

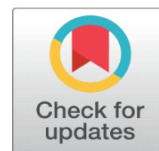
CONCEPT AND RATIONALE OF EVOLUTIONARY BARLEY BREEDING UNDER CLIMATE CHANGE IN JORDAN



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ABSTRACT

In this study, we reviewed the climate changing and the impact on crop production, and evolutionary breeding as adaptation key to crop resilience. The increasing climate change impact on the agriculture system has renewed interest to the broadest possible germplasm base for a resilient and sustainable food system. Heterogeneous populations developed through evolutionary plant breeding could be the ideal solution to reduce the effects of environment variability on cereal crop planted under low-input conditions. The study assessed the genetic basis of adaptation of a barley population which evolved in different rainfed locations and years in Jordan without any human selection as suggests model of plant breeding strategy to improve food security, nutrition, income and resilience of smallholder farmers in the dryland regions in the climate change scenarios. The study suggests that the breeder can shift the undesirable traits in evolutionary populations by practicing individual selection for specific adaptations, or individual selection from populations showing wide adaptations and high stability. On the other hand, the breeder can overcome the undesirable traits by keeping the highest variations within the population by seed sieving to remove small seed and plant mowing for tallest head.

Received 15 July 2021

Accepted 30 July 2021

Published 31 August 2021

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DOI

[10.29121/granthaalayah.v9.i8.2021.4122](https://doi.org/10.29121/granthaalayah.v9.i8.2021.4122)

Funding: This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

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Keywords: Barley, Climate Change, Evolutionary Population, Crop Adaptation, Crop Resilience.

1. INTRODUCTION

The Poaceae family (grasses) evolved 50–70 million years ago (Mya) Huang et al. (2002) Wang et al. (2011) and wheat, barley and oats grouped under the sub-family Pooideae which diverged around 20 Mya Inda et al. (2008), that found in the Fertile Crescent in the human Neolithic sites, which are dated to 8500 calibrated years (cal.) B.C. Badr et al. (2000), Diamond (2002), Salamini et al. (2002) Morrell et al. (2003), Willcox G. (2005), Feldman and Kislev (2007). The Fertile Crescent includes part of Jordan, Palestine, Lebanon, Syria, Southeastern Turkey, Iraq and western Iran. Barley (*Hordeum vulgare* L.), is one of the most important and earliest crops in Neolithic agriculture El-Hashash and El-Absy (2019), and barley grains have been found at various archaeological sites in the Fertile Crescent Diamond, J. (1998), Wang et al. (2011). Moreover, the Jordan valley in the southern part of the Fertile Crescent has the highest probability where the first domestication of barley may have taken place as suggested by experimental evidence Badr et al. (2000), Pankin et al. (2018). *Hordeum spontaneum* C. Koch is the barley wild relative, and in modern taxonomy, *H. vulgare* L. and



H. spontaneum C. Koch, as well as *Hordeum agriocrithon* A° berg, are considered subspecies of *H. vulgare* Bothmer and Jacobsen. (1985).

