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Review

Weed Flora Evolution in the Era of Climate Change: New Agronomic Issues as a Threat to Sustainable Agriculture

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Abstract

The impacts of climate change on Mediterranean weed flora were investigated to inform future weed management strategies. Projections indicate that rising temperatures and increased atmospheric CO_2 concentrations are likely to favor ruderal species characterized by rapid phenological development and high dispersal capacity. Enhanced abiotic stressors—such as elevated temperatures, water scarcity, and increased UV-B radiation—are expected to affect crops more severely than weeds, given the latter's greater evolutionary potential to develop stress-tolerant biotypes. Moreover, the increased frequency and intensity of extreme events (e.g., drought, flooding, and soil salinization) may reduce weed community diversity, potentially leading to dominance by a limited number of highly competitive species and consequently intensifying reliance on chemical weed control. Simplification of weed communities may also increase vulnerability to the introduction and establishment of alien species, particularly those originating from hot and arid regions, some of which may be parasitic, toxic, or allergenic. Climate change-induced phenological mismatches between flowering plants and pollinators are likely to favor wind-pollinated weed species, further compromising the aesthetic and ecological quality of agricultural landscapes. Additionally, increased production of wind-dispersed allergenic pollen, together with the anticipated rise in herbicide applications, may pose significant risks to human health. An effective agronomic strategy to address future weed scenarios should include the genetic improvement in crops to enhance adaptive plasticity, exploiting germplasm from ancestral lines and related wild species.

Keywords: global warming; wild flora; weed dynamics; agronomic management; agro-ecology

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1. Introduction

Climate change is challenging the sustainability of farming activities. The distinction between natural and anthropogenic factors altering the climate is not entirely clear, but anthropogenic influence is strongly supported by evidence [1]. Regardless of the cause, the well-documented climatic changes can severely affect the interactions between biotic communities within agroecosystems. Predicting whether, and to what extent, climate change interferes with human activities [2] and agricultural sustainability [3] is crucial. The efficacy of weed control largely depends on weed community composition. Because of the slow evolution of weed communities, the study on climate change effects on weeds requires medium–long term research, and predicting future weed flora composition is therefore of critical importance. Future climatic conditions are expected to favor weeds over crops [4]

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overall in the Mediterranean environment [5]. The challenge of managing the evolution of herbicide resistance in weed populations is likely to be further intensified by climate change, whose inherent variability and unpredictability may alter selection pressures and complicate the development of effective control strategies.

The great resistance of segetal weeds to agronomic disturbances provides them with a long persistence in cropland [6]. It derives from survival strategies, i.e., fast and enhanced reproduction capacity, marked dormancy and longevity of seeds, that provide the species a wide plasticity to various soils, climates and farming systems [7]. In cultivated land, weed flora coevolves with the crop, mainly as a function of the type and frequency of agronomic disturbances [8], but today, climate change is becoming an additional factor [9]. Its high selection pressure is due to climatic factors but also to human activities that are also performed out of the fields, such as in urban, peri-urban, and industrial areas, interwoven with cropland.

How can climate change threaten agricultural sustainability through weed evolution? The risks are serious because climate change effects are amplified by intraspecific diversity in weed populations that is significantly higher than that of crops [10]. The current modern cultivars are highly productive, and the major cultivated plants are very productive, but their genetic diversity is limited. Many genotypes of the wild ancestors and of past cultivars have been lost during domestication and by recent, intensive breeding programs [11]. While spontaneous flora can rapidly evolve into populations with a high fitness to new environments, the lower plasticity of modern cultivars limits their competitive ability. Thus, weed control in the future will likely become more difficult [12] also because of a greater number of weed generations per year [13].

This paper examines how weed flora is expected to respond to climate change. The findings provide insight into the future composition of weed communities to be managed under projected climatic conditions.

2. Climate Warming

Over the last century, global temperature increased significantly: in 2023, it reached 1.43 °C above the pre-industrial level (1.32–1.53 °C, as a likely range) [14], and the greenhouse gases (GHGs) are considered the main causes of this rise [15].

Water vapor is the most abundant greenhouse gas (GHG), although its atmospheric concentration is highly variable and primarily regulated by temperature-dependent processes. Carbon dioxide (CO_2) concentrations are influenced by both anthropogenic emissions and natural processes, particularly ocean–atmosphere exchanges and terrestrial biosphere dynamics. Similarly, methane (CH_4) originates from a combination of human activities and natural sources. The global regulation of these gases results from complex interactions among anthropogenic drivers, biogeochemical cycles, and large-scale Earth system processes. Among the major long-lived GHGs, nitrous oxide (N_2O) exhibits a particularly high global warming potential [16,17]. The progressive thermal increase will probably lead to a significant shift in weed communities, since temperature has a crucial role in promoting or hindering plant growth and reproduction. The rise in temperatures is expected to favor summer weeds [18]. In the Mediterranean area, many of them use the C_4 photosynthetic pathway, which implies higher light and water use efficiency than C_3 plants. Their growth rate is faster when hot and dry conditions cause prolonged closure of their stomata. Therefore, a milder climate will likely increase the occurrence of C_4 plants [19]. Under warming scenarios, C4 weed species may increase aboveground biomass by approximately 1–4% per 1 °C rise in temperature within their optimal thermal range, with potentially higher gains under favorable water and nutrient availability. A warm spring promotes an earlier emergence burst of summer weeds. This can lead to unusual late-spring interactions between winter crops (e.g., wheat *Triticum* spp.) and summer weeds (e.g., *Sorghum halepense* (L.) Pers.) (Figure 1). Similarly, a warm fall favors the early germination of winter weeds, like *Stellaria media* (L.) Vill., that can compete with summer crops during their maturation.

