of the mixtures together as one crop. The proportions of components were reported to vary widely not only across countries but from farmer to farmer and year to year. Farmers in Amorgos, Greece, observed wide variance in the proportion of components in *mighadi* (wheat-barley mixtures), based on rainfall and type of field (Halstead and Jones 1989). Woldeamlak et al. (2008a) report that farmers plant different ratios of the components depending on soil type, with relatively more wheat in soil with high water-holding capacity. Aiyer (1950) reported that wheat to barley ratios varied dramatically from 1:1 up to 9:1.

Farmers' motivations for growing maslins also have notable overlap across these same areas, especially as a risk management strategy important to smallholders practicing rainfed agriculture. In Eritrea, farmers plant mixtures of wheat and barley so that in years with typical rainfall, they harvest both wheat and barley but in dry years, they will harvest drought-tolerant barley at a minimum (Woldeamlak et al. 2008b). Greek farmers explained that they planted wheat-barley

mixtures as a strategy to reduce the chance of crop failure due to erratic precipitation patterns (Halstead and Jones 1989). They also reported that the mixture provides post-harvest protection, as farmers expressed that barley is more resistant to weevils than wheat (Halstead and Jones 1989). In Georgia, *zanduri*, a mixture of three wheat species, was known by farmers to be especially tolerant to drought, frost, and poor soils Mosulishvili et al. 2021. Similarly, in India, wheat-barley mixtures were planted as insurance against loss in productivity (Aiyer 1950; Prasad et al. 1988). Eritrean farmers reported that *hanfetz* outperforms single crops of wheat and barley especially in years with insufficient rain and has fewer issues with insects, disease, and weedy wild oats (Woldeamlak and Struik 2000). They also state that *hanfetz* is purported to provide higher yield stability, better tasting bread, disease resistance, and higher quality animal feed (Woldeamlak et al. 2008a). In general, many farmers described maslins as managing tradeoffs in yield and inputs, fodder and food quality, pest and pathogen resistance, drought and waterlogging tolerance, and prevention of postharvest losses. To further illustrate the traditional use of maslins, we share below two detailed case studies from our work in northern Ethiopia on cereal mixtures.

2.3 Case study 1: Amhara, Ethiopia

Field research conducted in 2011–2014 in North Gonder, Ethiopia, revealed the widespread use of maslins, especially wheat-barley mixtures. As part of a research project investigating the contributions of plant diversity to food systems (Ruelle 2015; Ruelle et al. 2019), a series of interviews were conducted with 30 farming families across 28 villages in the Debark District (2600–3000 m asl). As farmers listed the crop species and varieties they sowed in their fields, many of them mentioned *duragna*, which some described as similar to wheat (*sende*), others as similar to barley (*gebs*), but distinct from both. After several interviews, one farmer explained that *duragna* is a mixture of wheat and barley that are planted, harvested, and used together, and therefore considered a distinct crop. When mature *duragna* was observed, it contained up to three varieties of wheat and four varieties of barley (all *Hordeum vulgare*). Each of the wheat and barley varieties could be distinguished, described, and named by the farmer. One farmer identified one of the varieties of wheat included in the mixture as *duragna*. This variety, later identified as a type of durum wheat (*Triticum durum*) may be a particularly important constituent of the mixture, at least in some cases.

The wheat and barley included in *duragna* do not necessarily need to be separated for use in local foodways. Interviewees described using *duragna* to prepare *injera* (a soft sourdough pancake), bread (*dabo*), beer (*tella*), and *kollo* (a mixture of roasted cereals, legumes, and oilseeds consumed as snack food). Part of processing cereals for these uses involves

removing the outer hulls; this is generally easier with wheat than barley, because the hulls of the latter are fused to the grain. However, Ethiopia is home to many hullless and partially-hulled barley types (Asfaw 2000). Farmers in Debark mentioned such hullless and partially-hulled types (*temej* and *akiya*, respectively), and said that they were particularly advantageous in preparing *kollo*, but it was not clear if these or similar types were included in *duragna*. Further research is necessary to characterize the constituents of *duragna*, including hull attachment. To this end, it is important to speak with women farmers, who are typically responsible for processing and preparing cereals as food and therefore often more knowledgeable than the men about culinary traits. Furthermore, although primarily intended for household consumption, we observed farmers selling surplus *duragna* at the Debark market, but it remains unclear if the mixture makes any important contribution to household income.

The widespread use of *duragna* in Debark was confirmed by a randomized vegetation survey, which included 57 rain-fed fields. Of these, eight were planted with *duragna*, whereas only five were sole-cropped with wheat and three with barley. Interestingly, we also observed cereal mixtures including the novel hybrid triticale (*mogne sende*, × *Triticale*), which was reported by farmers to have been introduced to Debark in the 2010s. Five fields were planted with a mixture of triticale, barley and wheat, compared to only three sole-cropped with triticale. We also observed one field planted with a triticale and barley mixture and another with triticale and wheat. Other confamilial species mixtures were observed in Debark, including a mixture of field pea (*Pisum sativum*) and faba bean (*Vicia faba*) described as *tre* (an abbreviated version of *tratre*, which refers to an endogenous category of crops that includes most grain legumes). Like *duragna*, *tre* is typically planted, harvested, and used together, for example in the traditional dish known as *nifro*: boiled, salted peas, and beans served as a plant-based source of protein during fasting periods where meat is not eaten for religious reasons. The vegetation survey revealed that *tre* was one of the most widely planted crops; 15 of the 57 rain-fed fields surveyed had been planted with this mixture, exceeding any other crop. Furthermore, *duragna* and *tre* are sometimes planted in rotation on the same field, with 2 or 3 years of planting of *duragna* followed by one or sometimes two years planting *tre* to restore soil fertility. Producing four species of crops within these rotations represents an important agroecological intensification strategy.