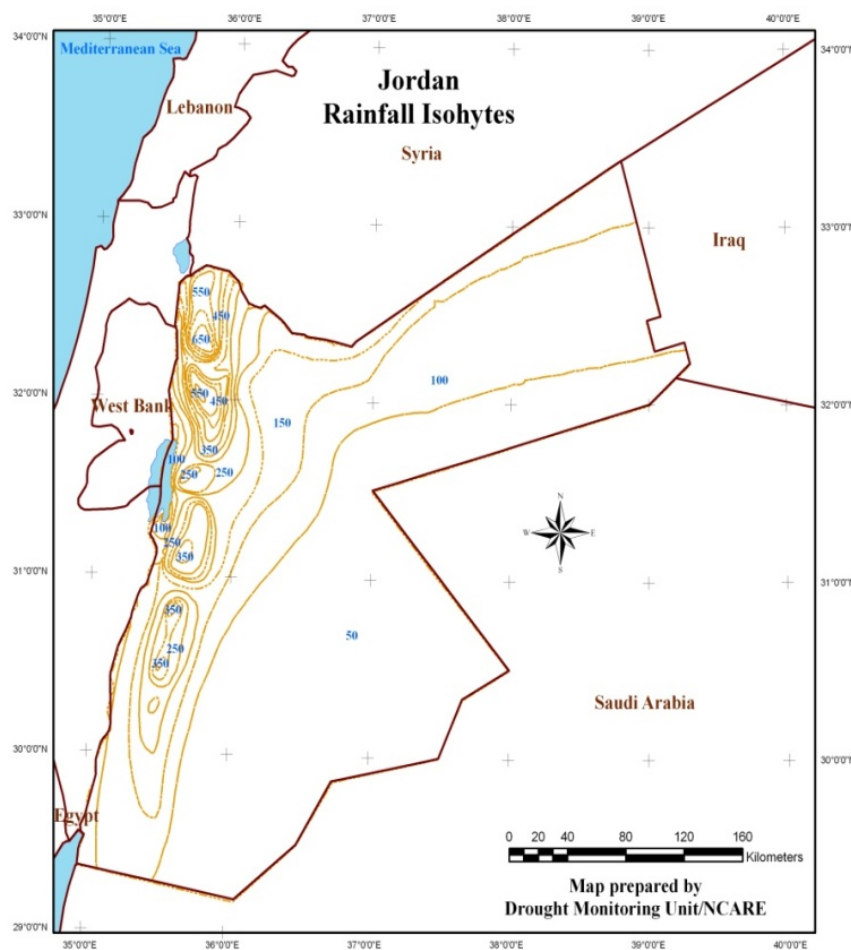
The greatest gigantic evolutionary experiment is the domestication of plants and animals, characterized by adaptation and speciation, and generating incipient species Darwin (1905). Cereal germplasm was domesticated through heavy selection pressure against unfavorable alleles related to time of flowering, naked seeds, rachis brittleness, and the size of seed traits Konishi et al. (2006), Pourkheirandish and Komatsuda (2007), Page and Chapman (2021). 20–30 years would be enough complete barley, einkorn and emmer wheat domestication under rudimentary farming practices, where it should be a rapid event Honne and Heun (2009), Peng et al. (2011). Spring barley type is a key of evolution event for post-domestication come from a predominantly winter ancestral state, which spread of temperate cereals Cockram et al. (2007), Marzougui (2021). Domestication produces cultivars characterized by human-dependency, and surviving only under human agricultural practices to meet his needs Gustafson et al. (2009), Nevo (2011). Therefore, the populations known as “landraces” are the first identified old breeding materials from domestication process Berthaud et al. (2001).

Barley (*Hordeum vulgare* ssp. *vulgare*) is cultivated globally, but its decrease in importance as food grain was due, in part, to the increased importance of wheat and rice. In recent times, 55%- 60% of the barley crop has been used for feed, 30%-40% for malt, 2% - 5% for food, and about 5% for seed Ullrich (2010). Barley subsequent wide migration provides outstanding evidence of adaptation to multi environments, agro-ecologies and uses Dawson et al. (2015). Barley is the predominant crop in the low-rainfall areas of the Middle East Hazell (2018), and is considered as one of the most important cereal crops in the Fertile Crescent, grown on around 5 million hectares Ceccarelli and Grando (2000). Barley landraces are mostly cultivated in marginal land, low-input system, and drought stress environment Ceccarelli (1984), Kumar et al. (2020), because of their heterogeneity and diversity provide stability of good yield in highly variable environments Ceccarelli (1994), Ceccarelli (1996), Azeez et al. (2018). Thus, the low-input or organic farming systems require a specific crop characteristic, for this reason they might have disappeared in the modern breeding materials targeted to high-input conditions Lammerts Van Bueren et al. (2005), Lammerts Van Bueren et al. (2011), Jalata (2011), Torricelli et al. (2014)