Figure 1. Wheat (autumn–winter cycle) ready for harvest but infested by an early development of *Sorghum halepense*, a weed characterized by a spring–summer biological cycle. Photo taken (Stefano Benvenuti) in the hills surrounding Bologna (Italy).

An additional advantage of a warm autumn for summer weeds is delayed senescence, which implies greater seed production. This has been observed (Figure 2) for many indeterminate growth species [20], especially in Northern Europe, where temperatures frequently limit the length of the growing season [21]. A warmer climate in northern countries can also promote the occurrence of weeds requiring long, favorable seasons (i.e., many "degree days"). At mid-latitudes, weed flora composition is less influenced by the thermoperiod length, but high temperature selects "opportunistic" species that can easily prolong flowering and dissemination under favorable climatic conditions.

Figure 2. Corn ready for harvest, infested with *Abutilon theophrasti*, capable of keeping seed production (autumn temperatures still not limiting) in cases of delayed crop harvest. Photo taken (Stefano Benvenuti) in the lowland agroecosystems around Pisa (Italy).

2.1. Alteration of the Thermo-Photoperiod

Photoperiodism is the phytochrome-mediated process that switches plant development from the vegetative to the reproductive phase [22]. This mechanism has evolved in integration with the thermoperiod requirement, so that a species is triggered to flower by photoperiodism but disseminates only when temperatures are suitable for the offspring's growth [23]. Climate warming can cause a sort of "confusion" in this delicate mechanism. Indeed, the duration of the photoperiod was kept constant, but it was temporally uncoupled from the thermoperiod [24]. This exerts a strong selection pressure on weed flora, rapidly leading to the dominance of neutral-day species, whose growth depends exclusively on thermal availability [25]. For example, wild sugarbeet (*Beta vulgaris* L. subsp. *maritima* Arcang.) is a strict long-day plant, but the modern cultivars flower markedly earlier than in the past [26], thus favoring an unwanted weed-crop hybridization. In the new climate, thermoperiod will likely become the exclusive stimulus for the flowering of weeds, as has occurred during the domestication of tree and field crops [27].

Regarding reproduction, future weed communities will probably be mainly composed of species whose pollination does not rely on mutualism for biotic seed dispersal [28] or insect-pollination [29]. Indeed, mutualistic pollination requires a perfect synchronization between flowers and pollinator presence in the ecosystem. If the synchronization is lost, the weed is doomed to disappear.

In Mediterranean agroecosystems, the weed with the highest fitness to the new scenario (weed "ideotype") will likely have an "opportunistic" aptitude only toward thermal availability, so that it can reproduce, regardless of photoperiod, even in occasional mild winters or cold springs. A high plasticity of flowering time is, in fact, the main characteristic of plants thriving in harsh habitats [30].

2.2. Faster Release of Cold-Mediated Seed Dormancy

The survival strategy of many weeds is based on the dormancy of seeds that prevents simultaneous germination [31]. In temperate and cold environments, exposure to several consecutive days of low winter temperatures progressively reduces dormancy, thereby enabling germination during subsequent spring periods [32]. A short or null cold period in winter penalizes weeds that are strictly "seed chilling requiring" [33] and their occurrence in future weed communities will likely decline [34]. On the contrary, climate change should favor weeds with fewer dormant seeds [35], and those with seed dormancy released by diverse stimuli, not only physiological but also physical [36] or morphological [37].

2.3. Insufficient Satisfaction of Vernalization Needs

Climate change will probably shorten the cold period during early plant growth that triggers flowering (vernalization) [38]. Some weeds, e.g., *Alopecurus myosuroides* Huds [39], *Alliaria petiolata* (M. Bieb.) Cavara & Grande [40], *Aegilops cylindrica* Host [41], and *Cyanus segetum* Hill [42], have a strong vernalization requirement that, if not satisfied, hinders their reproduction capacity. In temperate and cold climates, they are winter weeds that flower only in spring. The lack of cold-temperature stimulus delays flowering [43] and reduces the intensity of dissemination.