2.4 Case study 2: Tigray, Ethiopia

Maslins, locally called *hanfetz*, are commonly planted in the Enderta district of South Tigray, Ethiopia, and involve various combinations of emmer, durum, up to two bread wheat varieties, and up to two barley varieties, as well as other

polycultures (D'Andrea et al. 1999; D'Andrea and Haile 2002; Butler and D'Andrea 2000). Farmers expressed a preference for mixtures with synchronous maturation and reported a number of desirable qualities of mixtures over monocrops including higher yields of both grain and straw; risk minimization; reduction in lodging; and mitigating the spread of disease. Additional factors include the desired color of flour, baking quality, storability, and anticipated food product (D'Andrea et al. 1999; D'Andrea and Haile 2002; Butler and D'Andrea 2000). Farmers in the village of Adi Ainawalid sow *hanfetz* of *shahan* wheat and *burguda* barley in a ratio of 1:1. However, because the proportion of wheat gradually increases after two or three plantings, harvested mixtures vary from 1:1 to 7:3 (wheat:barley). These proportions are comparable to those observed on the Greek Island of Amorgos where the composition of wheat:barley mixtures varied from 1:4 to 4:1 (Jones and Halstead 1995). According to farmers in Adi Ainawalid, growing *hanfetz* affords several advantages, including the production of generally higher yields, and the wheat prevents the lodging of barley. Farmers stated that competition between wheat and barley seedlings results in stronger individual plants with higher yields of both grain and straw. Some reported that the presence of barley reduces the occurrence of smut in wheat. Farmers also commented that *hanfetz* flours produce better quality *taita* (also known as *injera*) and bread used in making the fermented beverage known as *sua*. The mixed crop is sown, harvested, threshed, and winnowed together, followed by hand separation of barley, which is then pounded to remove hulls. Women were observed to spend long hours hand-sorting grains of threshed *hanfetz*. If the wheaten bread known as *embasha* is needed, the wheat grains must be fully separated by hand from barley. Several farmers emphasized that the practice of growing bread wheat-barley mixtures is relatively recent, whereas the “more ancient” method involves mixtures of emmer wheat and *burguda* barley (D'Andrea et al. 1999; D'Andrea and Haile 2002; Butler and D'Andrea 2000). Adi Ainawalid farmers noted that in the recent past they used to cultivate other *hanfetz* mixtures including *tselimo* wheat and emmer.

At the villages of Adi Hana and Mai Kayeh, located approximately 50 km south of Mekelle, farmers were actively growing emmer as a monocrop and in diverse mixtures involving two or more cereal crops (D'Andrea et al. 1999; D'Andrea and Haile 2002; Butler and D'Andrea 2000). Farmers informed us that they cultivated emmer as a monocrop and intercropped with *burguda* and *sasae* barley and *shahan* wheat. The proportions of *shahan*:emmer varied from 1:1 to 2:1. Because *shahan* wheat has a higher market value, farmers aim for a 2:1 ratio. Others suggested that the 2:1 ratio produces a higher quality flour for bread-baking. Women will either add *shahan* wheat or remove emmer by hand-sorting to achieve the desired ratio and the grain mixtures

are ground together. Emmer is also interplanted with *burguda* barley with ratios varying from 2:1 (*burguda*:emmer) to 1:1. In cases where three crops are interplanted, the preferred proportions are 2:2:1 (*burguda*:*shahan*:emmer), and such mixtures can involve more than one barley landrace.

The benefits of maslins as expressed by farmers, along with the global breadth and time depth of maslin agriculture across a wide variety of climates, suggest that maslin cropping systems may present a promising and understudied agroecological intensification technique. Examples from Ethiopia, Eritrea, Georgia, Greece, India, and elsewhere demonstrate a wide range of ways that diversity is leveraged by farmers in maslin agriculture, with examples in Ethiopia of multiple varieties of bread wheat, emmer wheat, and barley all growing as a single crop, and over a dozen different unique types of maslins in Georgia alone. Despite this variation across cultures, most farmers, in addition to mentioning other benefits, consistently described maslins as a risk-tolerance strategy to ensure a yield under a range of environmental conditions—a potentially important characteristic when faced with extended droughts, increased extreme weather events, and other consequences of climate change.

3 Agronomy and ecology of maslins

Various mixed cropping systems have demonstrated benefits to productivity, pest control, ecosystem services, resource use efficiency, and other attributes (Malézieux et al. 2009; Mao et al. 2015) that may be important in adapting to climate change (IPCC 2022). Field trials measuring maslin performance compared to their monocropped components generally corroborate farmer perceptions of the maslin mixtures having increased yield advantage, yield stability, drought tolerance, and pest and weed resistance. The mechanisms underlying the increased performance of maslins have long been a topic of interest. Over a hundred years ago, Warburton (1915) asked, “Just why a mixture of barley and oats, for instance, is quite likely to yield more pounds of grain to the acre than either crop when sown alone.” Insights from varietal mixtures provide useful perspectives in formulating hypotheses about why maslins may possess some of these characteristics. Here, we consolidate the results of agronomic trials comparing maslins and monocultures, and discuss the purported mechanisms underlying performance differences.

3.1 Yield advantage and yield stability

Climate change is anticipated to simultaneously lead to a reduction in arable land area and an increase in the unpredictability of environmental conditions faced by crops, increasing the importance of yield advantage and yield stability in cropping systems. Field trials provide evidence of cereal

mixtures overyielding—producing a yield higher than the average yield of their components grown in monoculture. Experimental cereal mixtures have been shown to have increased yield compared to sole-cropped components in a number of experimental studies (e.g., Taylor 1978; Clark 1980; Fejer et al. 1982; Jokinen 1991a; Woldeamlak et al. 2001; Kalinina et al. 2014; Kholzakov et al. 2014; Sobkowicz et al. 2016; Olenin et al. 2017; Klima et al. 2020). In a field trial with Eritrean *hanfetz* (wheat and barley), the maslins outperformed sole-cropped wheat and barley by 20% and 11% respectively and yielded a higher quantity of flour per unit compared to pure barley (Woldeamlak et al. 2000). A separate 3-year study of Eritrean *hanfets* found that on average, the area under monoculture cultivation would need to increase by 50% in order to produce the same yield as the mixtures (Land Equivalence Ratio, LER of 1.51) (Woldeamlak et al. 2008a). Under dryland farming conditions in India, wheat and barley mixtures produced higher grain yield and longer and more heads compared to sole cropped alternatives (Prasad et al. 1988). In a 6-year study, Zavitz (1922, 1927) compared different combinations of oats, barley, and wheat with sole cropped equivalents and observed 117% of the sole crop yield for barley and oats, 118% for wheat with oats, 104% for wheat with barley, and 123% with all three. In a three-way wheat-oat-barley mixture, Jensen (1952) reported 98–123% efficiency.