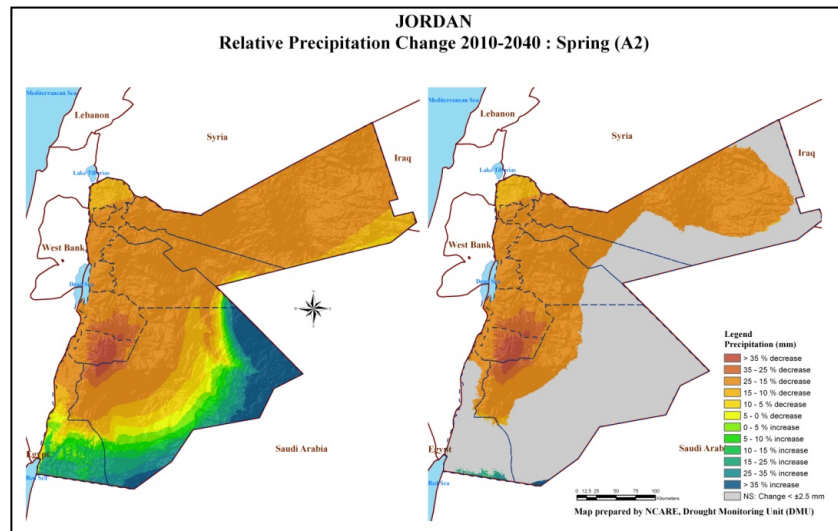
Adaptation is the key of Darwinian evolution outcome, that termed natural selection Diniz-Filho and Bini (2019), and heritable variation is the heart of evolution process. Improved varieties have limited capacity to evolve in response to adverse environmental conditions due to their genetic uniformity, and this is the opposite of what it has been done for millennia by the farmers. Furthermore, the unpredictable environmental fluctuations will dramatically increase due to climate change Murphy et al. (2013). Ceccarelli et al. (2013) emphasized that climate changes are a moving target for plant breeding. Evolutionary plant breeding (EBP), is the right strategy to deal with such challenge, while at the same time maintain and increase the agricultural biodiversity. In evolutionary populations (EP) of self-pollinating cereals, the natural selection operating upon the heterogeneous mixture of genotypes over generations and across environments and traits positively correlated to reproductive capacity, which increases over the time Suneson (1956), Allard and Hansche (1964).

Jordan is located about 80 km to the East of the Mediterranean Sea with a predominantly Mediterranean climate; hot and dry summers, and wet and cool winters. Jordan is also characterized by three distinct ecological systems: (i) the Jordan Valley which forms a narrow strip located below the mean sea level, and has

warm winters and hot summers with irrigation mainly practiced in this area; (ii) the western highlands where rainfall is relatively high and climate is typical of Mediterranean areas; and (iii) the arid and semiarid inland to the east (estimated to cover over 80% of the total area), known as the “Badia”, where the annual rainfall is below 50 mm. The spatial variation of precipitation is high and characterized by a general decrease from west to east and from north to south: temperature shows the same trend. Generally, the amount of rainfall and climatic conditions of the country do not support good rainfed agriculture. The rainfed agricultural zone is lying in areas where rainfall exceeds 250 millimeters although cereals production might be occurred in some areas where rainfall is between 200 and 250 millimeters (Map 1). Barley is cultivated in area where average rainfall is between 150 mm to 300mm; therefore, barley cultivation is facing challenges with more dry cycles and more frequent drought seasons, small farmers and herders are the ones who are the most affected. Finally, a number of studies emphasized the adverse effects of climate change in Jordan, where precipitation would be significantly decreased with a reduction in frequency and duration of rainy days as shown in Map 2, whereas temperature would be significantly increased Black (2009), Saba et al. (2014), Atashi et al. (2020). This will cause a reduction in crop yield and will threaten livestock sector.



Map 1 Jordan rainfall Isohyets



Map 2 Projected relative change map of Precipitation (2010 -2040) [Saba et al. \(2014\)](#)

Climate change effect renewed the interest in evolutionary breeding, which is based on a mass selection technique in heterogeneous populations of the crop [Murphy \(2005\)](#). A strong support to evolutionary plant breeding comes from the work of [Morran et al. \(2009\)](#) who proved that the adaptation of outcrossing population to environmental changes is more rapid than self-fertilizing organisms, therefore the majority of plants and animals reproduce by outcrossing as opposed to selfing [Crow \(1992\)](#), [Schlaepfer et al. \(2018\)](#). However, the self-pollinated crops even with outcrossing rates lower than 0.05 will be able to adapt to stress environments, such as barley and wheat (outcrossing rates as high as 0.07, and 0.035, respectively) [Morran et al. \(2009\)](#), [Wright et al. \(2013\)](#). Thus, different experiment provides a strong justification for evolutionary plant breeding to both self- and cross-pollinated crops.