3. Increase in Atmospheric CO_2

Over the last century, the atmospheric CO_2 concentration has rapidly increased and currently exceeds 400 ppm [44]. Carbon dioxide is not noxious to plants; on the contrary, its shortage represents a limiting factor of photosynthesis [45]. A further rise in CO_2 in the atmosphere is forecasted; therefore, the crucial question is the following: "Which species will gain a competitive advantage in the future atmosphere, rich in CO_2?" Probably those with the most efficient photosynthetic pathways will gain the advantage; thus, the specific photosynthetic pathway is crucial. Except for a few CAM species [46], spontaneous and cropped plants are divided into C_3 and C_4 species that respond differently to factors regulating photosynthesis (light, CO_2, temperature and water) [47]. C_4 plants use CO_2 more efficiently than C_3 plants because they can perform photosynthesis even when stomata are closed due to a lack of water and at high temperatures.

Increased air CO_2, high temperatures and water shortage are all factors that forecast a greater frequency of C_4 weeds in future weed floras at medium latitudes [48]. Climate change can also favor some C_3 weeds that are adapted to survive in environments characterized by extreme events (thermal oscillations, prolonged drought, submersion, etc.). An example is *Xanthium italicum* Moretti, a summer weed of medium latitude that can stand harsh conditions in all anthropogenetic habitats [49] (Figure 3). Indeed, elevated CO_2 concentrations (550–700 ppm) disproportionately stimulate C_3 photosynthesis by reducing photorespiration and alleviating CO_2 limitation, thereby shifting the C3–C4 competitive threshold toward higher temperature ranges and potentially reducing the relative advantage of C4 species under moderate thermal conditions, as demonstrated by FACE experiments showing significant biomass and photosynthetic enhancement in C_3 weeds such as *Xanthium italicum*. This species is capable of rapidly colonizing disturbed environments and exhibits high ecological adaptability, which confers a competitive advantage in dynamic and anthropogenically altered habitats. In particular, traits such as a short life cycle, pronounced ecological plasticity, and efficient dispersal mechanisms enhance their establishment and spread, thereby facilitating the invasion success of weedy species within the genus *Xanthium*.

Figure 3. *Xanthium italicum*, a xerophytic species capable of colonizing coastal dunes, whose stress tolerance makes it a weed with a probable increase in future agroecosystems. Photo taken (Stefano Benvenuti) in the dune ecosystem around Viareggio (Italy).

However, the predominance of C_4 species is not certain. The current rise in CO_2 content can be thought of as a sort of evolutionary reversal. C_4 species evolved later than C_3 species [50], and their spreading was due to CO_2 decline during the Carboniferous era (period of underground accumulation of coal, methane, and oil reserves) [51]. The higher efficiency in photosynthesis of C_4 plants then represented an important evolutionary trait. Now, the burning of fossil fuels by man is restoring the ancient CO_2 levels, and the importance of the C_4 pathway may decline.

High level of CO_2 was also found to accelerate the transition from vegetative to the reproductive phase of plants and to increase the number of seeds produced per plant [52]. Both traits are the basis of the survival strategy called "ruderality"; a term coined by Grime [53] that refers to the speed with which a species invades an ecological niche. This ability is possessed by many weeds that produce a great number of offspring in just a few weeks after emergence. It will certainly represent a major characteristic of weeds in the future agroecosystems.

4. Decreasing Rainfall and Increasing Desertification

In recent years, rainfall has been decreasing all over the Mediterranean area [54] with desertification problems in the southern regions. Rainfall patterns are also changing. Rains are concentrated in a few intense events that are often devastating. They cause erosion without replenishing the groundwater reserves, which are important in Southern Europe. These trends imply an increased frequency in the weed flora of xerophytic species, well-adapted to survive in water-deprived conditions [55]. Water stress can be avoided through physiological (osmoregulation, stomatal conductance) or morphological (waxy, pubescence, spinescence, etc.) traits that enable the plant to overcome adverse periods, increasing its competitiveness in severe drought [56].

An increase in water-stress-tolerant species has already been observed in the weed flora of both summer [57] and winter [58] crops. Indeed, this floristic shift is the most frequently reported consequence of climate change [59]. In areas where irrigation is not feasible, either due to scarcity or its high cost, the crop–weed interaction is an important factor influencing crop yields [60], and the specific water-use-efficiency (WUE) is crucial. In this respect, C_4 weeds (e.g., *Cynodon dactylon* (L.) Pers., *Sorghum halepense* (L.) Pers., *Amaranthus retroflexus* L.) have an advantage over C_3 species, thanks to their more efficient use of water [61]. But a high WUE is not the only survival strategy in dry areas. Plants thriving in localities with cyclic droughts are also those that can grow and disseminate rapidly after dry spells. From this point of view, many Asteraceae species will benefit most from the increasing dry climate, both because they are specialized in colonizing degraded areas [62] and due to their anemochorous dispersal strategy [63]. Some of them, e.g., *Conyza canadensis* (L.) Cronq., *Aster squamatus* Hieron., *Cirsium arvense* (L.) Scop., *Sonchus oleraceus* L., and *Senecio vulgaris* L., are already expanding over all anthropized ecosystems. Other Asteraceae are forecast to increase in pastures. The low forage production due to more frequent drought can lead to excessive grazing, exerting a strong selection pressure on plant communities [64]. The less palatable plants are likely to become dominant, especially if they are thorny, such as *Xanthium spinosum* L., *Silybum marianum* (L.) Gaertn. and *Tribulus terrestris* L. (Figure 4).