Yield stability is the capacity of a crop to provide consistent outputs (at high or low yield) across different environmental conditions, a trait essential in the adaptation to climate change (Olesen et al. 2011) and especially important for smallholder farmers (Madembo et al. 2020). In interfamilial species mixtures (Raseduzzaman and Jensen 2017) and intraspecific variety mixtures (Reiss and Drinkwater 2018), including cereal variety mixtures (Creissen et al. 2016), mixed cropping can demonstrate improved yield stability compared to sole-cropped equivalents. Yield stability advantages have also been observed in maslins. Woldeamlak et al. (2005) found that the mean yield of wheat-barley mixtures was 115.4% that of sole barley and 135.9% of that of sole wheat with a standard deviation intermediate (0.277) between barley (0.192) and wheat (0.303). A 3-year multi-site study testing both traditional and experimental Eritrean wheat and barley maslins found that the most stable yields were from species mixtures, but that not all mixtures were more stable than their components grown in monoculture (Woldeamlak et al. 2001, 2008a).

3.2 Ecological mechanisms influencing maslin performance

The enhanced performance of maslins relative to their components grown in monoculture is likely driven by combinations of mechanisms including the sampling effect, response diversity, complementarity, and facilitation. The role of these

mechanisms in diversity-based cropping practices such as multi-family polycultures and varietal mixtures has long been established but remains understudied in the context of intrafamilial cereal mixtures. Farmers take advantage of the sampling effect (Loreau and Hector 2001) by incorporating many species and/or varieties into cereal species mixtures (Ruelle 2015), increasing the likelihood that they will include a highly productive component in their maslins. The high levels of genetic diversity that farmers maintain within maslins may correspond to diversity in how components respond to a stressor in the environment. Two species responding differently to the same change in environmental conditions can ensure that one component survives (Yachi and Loreau 1999; Tilman 1999). Van Noordwijk and van Andel (1988) provide the example of Sudanese farmers growing a mix of rice and sorghum in an area that floods unpredictably. With rain, only rice grows in the flooded zone, and only sorghum grows under drier conditions. Analogously, in Eritrean wheat-barley maslins (Woldeamlak et al. 2008a) observe that “in dry years the *hanfets* exploits the better drought resistance of barley, while in wet years it exploits the higher yield potential of wheat.” Not only are farmers able to harvest components that survive, but response diversity also enables the maslin to adapt to strong selective pressures such as drought (Fig. 3). Differential tolerance to salinity, alkalinity, and drought in wheat and barley is believed to have driven the performance of traditional wheat and barley maslins in India (Prasad et al. 1988). Whether farmers replant the previous year’s maslin or deliberately add in new genetic diversity at the beginning of every planting season will influence the response diversity of the mixture. Maintaining high response diversity should result in a maslin that adapts over many years to the different pressures of each growing season, such as drought, fungal disease, and insect pests.

In the absence of stressors, species mixtures can produce more biomass through complementarity in components’ resource requirements (Fridley 2001; Mao et al. 2015). Plant species differing in resource use can not only exploit resources more completely than a single species in monoculture but may experience less competition from their interspecific neighbors than they do when competing with conspecifics in a monoculture (Woldeamlak et al. 2001). Woldeamlak et al. (2006, 2008a) attribute yield increase in Eritrean wheat-barley mixtures to niche differentiation due to variation in plant height, root depth, and phenology, which allows more efficient use of light and belowground resources spatially and temporally. As with some other mixtures (Morris and Garrity 1993), if maslins are indeed more effective at extracting nutrients and/or water from the soil, this could come with the consequence that these resources would need to be replenished through additional inputs, rotation, or extended fallow periods compared to monocropped components, an implication that warrants further research.

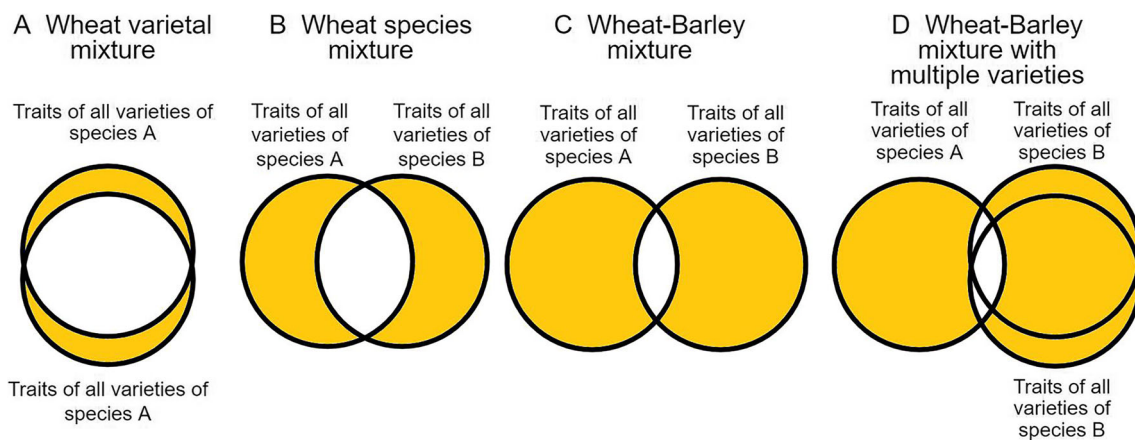


Fig. 3 Hypothetical trait portfolios available for different types of mixtures. Circles show an idealized depiction of all possible variations in traits to choose from across types of mixtures and overlap in traits available. Filled areas indicate the hypothetical extent to which variation in traits is available between components. Wheat varietal mixtures (**a**) would hypothetically have a smaller range of distinct traits to draw from when formulating mixtures compared to wheat species

mixtures (**b**). Intergeneric species mixtures (**c**) involving more functionally divergent components like wheat and barley would have still greater distinct trait variation to draw on. The varietal, intrageneric, and intergeneric maslins are not mutually exclusive, and combinations of different types of mixtures could further expand access to useful trait variation (**d**).