2. CLIMATE CHANGE IN JORDAN

The global carbon CO₂ increased significantly in the atmosphere because of human activity, and our climate was affected negatively at an alarming and accelerating rate [IPCC \(1996\)](#), [IPCC \(2001\)](#). The landmark Fourth Assessment Report of the Intergovernmental Panel on Climate Change [IPCC \(2007a\)](#) concluded definitively that “[w]arming of the climate system is unequivocal” and goes to define a certain exception of pervasive effects of future climate change. One of the projections to the year 2100 was expected increase of CO₂ emissions by 400 % and the concentrations of CO₂ atmospheric by 100% ([Figure 1](#), modified from [Cline, 2007](#)) [Ceccarelli et al. \(2013\)](#).

The future and current climate change in the Middle East study related to precipitation suggested a drying weather also the dominant precipitation mechanism will be from directly driven by storm tracks to having a greater leading by upslope flow of moist air masses [Evans \(2010\)](#). [Evans \(2008\)](#) revealed from 18 global climate models that Middle East rainfall is expected to decrease significantly by the end of the 21st century. On the other hand, the future eastern Mediterranean region climate scenario suggests that the rainy season will become significantly

drier with reduction of the frequency and duration of its events, with potentially negative impact on the population [IPCC \(2007\)](#), [Black \(2009\)](#). These changes may be associated with decreased precipitation and increased evaporation, and water availability reduction in southern Europe and the Mediterranean as a result to changes of the Mediterranean storm track strength [Pinto et al. \(2007\)](#), [Mariotti et al. \(2008\)](#). Furthermore, [Kitoh et al. \(2008\)](#), concluded, based on a high-resolution global climate model in the Middle East, which the Fertile Crescent will disappear due to unbalance between precipitation and evaporation equation [Demircan et al. \(2017\)](#). The annual discharge will decrease significantly (29 - 73%) in Euphrates River, as the stream flow in the Jordan River will. The heavy hourly and daily precipitation frequency will increase in the future: the hourly heavy precipitation will increase by 99.9%, while the value of hourly precipitation will increase by 7% in the near future and by 21% at the end of the 21st century [Kitoh et al. \(2009\)](#).

Jordan had severe dry years during the last 30 years (1901- 2010). Moreover, the future precipitation projection (2010- 2025) assumed moderate reduction up to 15 days of the total precipitation period, the reduction will be from 15-30 days in north and central areas, and few areas will face reduction up to 30 days [Saba et al. \(2014\)](#). These results are consistent with published work by [Black \(2009\)](#) about Mediterranean storm track under future climate scenarios. According to vulnerability analysis carried by the National Communication (TNC) to UNFCCC (JTNC report 2014), Eastern and Southern areas and the North mountainous areas in Jordan are expected to have the highest exposure to the impact of climate change; as the vegetation type is the highest sensitivity component for climate change, therefore the impact of climate change expected to be in the northern highlands and across the Middle areas in Jordan especially the Jordan Valley. The annual precipitation trend decreases significantly with time at a rate of 1.2mm per year. The decreased was recorded mostly in the western part of the country. Simultaneously, the air temperature tends to increase significantly by 0.02, 0.01, and 0.03 °C/year, for mean, maximum and minimum, respectively. [Falloon et al. \(2007\)](#) emphasized the above result by his prediction that the rainfall will decrease by around 26.6mm and the temperature will increase by around 6.5°C during 2000-2100.

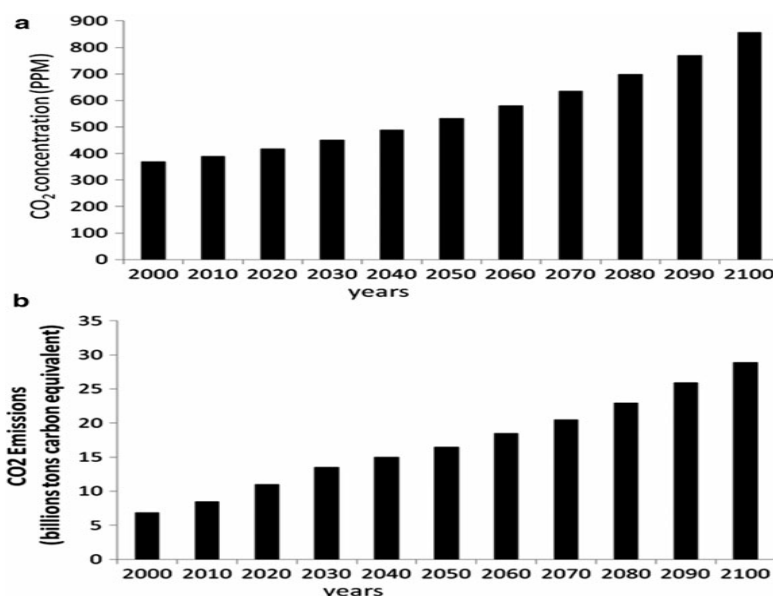


Figure 1 Projected atmospheric CO₂ concentration in parts per million CO₂ (a) and projected emission in billion tons carbon equivalent (b) (modified from Cline, 2007)