Figure 4. *Tribulus terrestris* weed, characterized by extremely thorny fruits, evolved to limit its water consumption in hot and dry environments. Photo taken (Stefano Benvenuti) in the hind-dune ecosystem around Viareggio (Italy).

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Climate change will likely also favor species that are adapted to fluctuating water availability [65], like many perennial grasses [66].

5. Higher Frequency of Extreme Events

Recently, extreme rainfall and wind events, sometimes associated with sudden drops or rises in temperature, are becoming more frequent [67], and their effects on the agroecosystem are disastrous [68]. The frequency of extreme events (flooding, freezing, drought, etc.) has a strong impact on weed flora composition, favoring species with high resilience [69], as was confirmed, for example, by studies on the flood damage in various parts of the world [70]. Weeds are more resilient than crops because they are generally more stress-tolerant and have a wider genotype diversity. For example, *Echinochloa crus-galli* (L.) P. Beauv. (Figure 5) can be found almost everywhere (from rainfed corn to completely submerged rice), thanks to its wide genotypic variability [71]. The highest resilience to extreme events has been reported for grass weeds [72], especially if they can also propagate from rhizomes [73].

Figure 5. *Echinochloa crus-galli* weed with high environmental "plasticity" capable of invading crops grown in arid environments (e.g., sunflower) and submerged environments (e.g., rice). Photo taken (Stefano Benvenuti) in an agroecosystem around Pisa (Italy).

6. Problems of Soil Salinization

The widening of saline soils in many coastal areas of the world can be partially ascribed to dry periods linked to climate change [74]. They result in an increasing extraction of groundwater for irrigation that causes intrusion of seawater into aquifers [75]. Another factor is the slow but steady rise in sea level that is due to the melting of Arctic glaciers [76]. Soil salinity has a strong influence on weed flora composition. Some species (defined as halotolerant) resist salinity by various mechanisms. Their roots preferentially absorb certain ions (little or no Na^+) that are transferred along the xylem at various speeds. The toxic ions (e.g., Cl^-, Al^{3+}) are "compartmentalized" in vacuoles, where their toxicity is reduced or eliminated [77].

Climate change promotes the spread of halotolerant species, a phenomenon that has already been observed [78] for *Portulaca oleracea* L. This plant represents a sort of "ideotype" of a salt-tolerant weed. It escapes salinity stress by morphological and physiological adaptations [79]. It has waxy leaves, reducing transpiration, and thick cell walls, providing efficient osmoregulation, which are combined with "ruderality" traits. Ruderal species, characterized by rapid growth and high reproductive and dispersal capacity in disturbed environments, are often favored under climate-driven disturbance regimes. Likewise, halotolerant species—species capable of surviving and maintaining physiological function under elevated soil salinity conditions—may become increasingly prevalent in areas affected by drought-induced salinization. *Portulaca oleracea* L. is so adapted to grow in highly saline soils, and it is even cultivated for soil desalination [80]. A marked salinity tolerance is also shown by many Chenopodiaceae [81] (e.g., *Atriplex prostrata* Boucher, *Chenopodium album* L., *Kochia prostrata* (L.) Schrad., and *Salsola kali* L. (Figure 6)) that can grow under strong osmotic pressure [82], and by several grasses, such as *Echinochloa crus galli* (L.) P. Beauv. [83] and *Setaria viridis* (L.) P. Beauv. [84], thanks to an accurate salt metabolism and to their broad genetic base. In summary, climatic stressors rarely act in isolation; for instance, prolonged drought can intensify soil salinization through reduced leaching and increased evaporative salt accumulation, thereby compounding osmotic stress and altering weed physiological tolerance and competitive dynamics under concurrent UV-B radiation and heat stress.

Figure 6. *Salsola kali* wild species belonging to the Chenopodiaceae botanical family that can survive in extreme conditions of salt stress. Photo taken (Stefano Benvenuti) in the dune ecosystem around Tirrenia (PI), Italy.

7. Increase in UV-B Radiation

The thinning of the ozone layer in the stratosphere due to human activity increases the amount of ultraviolet radiation (especially UV-B, with 280–315 nm wavelengths) reaching the Earth's surface [85]. This phenomenon, which is particularly acute in summer at high latitudes [86], can alter the interactions between organisms in both natural [87] and agroecosystems [88]. It can also interact with the factors of climate change [89]. However, significant biological responses were found only at high levels of radiation [90].

Because of the degradation of many herbicides caused by energetic rays, a more intense UV-B radiation is likely to impair weed control [91], also prompting the development of resistant biotypes, as reported in *Abutilon theophrasti* L. Medicus [92].