Woldeamlak et al. (2001) further assert that barley's early establishment of biomass and high leaf area serves to suppress weeds and decrease evaporative water loss from the soil, helping wheat establish its biomass later in the season. Facilitation—one species or variety altering the environment to the benefit of another (Fridley 2001)—may also play a role. Lodging resistance afforded to barley by the sturdy wheat stems later in the growing season likely plays a role in overyielding (Woldeamlak et al. 2001). Farmers have also observed rye physically supporting wheat in wheat-rye maslins (Picton 1937; Forte 2010). A barley-oat maslin grown in Scotland that overyielded had barley with more tillers and oat with heavier grains than in its respective monocultures (Taylor 1978). Complementarity was thought to have allowed the barley to tiller early in the season, and barley may have facilitated the increase in oat height that led to better light access and heavier grains. Further mechanistic experiments are necessary to tease apart these various potential drivers of higher yields in maslins.

Due to plastic responses of components grown in mixtures, yield advantage benefits may sometimes only be revealed under certain conditions, for example under abiotic or biotic stress (Karjalainen and Jokinen 1993; Woldeamlak et al. 2008a; Sobkowicz et al. 2016), suggesting the need for further trials in a wide range of environmental contexts. Although farmers commonly grow maslins to ensure a harvest despite limited rainfall or infertile soil, many of these agronomic trials provide examples of maslins overyielding even when grown with irrigation and fertilizers (Szemplinski and Budzynski 2011) or at different field sites (Jokinen 1991). However, several studies report maslins overyielding in certain environments and underyielding in others (Woldeamlak et al. 2001, 2008a). Indeed, maslins evolve in response to selective pressures from farmers and the dominant abiotic and biotic

stressors at their locales. Mismatch between the dominant stressors at an agricultural experimental station and the stressors at smallholders' farms may be driving some of the variability in maslin performance in the literature. For example, experiments conducted in fertile soil with ample water might not reflect the yield benefits perceived by farmers in Greece, India, Eritrea, and Ethiopia. In addition to growing conditions, competition between the components of maslins is another factor that may cause them to overyield only slightly or produce slightly less than the most productive component in monoculture (Juskiw et al. 2000; Sobkowicz et al. 2016). Studies centered around specific abiotic and biotic stressors demonstrate the context-based advantages of maslins.

3.3 Drought tolerance

Increased frequency and severity of drought is anticipated due to climate change (IPCC 2022). Mixtures of wheat and barley allow farmers to harvest the more drought-tolerant barley if the wheat fails. This strategy of mixing to ensure the harvest of the more drought-tolerant component is also used by farmers growing mixtures of sorghum and rice in Sudan (van Noordwijk and van Anandel 1988). Interactions between the wheat and barley plants in the mixture can result in the mixture being more drought tolerant than monocultures of its components. Woldeamlak et al. (2001, 2006) conducted a drought experiment and found that the yields of wheat and barley mixtures did not differ significantly between the drought treatments and controls. Mixtures overyielded under both drought treatments (drought stress at the seedling stage and at the heading stage). The authors suggested that the mixture overyielding may have been the result of the late-maturing wheat continuing to take up water after the barley

had matured, allowing the mixture to use soil moisture more completely than its components in monoculture. By calculating coefficients of competition at different stages of growth for a wheat and barley maslin, Molla and Sharaiha (2010) confirmed that barley is competitive earlier than wheat, but that wheat becomes more competitive than barley when the wheat nears maturity. The experiment predicted that this niche complementarity would enhance the maslin's water use efficiency. Studies that directly compare the performance of maslins to the performance of their components in monoculture under drought are needed to extend these predictions to measurements of yield.

3.4 Pathogen and pest resistance

Pest and pathogen ranges are anticipated to change dramatically in response to shifts in climate (Battisti and Larsson 2015; Bebber 2015). A number of studies report cereal mixture resistance to fungal pathogens, particularly in oat-barley maslins. In studies of joint sowing of rye, wheat, and triticale, mixtures significantly reduced the incidence of leaf blotch, glume blotch, and fusarium foot rot (Boliłowa et al. 2017, 2018). A nine-year study of oat-barley mixtures indicated much reduced fungal disease pressure in both species (Kurowski et al. 2007), a similar trend to that observed earlier by Clark (1980) who found barley in barley-oat mixtures to have up to 50% lower severity of spot blotch (*Cochliobolus sativus*) compared to sole cropped barley. Karjalainen and Jokinen (1993) found that oat-barley maslin plots had less leaf area affected by barley scald disease (*Rhynchosporium secalis*) than plots of the components grown in monoculture. There is reason to believe that maslins would possess the capacity for increased pathogen resistance based on the same mechanisms at work in varietal mixtures. In varietal mixtures, plants from a resistant variety can physically block the pathogen from moving to susceptible plant hosts, and can also serve to decrease the overall density of susceptible hosts (Finckh et al. 2000; Faraji 2011). Indeed, in a wheat-barley maslin, reducing the density of susceptible hosts decreased the prevalence of powdery mildew (*Blumaria graminis*) in comparison to its prevalence in pure stands (Burdon and Chilvers 1977). However, powdery mildew has also been found to track the proportion of barley in wheat-barley maslins (Burdon and Whitbread 1979). In a field experiment planted in Canada, the leaf area affected by fungal disease did not differ between wheat and barley maslins and their corresponding monocultures (Pridham and Entz 2008). A 4-year field experiment measuring fungal pathogen prevalence in barley-oat, barley-wheat, and barley-wheat-oat maslins concluded that resistance to fungal disease is variable and linked to component identity (Vilich-Meller 1992; Vilich 1993). The advantages derived from species diversity were found to be approximately equivalent to the protection offered by the fungicide

treatments available at the time. The mixed results for wheat-barley maslins and evidence supporting the advantages of oat-barley maslins highlight the critical role of plant identity in maslin performance under pathogen pressure.