3. CLIMATE CHANGE AND CROP RESILIENCE

An increasing sense of urgency characterizes the local and global dialogue on climate change. Many evidence emphasized climate change existence, where the dry and wet regions will become drier or wetter as response to warming, respectively [Durack et al. \(2012\)](#), [Yang et al. \(2019\)](#). On the other hand, some studies have predicted the potential of climate change impact on increased extinction rate in natural ecosystem [Pecl et al. \(2017\)](#), [Sintayehu \(2018\)](#). As the agriculture sector is extremely vulnerable to climate change, climate change will adversely impact on food production and quality, [Atkinson et al. \(2008\)](#). The ecologically vulnerable zone included the arid and semiarid zones, and the mountains and hills that characterize by low- poor resources, highly heterogeneous, and where the majority of the world's rural poor live [Conway et al. \(1997\)](#).

The International Food Policy Research Institute estimated a 30%, 47%, and 20% crop yields reduction (to the year 2050) for rice, maize, and wheat, respectively, due to climate change [Nelson et al. \(2009\)](#). [Lobell et al. \(2008\)](#) validated this result. Adaptation to climate change is defined by the Intergovernmental Panel on Climate Change as “any adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities.” [IPCC \(2007\)](#). Agriculture adaptation to climate change can include spontaneous adaptations [FAO \(2007\)](#) to encompass research improvement, genetic improvement, increase crop diversity resulting in improved crop performance under climate change [Newton \(2009\)](#).

Ongoing climate change included droughts and other anticipated changes which has potent selective factors [Franks et al. \(2007\)](#), that can impose natural selection to buffer species using phenotypic plasticity to tolerate the habitat degradation based on evolutionary shifts [McCairns et al. \(2016\)](#). These shift provide good opportunities to study how natural populations undergo adaptive evolution. Farmers since millennia used his way to act the natural selection in harsh environments to make autonomous adaptations on a crop, such as barley in the Fertile Crescent [Ceccarelli and Grando \(2000\)](#), [Ceccarelli et al. \(2007\)](#).

4. IMPORTANCE AND UTILIZATION OF EVOLUTIONARY PLANT BREEDING

Evolutionary breeding (EB) generates plant populations defined as Suneson, 1956 as ‘core features are a broadly diversified germplasm, and a prolonged subjection of the mass of the progeny to competitive natural selection in the area of contemplated use’. It's created through saving and re-sowing seed in bulking over several plant generations, therefore as Darwinian selection where the plant population reproductive fitness physical mixing will be gradually increases [Döring et al. \(2011\)](#), [Lammerts et al. \(2018\)](#). Evolutionary Plant Breeding can make use of populations such as Composite Cross Populations (CCPs) or of varietal mixtures; the difference is that CCPs are created by crossing while mixtures are created by mixing seed of existing varieties [Döring et al. \(2011\)](#). Therefore, CCPs and varietal mixtures have been named ‘modern landraces’ where they are similar to traditional landraces on creating and purpose of creating [Carolina et al. \(2005\)](#), [Murphy et al. \(2005\)](#).

The idea of plant evolutionary breeding is not new. Harlan and Martini created the composite cross (CC) method for breeding barley in 1929 [Harlan and Martini](#)

(1929). The method relies on bulking the F1 progenies to generate a heterogeneous population of recombinant genotypes; where F1 progenies obtained by hybridization of diverse origin varieties and genetic make-up. In 1956, 'evolutionary plant-breeding method' idea has been improved and proposed formally by Suneson (1956). Using this breeding method, nine barley CCs were registered by Suneson, (1969), and intended to be used as parental populations (PPs) to generate a new variety, and also as research material for the population genetics studies Suneson, (1956). Recombination and segregation in the populations is the key for the success of such a breeding method, and the extent to survival mass-propagated populations over many generations is positively correlated with agricultural value Allard and Hansche (1964).