Few plants have a real tolerance to UV-B rays; *Digitaria sanguinalis* (L.) Scop. [93] is one of the most resistant. Other tolerant weeds are some Asteraceae that are pioneer species of human-disturbed environments frequently exposed to high solar radiation (e.g., *Senecio vulgaris* L., *Aster squamatus* Hieron., *Conyza canadensis* (L.) Cronq. (Figure 7), *Sonchus asper* (L.) Hill, and *Picris echioides* L.) [94]. As for other tolerances, weeds can become more resistant to UV-B than crops thanks to their broader genetic base [95].

Figure 7. *Conyza canadensis*, a wind-dispersed weed, belongs to the botanical family Asteraceae, the pioneer of anthropized habitats. Photo taken (Stefano Benvenuti) in a lowland agroecosystem around Pisa (Italy).

8. Increased Occurrence of Parasitic Weeds

Some of the world's worst weeds are totally or partially parasitic species [96]. Two of them belong to the genus *Striga* (*S. hermonthica* Delile Benth. and *S. asiatica* (L.) Kuntze) and are very detrimental. They are endemic to tropical Africa and Asia, respectively [97], and parasitize various grass crops [98,99], such as sorghum (*Sorghum bicolor* (L.) Moench), maize (*Zea mays*), and, above all, sugarcane (*Saccharum officinarum* L.). Because of their

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negative effect on crop yields [100–103], their entry into the South European flora would be detrimental, especially to wheat, which in laboratory trials was found to be a possible host [104]. Both species produce an extraordinary number of seeds that are dormant and capable of persisting for several decades in the soil. When buried, they germinate only after having encountered the root exudates of the host plant.

The increasing occurrence of hot and prolonged summers due to the persistence of warm air masses of African origin may facilitate the establishment in southern Europe of *Striga* species introduced through human activities. Their parasitic activity and survival strategy are favored by both high temperatures and water shortage, which are linked to climate change. In the U.S.A., a 3 °C increase in average temperature was estimated to cause their spreading from South Carolina to the "Corn Belt" area.

The predicted higher temperatures will probably widen the geographic distribution of other parasitic plants, especially of the Orobancaceae (*Orobanche* spp. and *Phelipanche* spp.), which are already present in Mediterranean flora [105]. The major species (*O. crenata* Forssk. and *O. ramosa* L.) are holoparasitic plants that are favored by hot and arid conditions, where they find optimal growth conditions [106]. Climate change will likely expand their distribution northwards [107], where they can compete with many vegetable crops [108,109].

Another holoparasitic weed whose occurrence may increase under climate change is *Cuscuta campestris* Yunk., which is already widely distributed in the Mediterranean area, mainly infesting alfalfa (*Medicago sativa* L.), sugar beet (*Beta vulgaris* L.), and sunflower (*Helianthus anuus* L., Figure 8). Dry weather can indirectly encourage its parasitic activity. To avoid water stress, host plants counterbalance the osmotic deficit by increasing their sugar content [110]. High carbohydrate availability in the host plant is crucial for successful parasitism, as a lot of energy is required when haustoria penetrate host tissues [111]. This mechanism was observed for the *Cuscuta campestris* parasitism of sugarbeet, subjected to increasing levels of salt stress [112].

Figure 8. *Cuscuta europaea*, a holo-parasitic weed (on sunflower plant), is characterized by strong aggressivity even under conditions of deep-water stress. Photo taken (Stefano Benvenuti) in lowland agroecosystems around Pisa (Italy).

9. Loss of Biodiversity

The community agrees that climate change will reduce biodiversity [113] and simplify the interactions between organisms [114]. It will increase the risk of plant extinction in all agroecosystems [115], even in the ecological oases, i.e., cropland where environmentally friendly practices maintain a certain diversity in weed flora [116]. Many spontaneous species will become rare mainly due to the alteration of delicate balances with other organisms [117]. For many of them, survival depends on the activity of pollinators (e.g., social and solitary bees, dipterans, and lepidopterans [118]) that inhabit the same ecosystem. Today, rare weeds can be found almost exclusively in mosaics of diversified land use (cropland arranged in a mosaic of pastures, woods, and uncultivated areas), which provide the pollinators with suitable niches to nest.

Climate change can affect the vulnerable balance of the ecological community in several ways. It can directly alter the interactions (i.e., competition, parasitism, predation, and mutualism) between species, or indirectly, by regulating the population size of the interacting species (e.g., rhizobia-leguminous plants), and strongly depends on environmental conditions and resource availability. For the mutualism between pollinating entomofauna and plants, climate change can desynchronize the presence of flowers and insects by modifying the usual connection between photoperiod and thermoperiod. For the obligate-pollinators Lepidoptera, the desynchronization was found to affect not only the insect–flower presence but also the interaction between the insect and suitable plants for oviposition and larvae nourishment [119]. From this perspective, insect-pollinated weeds (Figure 9) are the species most threatened by climate change. Conversely, weeds that lack mutualism might be advantaged, especially the autogamous and anemophilous species that have already been found to be highly resistant to intensive cropping systems [120].

Figure 9. Solitary bee on the inflorescence of *Glebionis coronaria*, a species frequently visited by pollinating insects. Photo taken (Stefano Benvenuti) in a natural meadow around Grosseto (Italy).