Maslins should offer some resistance to insect pests and insect-vector viruses, based on evidence from the varietal mixture literature. A large body of work has examined the impact of varietal diversity and insect pest pressure, finding advantages (Tooker and Frank 2012; Shoffner and Tooker 2013; Reiss and Drinkwater 2018) and a relationship that is context-dependent (Smithson and Lenné 1996; Snyder et al. 2020; Dahlin et al. 2020). For viruses that are transferred when the vector feeds for a sustained period of time, a mixed stand of preferred and non-preferred host plants can increase the vector's movement, decreasing the chances of it passing on the persistent plant virus (Power et al. 1991). Just as varietal diversity does not always confer resistance to insect-vector viruses (Karjalainen and Peltonen-Sainio 1993) or insect pests (Mansion-Vaquie et al. 2019; Grettenberger and Tooker 2020), cereal species mixtures' resistance is likely dependent on host plant identity, insect species behavior and virus identity. Experimental studies of species mixtures are needed to elucidate the relationship between intrafamilial diversity, insect pest pressure, and virus resistance.

3.5 Weed resistance

Climate change is anticipated to continue to lead to rapid range shifts of weedy species (Peters et al. 2014). Meanwhile, input-intensive chemical weed control has contributed to pollution in farmlands and waters (Vonk and Kraak 2020). While weed suppression recorded in varietal mixtures has been limited (Kaut et al. 2009; Lazzaro et al. 2018), some species mixtures appear to have weed suppression capability compared to pure stands (O'Donovan et al. 1985; Kaut et al. 2008; Szemplinski and Budzynski 2011; Buczek et al. 2012; Kalinina et al. 2014; Kholzakov et al. 2014). Mechanisms for this suppression have been attributed to niche complementarity across components, with limited empty niches available for weeds. For example, barley's rapid growth during the early season is thought to occupy the niche of some weedy species while not competitively excluding wheat, and even facilitating the growth of wheat in the mixture (O'Donovan et al. 1985; Cousens 1996). A similar mechanism was proposed by Woldeamlak et al. (2008a) to explain farmers' observations that wild oats are less abundant in maslins than in pure stands. Weed suppression or competitive ability in maslins may be an area of particular interest, with promising experimental data indicating that increased functional diversity may allow them to suppress weeds to a degree that is more difficult to accomplish with varietal mixtures. Additionally, in conditions of heavy weed pressure, maslins are compatible with the use of dicotyledon-specific herbicides, unlike in cereal-legume

intercropping systems. This characteristic may make this strategy more readily adopted by industrial production systems.

Direct evidence for yield advantage, yield stability, fungal pathogen resistance, and weed suppression in maslins is promising but remains relatively limited compared to research on varietal mixtures. Studies have begun to address maslin performance in response to viral pathogens and drought, but have yet to examine their role in the management of insect pests. However, insights from experiments with varietal mixtures may be translatable, as similar mechanisms such as niche partitioning, facilitation, and response diversity likely underlie maslin performance advantages over monocrops. Future studies must address the many sources of variability in maslin performance. They must use varied species, varieties, and environments to develop maslins as an actionable agroecological strategy for farmers.

4 Maslins compared to other mixed cropping practices

Monocultures, varietal mixtures, and interfamilial polycultures are often conceptualized as a continuum with a series of tradeoffs between services such as nutritional diversity, ease of implementation, labor saving, and yield (Snyder et al. 2020). However, species mixtures including species in the same family or genus such as maslins are often underrepresented in such schemata and may represent an intermediate strategy that balances tradeoffs. This intermediate status, along with unique properties such as the potential to passively shift species composition from year to year based on environmental stressors, makes maslins a promising climate-resilient cropping strategy for further investigation.

4.1 Balancing trade-offs and expanding trait portfolios

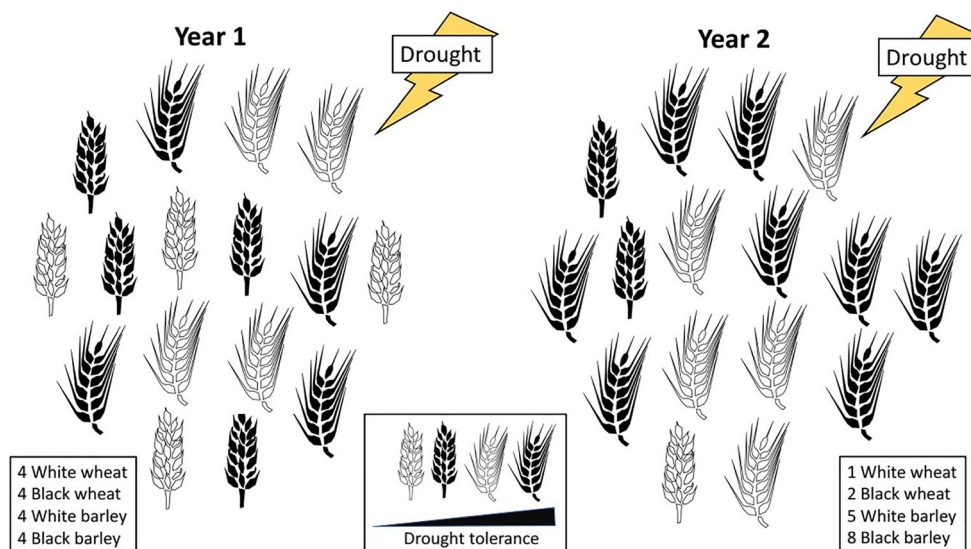
Given the potential for the greater functional distance between mixture components in maslins compared to varietal mixtures, one may expect a different suite of trade-offs than varietal mixtures or interfamilial polycultures. Certain cereal varietal mixtures with complementary traits have demonstrated benefits to yield advantage, yield stability, and disease tolerance compared to their monocultures (Creissen et al. 2016; Barot et al. 2017; Borg et al. 2018). Adding confamilial species as options for mixtures expands the breadth of the available trait portfolio when designing mixtures (Fig. 4), possibly augmenting the potential for agronomic benefits or nutritional diversity. At the same time, the relative homogeneity of intrafamilial small grain mixtures compared to interfamilial mixtures may lessen some of the tradeoffs often present in the latter. For example, interfamilial mixtures often involve additional labor and/or difficulty of mechanization (Reiss and Drinkwater 2018; Snyder et al. 2020). Farmer practices from Ethiopia