The key science in improving crop production is plant breeding, which has contributed an estimated 50% to increased agricultural productivity Ceccarelli (2015), Qaim, 2020). High and stable crop yield are an important goal in plant breeding Johnson (1977), Lammerts et al. (2018). In March 1968, "Green Revolution" term coined by William S. Gaud indicated a development strategy in which mainly self-pollinated crops varieties were produced commercially with high genetic uniformity, due to their high production and wide geographic adaptation Soliman and Allard (1991), Ceccarelli (2009), Pingali (2017), rather than wide 'environmental' adaptation Ceccarelli (2009). In addition, these varieties had poor performance under marginal environments or without the external inputs Ceccarelli (1996), Mustafa et al. (2019). Therefore, around 1.4 billion people who lives in marginal agricultural environments and limited use of external inputs, and poor farmers are depending on traditional agricultural systems Ceccarelli (1996), Murphy (2005). Modern plant breeding produces a small number of varieties for major crop and for high input conditions, with a reduction in agrobiodiversity and a threat to global food security for some crop cultivated in the regions affected by climate change with a negative impact on agriculture Nelson et al. (2009), Ali et al. (2017).

Since a few decades, the interest for agrobiodiversity has started to be "re-discovered" all over the world, and is still growing up, and mainly for organic and low input agriculture. Diversity is recognized as important s for disease and pest management, to mitigate abiotic stresses, and to increase productivity and long-term stability of the system Hajjar et al. (2008), Morales-Castilla et al. (2020). Serpolay-Besson et al. (2014) conclude OPVs (open pollinated varieties) are evolving quickly due to their genetic heterogeneity under the combined effect of human and natural mass selection in organic and low input conditions. This result was emphasized by Pixley (2006), in comparing yields of OPVs (7%) and hybrids (20%) in a meta-analysis, however this difference was reduced in the "marginal environments" where the performance of heterogeneous varieties was relatively better. These environments can be described by: high variability in mean of time and space, low fertility, and subjected to high stress (drought, cold...etc) in general Ceccarelli (1994). Ceccarelli and Grando (2000) validate this result, where natural selection act in harsh environments on a crop as example the Fertile Crescent, where farmers cultivate predominantly heterogeneous barley populations rather than a small number of genotypes with superior adaptation. Here, the landraces carry a lesson about its structure; that represent an evolutionary approach to keep it survival and good performance under arid and semiarid conditions Schulze (1988), Lodhi et al. (2020). Interestingly, a study comparing barley landraces and modern cultivars showed that landraces yielded on average 60% more under stress, whereas modern cultivar yielded on average 14% more when the stresses absent Ceccarelli (2015), Cantalapiedra et al (2017).

EBP offers a great possibility of reconciling agro-biodiversity; also it can contribute to cropping systems development with yield stability and greater resilience in the environment variability [Döring et al. \(2011\)](#), [Barot et al \(2017\)](#). Despite Robert W. Allard and co-workers [Allard and Adams \(1969\)](#), [Allard \(1988\)](#), [Jain and Allard \(1966\)](#) make a prolific research about EBP, this technique has never been used in commercial breeding practice [Phillips and Wolfe \(2005\)](#). [Frey and Maldonado \(1967\)](#) suggested that the benefit of heterogeneous cereal population will be more obvious in resource-limiting environments [Murphy et al. \(2013\)](#), [Merrick et al. \(2020\)](#). [Soliman and Allard \(1991\)](#) validate this result by make a comparison between barley composite crosses with commercial cultivar across a range of marginal environments that showed significantly yield stability for CC. The most effective way to increase EP grain yield is by expose it to constant and directional selection pressures [Degago and Caviness \(1987\)](#), [Murphy et al. \(2013\)](#).