Therefore, climate change will most likely reduce the number of weed species. This decline poses not only environmental problems (biodiversity reduction) but also agronomic issues, since the control of complex weed communities is significantly easier than that

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of simpler weed floras, which are often dominated by aggressive and herbicide-resistant weeds [121]. Moreover, the "biological vacuum" in current agroecosystems, due to the almost exclusive presence of plants of the cropped species, aggravates the risk of invasion by exotic plants [122] that can be alleviated by maintaining a high floristic diversity [123].

10. Weed Control Problems

Climate change can hinder weed management [124] because it can reduce herbicide efficacy [125] and promote the establishment of pioneer species, well-adapted to thrive in harsh environments [126]. Rising temperatures combined with elevated atmospheric CO_2 concentrations speed up and increase the production of weed seeds, thanks to the enlargement of the "window" of temperatures, which could allow species with a longer biological cycle to flower and disseminate [127]. The weed seed bank can thus increase, and the milder temperatures can allow more generations in a single growing season. Moreover, the thermal increase could reduce the occurrence of rare long-leaved species [128], thus narrowing biodiversity. More generations per year under strong selection pressure aggravates the risk of the evolution of herbicide-resistant biotypes [129]. In warmer winters, summer weed species can compete, at least in their early growth stages, with winter crops. Indeed, weed floras in winter and summer crops are becoming surprisingly "globalized" through the seasons. Although weeds that emerge in autumn cannot compete with crops during their entire life cycle, they interfere with early crop growth. Similarly, an earlier spring emergence of summer weeds in winter crops can be harmful. Although the growing stage of winter crops in early spring is generally beyond the so-called "critical period" (period of significant competition between crop and weed), summer weeds can hinder crop harvesting.

This happens with summer species, such as *Abutilon theophrasti* L. Medicus, *Chenopodium album* L. and *Datura stramonium* L., which can compete with wheat, already at the tillering stage (Figure 10).

Moreover, under warmer climate scenarios, some species that are now frost-mediated annuals may become "agronomically perennial" [130] because senescence is no longer triggered under milder winter conditions. This has been observed in *Solanum nigrum* L. in the absence of winter frost. Insufficient winter chilling can also lengthen the vegetative stage of perennial weeds, as was found at high latitudes for *Elymus* repens (L.) Gould., *Cirsium arvense* (L.) Scop., and *Sonchus arvensis* L. [131]. This is a problem because perennial weeds are less susceptible to pre-emergence treatments [132] and even to post-emergence herbicides, as reported for *Sorghum halepense* (L.) Pers. emerging from rhizomes [133]. For other perennial species, such as *Cirsium arvense* (L.) Scop., increased CO_2 concentrations foster the growth of underground plant organs that cannot be reached by herbicides [134].

Other weed control issues may result in the dominance of xerophytic species in the Mediterranean weed flora of xerophytic species, with leaves that are thorny or covered with waxy substances. These traits reduce water loss and protect plants from UV-B radiation, but may also decrease the efficacy of post-emergence herbicides [135]. The tolerance of weeds to herbicides can also be increased by high levels of CO_2.

All these factors suggest that higher herbicide application rates may be required in the future [136]. Moreover, higher application rates may also be necessary due to the reduced persistence of several active substances at high temperatures [137]. Therefore, a more intensive chemical control will probably be needed in the forecasted climate scenario, with higher rates, more herbicides, and multiple applications.

Figure 10. Wheat during the early autumn growth stages, in which, paradoxically, species with a spring–summer cycle are also present, such as (from left to right) *Abutilon theoprasti*, *Datura stramonium* and *Amaranthus retroflexus*, as well as the common autumn-winter *Sinapis arvensis* (yellow flowers on the right). Photo taken (Stefano Benvenuti) in the lowland agroecosystems around Pisa (Italy).

The impact of UV-B radiation on weed control is controversial, as it depends both on the herbicide and on weed physiology. Generally, UV-B radiation tends to oxidize herbicide active substances, inhibiting their phytotoxicity and reducing their biological efficacy over time [138]; however, experiments under simulated conditions have shown that UV-B can enhance the herbicidal action on the metabolism of certain species.

11. Aesthetic Deterioration of the Rural Landscape

The landscape acts as a mirror to the impact of human activities that modify the environment both directly (through cropping systems) and indirectly (through climate change). It reveals the sustainability of the management of agricultural and forest land and of other anthropogenic systems. Moreover, the landscape also has aesthetic value provided by agricultural systems.