(Ruelle 2015), Eritrea (Woldeamlak and Struik 2000), and Georgia (Naskidashvili et al. 2013) demonstrate that the strategies of varietal and interspecific mixtures do not need to be mutually exclusive. In some cases, these mixtures contain diversity at varietal, species, and generic levels as in the example of Ethiopian *duragna*, which may contain not only a single barley and bread wheat, but often multiple species and varieties of wheat along with multiple varieties of barley. Future work explicitly characterizing the trade-offs present across categories, and the potential to leverage multiple types of the mixture in the same maslin would help clarify the viability of maslins for coping with climate change, improving performance, and reducing inputs.

4.2 Potential for species composition shifts to buffer multi-year stressors

While maslins may be intermediate between varietal mixtures and multi-family polycultures, they may also possess unique characteristics, like the ability to passively shift species composition in response to environmental conditions, tracking multi-year trends. Wild grasslands can shift in species composition when exposed to stressors in a way that buffers impacts on net primary production (Liu et al. 2018), and given that many farmers in Greece (Halstead and Jones 1989), Ethiopia (Ruelle 2015), and Eritrea (Woldeamlak et al. 2008a) do not readjust mixture proportions from season to season, a similar effect may be possible with maslins. Experiments tracking the composition of wheat-barley and barley-oat maslins report consistent increases in the frequency of barley in the maslins after harvest, possibly in response to weeds and abiotic stress (Kaut et al. 2008, Jokinen 1991). The underexplored adaptive capacity of maslins, as well as the shift of varieties in varietal mixtures across years, have implications for climate change-resilient farming. Under this passive strategy, the biotic and abiotic conditions present in a given year would alter the proportion of seeds harvested from a given component and used to plant the following year's crop. This ecological shift in the maslin plant communities could potentially buffer the impact of multi-year stressors, such as droughts. For example, if a mixture comprising two components, one with relatively higher drought tolerance, is grown over the course of a 2-year drought, one would expect the drought tolerant component to represent a relatively high proportion in the mixture, predisposing the mixture to greater success against the drought the next year. Mixtures involving multiple varieties in addition to multiple species, may augment this effect, with evolutionary shifts in genotypes accompanying ecological shifts in species (Fig. 3). However, in cases where mixtures have gradually shifted proportions tracking a stressor such as a drought over multiple years, and then face dramatically different conditions (e.g., a wet year), this effect may have the alternative impact of making the mixture relatively maladapted for a period after the change

Fig. 4 Hypothetical example of component ratios in maslins passively shifting in response to stressors over multiple years. Barley icons have long awns and a curved rachis while wheat icons are depicted with short awns and loose heads. After the first drought year, the farmer harvests a different ratio of components than were sown that favors drought-tolerant components. The following year, the farmer plants the mixture in the modified ratios as harvested, potentially buffering the impact of another drought year on the mixture's productivity.



in conditions. This phenomenon in maslins, like composition shifts tracking multi-year stressors in general, has not been investigated but warrants further study.

Plant species within polycultures of non-cultivated plants increase in complementarity over time, leading to higher biomass production (Cardinale et al. 2007, Fargione et al. 2007). Our current understanding of farmers' willingness to let maslins evolve suggests that a similar increase in the complementarity of maslin components over time is possible.

Maslins may present a unique complement to varietal mixture and interfamilial mixture cropping systems for sustainable and agroecological intensification. Access to an expanded portfolio of traits may add flexibility to the formulation of cereal mixtures, allowing for combinations of biotic and abiotic tolerance traits, unattainable with varietal mixtures alone, while not presenting the same trade-offs present in more functionally differentiated mixtures such as those involving cereals with legumes. At the same time, maslins may also possess unique properties, such as the ability to passively shift in species composition from year to year, tracking environmental pressures—a characteristic that warrants further exploration in the context of climate change phenomena such as multi-year droughts and temperature shifts on decadal scales.

5 Prospects for reviving maslin agriculture to confront climate change-related threats

Ethnographic, historical, ecological, and agronomic lines of evidence suggest the potential for maslins as an agroecological strategy for climate-change adaptation in smallholder and industrial agricultural systems. Farmer perspectives and experimental data from field trials point to a number of promising characteristics that align with many of the specific needs for agriculture to adapt to ongoing and predicted climate

change impacts (Table 1). While further investigation is required, especially into farmers' observations of resistance to arthropod predation and tolerance to poor soils, maslins could potentially be supported, revitalized, or scaled up as an agroecological intensification strategy. Implementation would require attention to the specific needs of smallholder systems and industrial systems, as well as environmental variation.