Ongoing climate change can impose natural selection on certain ecologically important traits that in turn will be affected the ecological dynamics of many plant species. The consequence of operating the natural selection on phenology, imposed by climate change, is evolutionary shift based on genetic [Franks et al. \(2007\)](#), [Bemmels and Anderson \(2019\)](#). Crops phenology is very important in relation to drought tolerance allowing the crops to complete their life cycle before the onset of drought [Baum et al. \(2003\)](#). Therefore, it's one of the main adaptations traits to adapt to climate change. In addition, the theory of selection shows that decentralized (i.e., selection conducted directly in the target environment) is more efficient than centralized in terms of response to selection [Simmonds \(1991\)](#), [Ceccarelli \(2015\)](#). In participatory plant breeding (PPB), defined as collaboration between farmers and scientists in plant breeding [Ceccarelli and Grando \(2007\)](#), for the selection of high yielding varieties, the selection process is carried out in individual farmers fields [Ceccarelli et al. \(2000\)](#). This effective result has been shown on major cereal crops varieties selection, including barley, maize, wheat, and rice [Sthapit et al. \(1996\)](#), [Bänziger and Cooper \(2001\)](#), [Ceccarelli et al. \(2001\)](#), [Witcombe et al. \(2003\)](#), [Thapa et al. \(2009\)](#), [Bachmann \(2010\)](#), [Medina \(2012\)](#). Participatory Plant breeding (PPB) is another pathway to reconciling agro-biodiversity with a rapid moving of varieties both in time and space, making plant breeding more efficient by increasing the adoption ratio of varieties, selection gains, and the benefit/cost ratio [Ceccarelli et al. \(2013\)](#), [Madalla \(2021\)](#).

Evolutionary participatory breeding (EPB) is a method that merges farmer participatory breeding with evolutionary breeding to develop high-yielding of desired quality cultivars and disease-resistant, with maintaining their ability to adapt to environment fluctuations conditions through a high degree of genetic variation [Murphy et al. \(2005\)](#), [Ceccarelli and Grando \(2019\)](#). In the actual climate change scenario, evolving crop populations can be a source of useful genetic diversity conservation and a source of genes for breeding purposes, on the contrary of modern plant breeding purposes [Ceccarelli et al. \(2013\)](#) and this contradiction will be appearing obviously if climate change is considered.

5. CASE STUDY OF EVOLUTIONARY PLANT BREEDING IN JORDAN

The study assesses the genetic basis of adaptation of a barley population which evolved in different rainfed locations and years in Jordan; provide the national breeding program and farmers with a continuous flow of novel genetic diversity occurring within an evolutionary population. The reports on analysis of twenty-one

agro-morphological traits recorded on five populations that evolved during six years in five low-input locations without any human selection. The experiments were conducted in five low-input locations, namely Ramtha east and west, Mushaqaer east and west, and Ghweir. Each experiment included each of the five evolutionary populations with their evolving generations and five local controls. The experiments were conducted under farmer fields' conditions using partially replicated row-column design.

The twenty-one agro-morphological traits were analyzed using bi-dimensional spatial analysis, cluster analysis, multivariate approach and stability analysis. Seed quality improved in the sixth generation (G6) of evolution compared with the original population (G0); the improvement differed according to the location. The results showed that natural selection was operating on the populations for some of the traits namely plant height, number of seed per spike, and seed size. The different generations were superiors to the best local control in at least one of the yield traits namely spike weight, number of seeds per spike, weight of seeds in a spike, and grain weight.

The analysis among populations tested together in the five locations showed that two to four morphological clusters were identified by cluster analysis in each location. The largest populations number were grouped in one cluster compared with the rest of the clusters which were characterized mainly by heavier spike with higher number of seed per spike, tall plant, long peduncle. Interestingly, the frequency of the population divided upon to control architecture, showing good plant and spike characters for six row type, and good grain yield for two row types. Stability analysis based on high mean and low coefficient variations, showed a number of populations from Ramtha west, Mushaqaer west and Ghweir having high grain yield and high stability in most of the locations.

The analysis of each evolving populations tested in the five locations showed that two to three morphological clusters were identified by cluster analysis for each population. The populations were grouped together in one cluster, except in Mushaqaer east, compared with the rest of the clusters which were characterized mainly by good grain yield, and by a positive expression of at least one of the yield-related traits. The grain yield fluctuated during the evolution of these populations. Stability analysis showed that Ramtha west and Mushaqaer east populations were highly adapted to their low input locations but not stable, and Ramtha east, Mushaqaer west, and Ghweir had stable populations over all location from their last generation.

The study suggests that the breeder can shift the undesirable traits in these populations by practicing individual selection in each location for specific adaptations, or individual selection from populations showing wide adaptations and high stability. On the other hand, the breeder can overcome the undesirable traits by keeping the highest variations within the population by seed sieving to remove small seed and plant mowing for tallest head.

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