It is not a coincidence that mutualistic species have flowers with an undeniable aesthetic impact. Many of them (collectively referred to as "wildflowers") have flowers and inflorescences that evolved to attract pollinators through their chromaticity and morphology [139]. They are an important feature of ancient agricultural landscapes [140] that still occasionally reappear, but almost exclusively in ecologically managed areas. For example, the main species that "colored" ancient wheat fields were *Centaurea cyanus* L., *Agrostemma githago* L., *Nigella damascena* L., *Gladiolus italicus* Mill., *Papaver rhoeas* L., *Anthemis arvensis* L., and *Consolida ajacis* (L.) Schur. Often, they did not cause significant yield losses due to their low competitiveness; sometimes their presence even increased crop production thanks to an increase in pollinator visits [141]. Their decline in cropland is certainly not entirely due to climate change, but in the new climate, their presence is expected to further decrease, even in the agro-ecological oases. As already reported, any environmental imbalance threatens the delicate interactions between flora and fauna organisms. Therefore, it is highly probable that climate change will hinder or prevent seed formation in species whose self-pollination is often impossible, as in *Papaver rhoeas* L. [142]. In the new climatic scenario, this aesthetic component of the rural landscape will probably disappear [143]. They will be replaced by species that do not require any interaction with pollinators. Unfortunately, their flowers lack any aesthetic appeal because their evolutionary strategy was not based on attractiveness [144]. Many of them are already prevalent in modern agroecosystems. Examples are grass weeds that are typically found in wheat and other winter cereals (*Lolium multiflorum* Lam., *Avena* sterilis L., *Alopecurus myosuroides* Huds., *Phalaris minor* Retz.) and in summer crops (*Sorghum halepense* (L.) Pers., *Setaria viridis* (L.) Beauv., and *Digitaria sanguinalis* (L.) Scop.), and anaesthetic dicotyledons that are common in winter cereals (*Rumex crispus* L. and *Galium aparine* L.) and in summer crops (*Amaranthus retroflexus* L., *Xanthium strumarium* L. and *Chenopodium album* L.).

12. Hazards to Human Health

In many predictions, climate change will affect human health, mainly due to the invasion of toxic alien weeds [145] coming from warmer environments [146]. For example, some wind-dispersed *Senecio* spp., rich in carcinogenic pyrrolizidine alkaloids [147], have been accidentally introduced into Europe, and their spread is forecasted to rapidly increase [148] (Figure 11).

Climate change can also favor weeds (mainly grasses [149]) that host pathogenic endophytic fungi infecting plants under abiotic stress [150]. Many of them are asymptomatic under normal conditions but become aggressive or produce mycotoxins at high temperatures and CO_2 [151]. Mycotoxins pose significant risks to human and animal health.

One of the recent concerns linked to climate change is the spreading of *Sorghum halepense* (L.) Pers. in the pastures [152]. This grass produces dhurrin, a highly toxic cyanogenetic glycoside that, in the cattle rumen, produces lethal hydrogen cyanide (HCN) [153]. Its plant content is elicited by water stress [154].

Further food security issues, aggravated by climatic changes, are expected to arise from the predicted intensification of chemical weed control [155] that will be required both by the evolution of weed flora [156] and by the lower efficacy of herbicides [157]. An indirect effect of higher chemical weed control concerns the increased exposure and sensitivity of bees and other pollinators to many active substances. The pollinators' disappearance, which will be due to a combination of multi-environmental stresses [158], is expected to reduce agroecosystem productivity.

Human health may be affected by weeds not only through the presence of toxic species, but also through the pollen produced by anemophilous plants [159], which represents a major cause of respiratory allergic diseases [160]. Several exotic species recently introduced into Mediterranean weed communities combine high pollen production—facilitating rapid dispersal—with strong tolerance to environmental stress associated with intensive agricultural systems. An example is the pioneer weed *Conyza canadensis* (L.) Conq. [161], which is widespread in anthropogenically disturbed areas. Among species producing highly allergenic pollen [162], *Ambrosia artemisiifolia* L. is considered one of the most clinically relevant. Introduced into Europe several decades ago, this species is expected to be favored under future climate change scenarios [163]. It produces large quantities of highly allergenic pollen that can be transported by wind over considerable distances, resulting in pollinosis across

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broad geographic areas [164]. The pollen production was found to be increased by CO_2 content in the atmosphere [165], similar to what happens for other allergenic species [166]. Moreover, the biological effects of allergens are amplified by the interaction of pollen with the vast range of pollutants contained in the current atmosphere [167]. Consequently, an increase in the incidence and severity of pollinosis is anticipated under future climate scenarios characterized by heightened environmental vulnerability [168].

Figure 11. *Senecio inaequidens*, an alien xerophytic weed, rich in toxic pyrrolizidine alkaloids, is today widespread in many Mediterranean agroecosystems. Photo taken (Stefano Benvenuti) in the lowland agroecosystems around Pisa (Italy).

13. Conclusions

The assessment of the potential impacts of climate change on weed–crop interactions indicates that crops are generally more vulnerable to altered climatic conditions than weed species. The main climatic drivers considered in this study are summarized in Table 1.