5.1 Considerations for implementation in smallholder systems

Introduction or reintroduction of maslin cropping may be of particular interest in the context of smallholder farmers, who often highly value yield stability. Globally, maslins have mostly persisted in smallholder settings with unpredictable growing conditions, where farmers see them as a strategy to ensure a harvest of staple carbohydrate crops under a wide range of potential precipitation, temperature, and pathogen regimes on relatively less land. Maslins provide redundancy in starch crops that are often staples—redundancy which is not always present in genetically uniform monocultures or multi-family polycultures. While unique in some ways, the intrafamilial mixture can be seen as an extension of the technique of planting varietal mixtures. However, while functional differences present in varietal mixtures may be sufficient to create significant benefits (Barot et al. 2017), smallholder farmers who may not have access to global germplasm may need to draw on species mixtures to capture the same functional breadth available to a breeder with access to a large number of varieties for mixing. Smallholder farmers whose cereal crops are also a source of fodder for livestock may be able to leverage maslins for improved fodder quality (Woldeamlak et al. 2001). While not as dramatic as in most multi-family polycultures, some maslins may also possess dietary complementarity important to smallholders. For

Table 1 Maslin characteristics aligned with the needs for agriculture to adapt to ongoing and predicted climate change impacts as outlined by the Intergovernmental Panel on Climate Change's Sixth Assessment Report (IPCC 2022).

Impact of climate change on agriculture	Ethnographic evidence of maslin benefits	Agronomic evidence of maslin benefits
Increased variability in rainfall, decreased water availability	Tolerance to water stress (Aiyer 1950; Prasad et al. 1988; Halstead and Jones 1989; Woldeamlak and Struik 2000; Woldeamlak et al. 2008a; Mosulishvili et al. 2021)	Tolerance to water stress (Woldeamlak et al. 2006; Molla and Sharaiha 2010)
Increase in pest and disease pressure	Resistance to pests and diseases (Halstead and Jones 1989; D'Andrea et al. 1999; Woldeamlak and Struik 2000; D'Andrea and Haile 2002; Butler and D'Andrea 2000)	Fungal resistance (Burdon and Chilvers 1977; Clark 1980; Vilich-Meller 1992; Karjalainen and Jokinen 1993; Vilich 1993; Pridham 2006; Kurowski et al. 2007; Pridham and Entz 2008; Lapshin and Byrkanova 2014; Boligłowa et al. 2018;)
Range expansion of weed species	Weed suppression and competitiveness (Woldeamlak and Struik 2000)	Suppression or competitiveness with weeds (O'Donovan et al. 1985; Kaut et al. 2008; Szemplinski and Budzynski 2011; Buczek et al. 2012; Kholzakov et al. 2014; Kalinina et al. 2014; Olenin et al. 2017)
Extreme weather events	Frost tolerance (Mosulishvili et al. 2021); Lodging resistance (D'Andrea et al. 1999; D'Andrea and Haile 2002; Butler and D'Andrea 2000; Forte 2010)	Lodging resistance (Woldeamlak et al. 2001)
Decrease in arable land area	Yield and yield stability (D'Andrea et al. 1999; Woldeamlak and Struik 2000; D'Andrea and Haile 2002; Butler and D'Andrea 2000; Woldeamlak et al. 2008a)	Yield (Warburton 1915; Zavitz 1922, 1927; Aiyer 1950; Syme and Bremner 1968; Taylor 1978; Clark 1980; Fejer et al. 1982; Prasad et al. 1988; Jokinen 1991a, 1991b, 1991c; Juskiw et al. 2000; Bishaw 2004; Sobkowicz and Tendziago 2005; Kara et al. 2010; Woldeamlak et al. 2008b; Kholzakov et al. 2014; Zając et al. 2014; Olenin et al. 2017; Klimek-Kopyra et al. 2017) Yield stability (Woldeamlak et al. 2001, 2005, 2008a, 2008b)
Reduced soil health	Tolerance of poor soil quality (Mosulishvili et al. 2021)	Tolerance of poor soil quality (Jokinen 1991; Araya et al. 2012)

example, barley tends to be relatively higher in fiber and riboflavin than wheat, but wheat is relatively high in vitamin B5 and manganese (USDA 2022).

Regions with marginal growing conditions and regions where traditional maslin farming has been abandoned for various reasons may be potential areas of focus for exploring reintroduction or promotion of this strategy. For example, some areas with maslin traditions such as northern India, East Africa, the Mediterranean, and highland Central Asia, are anticipated to face growing challenges to agricultural production due to climate-related threats such as reduced, and less predictable, precipitation (Mall et al. 2006; Tenge et al. 2013; Reyer et al. 2017; Abd-Elmabod et al. 2020), that may threaten the livelihoods of smallholder farmers, many of whom have converted to high-input monoculture cropping systems. Existing evidence from farmer interviews and agronomic studies suggests that maslins may be useful in addressing some of these issues, especially in rain-fed systems.

5.2 Considerations for implementation in industrial agriculture

Despite interconnected challenges to implementing diversification strategies in industrial systems across value chains

(Meynard et al. 2018), maslins may also present an opportunity for larger-scale and industrial farming systems to reduce inputs or increase yield stability in the face of climate change. The scaling up of more differentiated polycultures such as coffee agroforestry systems or maize-beans-squash systems involves unique challenges to mechanization (Snyder et al. 2020). While maslins may pose challenges, for example in phenological variability, the ability to separate grain species on an industrial scale has existed for many decades (Picton 1937). Another challenge, as in the case of varietal mixtures (Finckh et al. 2000), is consumer preference (Woldeamlak et al. 2001). In the 20th century, industrially produced white bread became tied to concepts of purity, hygiene, and progress in many parts of the world (Bobrow-Strain 2008), but specialty markets also exist for mixed-grain bread in many countries, which can have desirable properties (Tsvetkov et al. 2004; Aly et al. 2021) and a number of traditional breads are already commonly made with mixtures such as pumpnickel or pain de méteil. Mass-produced wheat breads often incorporate malted barley or oats, which are used to enhance loaf volume and nutrition (Mäkinen and Arendt 2012).

Opportunities to explore the implementation of maslin agriculture exist in smallholder and industrial agricultural contexts, especially in marginal growing conditions and under

low-input systems. For smallholders, increased yield stability and nutritional diversity potentially afforded by maslins could be provisioned by maslin cropping systems. Maslins could be particularly useful in areas anticipated to face the most extreme impacts of climate change. Maslin agriculture may also be compatible with larger-scale industrial agriculture and production due to the relative simplicity of mechanization compared to more differentiated polyculture systems. Specialty markets for mixed grain breads and the common practice of incorporating malted grains of several cereal species into commercial wheat bread indicate that maslins may also be compatible with producer and consumer preferences.

6 Conclusion

Maslins can be conceptualized as an intermediate strategy between varietal mixtures and multi-family polycultures that might be employed to balance trade-offs, while also possessing unique characteristics. Maslins represent an extension of and complement to cereal varietal mixtures in the sense that they expand the portfolio of traits available to farmers creating mixtures, while still potentially providing redundancy to ensure the harvest of staple crops. Meanwhile, the morphological similarity of maslin components likely makes their cultivation and harvest more similar to varietal mixtures than some multi-family polycultures, potentially facilitating harvest, processing, or mechanization of these tasks. Unlike varietal mixtures, maslins mimic multi-species grassland communities found in wild contexts and have the potential to shift species composition in response to stressors across multiple seasons, potentially preserving productivity in the face of multi-year environmental trends.

While varietal mixtures and multi-species polycultures have been presented as promising climate-resilient cropping systems, maslins represent an underexplored agroecological intensification strategy that leverages diversity to increase resilience to climate change while reducing reliance on inputs. Despite this possibility and maslins' historical depth potentially reaching back to the origins of agriculture and geographical breadth spanning Eurasia and North Africa, a concerted global effort to characterize and revitalize maslins has been limited, with literature heavily siloed by disciplines and languages. However, from the available literature on farmer experiences and agronomic trials, these interspecific cereal mixtures appear to possess the potential for a variety of desirable characteristics which may be advantageous in adapting cropping systems to climate change—including heightened yield advantage, yield stability, pest and pathogen resistance, weed suppression, and drought tolerance. These findings suggest that the preservation, as well as revitalization and introduction to new areas of maslins warrants further exploration on both

smallholder and industrial scales, especially in areas with marginal growing conditions.

A wide range of questions remain unanswered in regard to the agronomic and ecological aspects of maslins. For example, little is known about nutritional complementarity (Lapshin and Byrkanova 2014), potential for proportions of components to track multi-year environmental trends, capacity for carbon sequestration, performance of diverse mixtures under a wide range of conditions, ecological parallels to wild grassland communities, and ecological mechanisms underpinning performance differences. Maslin research is uniquely situated to draw on methods and theory developed from research on mixed cropping systems, for example, promising advances in modeling for annual crop polycultures (Gaudio et al. 2019, 2022) could be applied to contribute to the understanding and design of maslins. Clarifying these and other questions could elucidate the potential for maslins as a strategy for sustainable agriculture and climate adaptation.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s13593-022-00832-1>.

Acknowledgements We would like to thank Prof. Zemed Asfaw, Dr. Sarah Tewolde-Berhan, Dr. Asmare Dejen, and Dr. Feleke Woldeyes for support of our field research in Tigray and Wollo, Ethiopia. We are particularly grateful to Tesfanesh Feseha for her translation and cultural insights during fieldwork. For the case study in Enderta, we are grateful to the people of Adi Ainawalid, Adi Hana, and Mai Kayeh who consented to participate in our research, and Dr. Ann Butler for her important contributions to the project. We thank the Authority for Research and Conservation of Cultural Heritage (ARCCH) and the Tigray Culture and Tourism Bureau (TCTB) for granting permission to complete fieldwork in Eastern Tigray. For the case study in Debark, we thank farming families from Debir, Gomya, Kino Libanos, Koha Zebzeba, Mikara, and Zebena for sharing knowledge about their food systems. We are indebted to Amanuel Berhanie, Fekadu Alem, and Yohannes Desalegn for their many contributions as research assistants. Finally, we would like to thank Luwei Wang, Anya Osatuke, and Wang Bo for their translation of documents.

Authors' contributions Alex McAlvay, Anna DiPaola, Morgan Ruelle, and Alison Power jointly developed the conceptualization and overarching goals. Case studies were conducted and contributed by Catherine D'Andrea and Morgan Ruelle. Catherine D'Andrea, Marine Mosulishvili, and Paul Halstead contributed regional expertise and archaeological background on maslins to the ethnographic portion. Alex McAlvay and Anna DiPaola wrote the manuscript. All authors contributed to the revision of the final manuscript and approved the final version for submission.

Funding This research was supported by the McKnight Foundation's Collaborative Crop Research Program and the Cornell Atkinson Center for Sustainability. Research in Enderta, Ethiopia was supported by the Social Studies and Humanities Research Council of Canada (SSHRC), Grant No. 410-96-1520. Research in Debark, Ethiopia was provided by the National Science Foundation through a Graduate Research Fellowship (DGE0707428) and the Food Systems and Poverty Reduction Integrative Graduate Education and Research Traineeship at Cornell University (0903371), and the Toward Sustainability Foundation.

Availability of data and material All data generated for this project are included in the present paper and supplementary materials.

Code availability Not applicable.

Declarations

Conflict of interest The authors declare no competing interests.

Ethics approval The research in Enderta was carried out with permission from the Authority for Research and Conservation of Cultural Heritage (ARCCCH) and the Tigray Culture and Tourism Bureau (TCTB). The research in Enderta was carried out in 1996–1998, prior to the existence of ethics boards in Canada. The research in Debarq (North Gonder, Ethiopia) was carried out with permission from the Ethiopian Biodiversity Institute and the Debarq District administration. Interview protocols were approved by the Cornell University Institutional Review Board.

Consent to participate Free and informed prior consent was obtained from all research participants in Debarq, and Eastern Tigray.

Consent for publication Free and informed prior consent from research participants in Debarq and Eastern Tigray included consent to publish findings from the research project.

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