A diversified evolutionary response of weed populations is expected, but weed flora composition in the future climate scenarios remains uncertain. Some trends, such as increases in UV-B and CO_2, may become more influential. Conversely, temperature rise, drought frequency, and, in some localities, soil salinization, are already influencing or driving shifts. The change in climatic conditions, which is already evident in Mediterranean agroecosystems, is causing a reduction in species diversity by breaking fragile interdependences of the agroecosystem components. The weeds that mostly tolerate environmental disturbance are favored, and they increase the resilience of the weed community. The consequent weed flora will be less biodiverse and more aggressive, making weed control more complicated. There will be a dominance of weeds with high environmental plasticity, mainly pollinated and dispersed by wind, characterized by high competitive ability. The progressive disappearance of insect-pollinated species (with beautiful flowers) will be replaced by self-pollinating and anemophilous species, with a drastic deterioration of the agricultural landscape. Poorly diversified plant communities may facilitate the establishment of exotic weed species within agroecosystems, some of which are toxic, poisonous, or highly allergenic. Increased herbicide use is anticipated, as simplified weed communities are likely to be dominated by herbicide-tolerant species or species characterized by low leaf permeability. A potential increase in the number of weed generations during extended warm seasons, combined with enhanced overwinter survival of certain species, may further complicate weed management. Climate change, therefore, appears to threaten the already fragile ecological and economic sustainability of agricultural systems. Even more severe consequences are projected for the economically disadvantaged regions of the Mediterranean area, where socio-economic vulnerability may exceed ecological resilience. Consequently, future climate scenarios may contribute to widening disparities between economically stronger and more vulnerable countries. On the other hand, future floristic evolution is expected to remain highly uncertain, not only because of the intrinsic complexity of climate change, but also due to its unpredictable interactions with herbicide resistance, crop system simplification, and the impact of emerging agroecosystem management strategies.

Table 1. Overview of some of the most likely impacts of recent climate change on the floristic evolution of weed communities in Mediterranean agroecosystems.

Climatic Change Parameter	Weed Evolution	Agronomic Problems
Temperature increase	Increase in macrothermal species; increase in their dissemination due to greater “thermal sums”; increase in “perennial weeds”; photoperiod-thermoperiod desynchronization; reduction in microthermal species, especially those requiring “vernalization”; macrothermal species infesting the early stages of development of autumn–winter crops; risk of invasiveness of parasitic species already present (*Orobanche*, *Cuscuta*, etc.) or from Africa; risk of invasiveness of toxic species	High “aggressiveness” of warm-weather weeds; increase in annual seed production (late senescence); difficulty in controlling “perennials”; opportunistic seed production regardless of the time of year (photo-indifference); multiple generations of weeds in a single year; difficulty in controlling parasitic species; difficulty in controlling exotic warm-weather species
Winter frost rarefaction	Reduction in weeds requiring vernalization for flowering induction and/or reduction in dormancy-loss in “cold-mediated” physiological seed dormancy: Lengthening of the agronomic cycle of spring–summer weeds	Biodiversity reduction in many microthermal species. Increased “seed rain” of spring–summer weeds
Drought and desertification	Increase in xerophytic species, reduction in species with mutualistic relationships; increase in “colonizer” species such as many Asteraceae; increase in self-producing and/or anemophilous species; increase in the invasiveness of exotic species, especially those with allelopathic action	Morphological and physiological barriers to herbicide absorption; reduced biodiversity; deterioration of the agricultural landscape; increase in “allergenic” species; difficulty controlling invasive alien weeds; increase in parasitic weeds; easier eradication of toxic and/or poisonous species
Soil salinization	Increase in halotolerant weeds such as *Portulaca oleracea*, some Chenopodiaceae and Graminaceae	Osmotic stress factor is almost always able to promote weeds in the competitive weed-crop balances

Table 1. *Cont.*

Climatic Change Parameter	Weed Evolution	Agronomic Problems
Increase in CO_2	Increase in C_3 weeds; higher and faster seed production (ruderality); increased production of allergenic pollen	Competitive imbalances to the advantage of C_3 weeds, especially compared to C_4 crops; pollinosis in rural and urban populations
Extreme events	Increase in species that are tolerant to stress of an often-opposite nature and/or capable of being "resilient" to it	Greater "vulnerability" of the crop with competitive imbalances to the advantage of weeds
Increase in UV-B rays	Slow-growing species lacking in carotenoids and epicuticular waxes, increase in weeds with protective leaf hairs and/or waxes	Increase in species rich in protective pigments and epicuticular waxes with lower susceptibility to herbicides

The new objective of crop breeding should no longer be focused on yield rise, which requires more inputs, but rather on increasing crop adaptability to variable climates. For this scope, the collection of germplasm from wild relatives and the retrieval of wild species that can hybridize with crops will be crucial. Most of them are weeds that should not be extinguished. Future crop genetic improvement strategies should prioritize the introgression of drought-resistance traits from wild relatives—such as *Triticum dicoccoides*, a wild progenitor of wheat—into elite cultivars to enhance stress tolerance and competitive ability against weeds under climate change scenarios, as demonstrated by recent breeding programs exploiting wild germplasm for improved resilience and yield stability.

The challenging future climate will require rational management of weed flora to obtain sufficient agricultural products for our generation, but also to leave optimal environmental conditions for the life of future generations.

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