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Opinion

PlantACT! – how to tackle the climate crisis

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Greenhouse gas (GHG) emissions have created a global climate crisis which requires immediate interventions to mitigate the negative effects on all aspects of life on this planet. As current agriculture and land use contributes up to 25% of total GHG emissions, plant scientists take center stage in finding possible solutions for a transition to sustainable agriculture and land use. In this article, the PlantACT! (Plants for climate ACTion!) initiative of plant scientists lays out a road map of how and in which areas plant scientists can contribute to finding immediate, mid-term, and long-term solutions, and what changes are necessary to implement these solutions at the personal, institutional, and funding levels.

Highlights

Agriculture contributes to global climate change by producing 20–25% of greenhouse gases (GHGs).

CO_2 is released from deforestation and land conversion, methane from rice paddy fields, and nitrous oxides from overfertilization.

An increasing world population requires a change in the agro food systems, including a reduction in chemical fertilizers and pesticides as well as the production and access to food.

The climate emergency

Humanity is facing an unprecedented challenge from climate change [1]. The CO_2 concentration in the atmosphere has dramatically increased from 280 ppm (pre-industrial) to 420 ppm within 150 years. As a consequence, the global average temperature has increased by 1.5°C. This anthropogenic climate change is associated with altered rainfall patterns, extreme weather events, and less predictable weather patterns. This presents a major challenge to crop production and food security, and thus threatens the foundations of human civilization.

The International Panel on Climate Change (IPCC) had set the goal of limiting global warming to less than 1.5°C [2]. Although the goal of 1.5°C is probably no longer possible, achieving climate neutrality by reducing net CO_2 emissions to zero through a 45% reduction in emissions within 10 years is more important than ever [1]. This represents a disruptive goal which demands new thinking, new solutions, and new commitments.

The atmospheric temperature increase caused by rising CO_2 concentrations will not decrease significantly even after zero carbon emissions (peak carbon) have been achieved [3]. The climate effects of atmospheric CO_2 at peak carbon will remain irreversible for at least 1000 years, if not counteracted by a net reduction in atmospheric CO_2. In reality, anthropogenic climate change

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is irreversible over the next ten generations at least, unless rapid measures are taken to sequester CO_2 from the atmosphere [3].

The global carbon cycle describes the dynamic cycling of carbon between the atmosphere and marine as well as terrestrial ecosystems (Figure 1). Overall, terrestrial and aquatic net primary production is in the range of 130 gigatons of carbon per year. The vast majority of this assimilated carbon is returned to the atmospheric CO_2 pool via respiration. Hence, the natural global carbon cycle (not considering anthropogenic emissions) is nearly balanced [4]. However, human activities perturb the global carbon cycle, leading to a continuous increase in atmospheric CO_2 concentration. Net anthropogenic annual carbon emissions are leading to an estimated 5.2 gigaton increase in atmospheric CO_2 in 2022 [4] (Figure 1). All paths towards the 1.5°C goal depend on a rapid reduction in the carbon footprint of agriculture, forestry, and land use, combined with the use of bioenergy with carbon capture and storage [5–7].

Agriculture as a contributor to climate change

Agriculture is both a victim and a culprit of global climate change, as 20–25% of GHGs are released through agricultural activities. Apart from CO_2, significant amounts of methane and nitrous oxide are emitted as a result of agriculture; these are even more potent GHGs than CO_2 (>20 and 300 times, respectively). Methane is produced by rice paddy fields, livestock (via enteric fermentation and manure), and organic waste in landfills [8]. Nitrous oxide emissions are an indirect product of the use of organic and mineral nitrogen fertilizers. However, both gases have a shorter lifespan than CO_2: methane and nitrous oxide remain in the atmosphere for 12 and 114 years, respectively, compared to 300–1000 years for CO_2 [9]. Hence, unlike CO_2, reductions in both of these other GHGs would deliver rapid benefits (Box 1).

The nitrogen fertilizer supply chain currently contributes >2% of GHG emissions [10]. Global use of synthetic nitrogen fertilizers is predicted to increase by 50% by 2050 [11]. When nitrogen fertilizers are applied, significant amounts of nitrous oxide are generated through microbial conversion in the soil [10]. In the short term, the most effective strategy is to reduce the amount of nitrogen applied [12] to avoid over-fertilization through improvements in agronomy, extension advice, and management practices. In the short to medium term, a switch to agrosystems utilizing legume crops able to fix nitrogen naturally represents an urgent priority [13]. In the medium to longer term, improvements in nitrogen use efficiency in cereal crops (currently <50%) through breeding for key traits such as root architecture would also provide major gains, but might also carry the danger of inducing rebound effects [14]. These plant-based solutions are not reliant on major scientific breakthroughs but exploit existing knowledge that collectively act to reduce fertilizer-related production, usage, and emissions.

Most of the CO_2 generated by agriculture arises from changes in land use, particularly deforestation for fodder and grazing [15]. Livestock and fodder production each generate more than 3 billion tons of CO_2 equivalent. Changes in food and dietary choice will help to reduce GHG emissions [16]. For example, currently 10–30 kg plant proteins are required to produce 1 kg beef. Increasingly shifting away from animal to alternative protein sources would provide major benefits [17]. In the short term, reducing demand for animal feed would have major benefits through decreased land conversion [18]. In the mid to long term, adopting plant-based diets remains an efficient option. Plant scientists could contribute to the development of alternative plant-based protein sources by working with food and social scientists.

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Given the central importance of food, a reduction in GHG emissions from agriculture is a major challenge and will require the implementation of a range of techniques and tools, including capturing or reducing methane emissions at the source, more efficient use of fertilizers, and improved efficiency in meat, dairy, and cereal production. Overall, these measures should be part of a circular agricultural system integrating crop improvements, mixed crops, field rotations, and social interactions with local farming communities.

Challenges for future global food production

Growing global populations, shifting dietary patterns towards greater meat consumption, and increased food waste at both the consumer and supply-chain levels are major factors impacting global food systems. It is unclear how an increase in food production of 70–100% to meet global demands can be achieved in either a sustainable or equitable manner. Given the widespread degradation of terrestrial systems, there is no major surplus of arable lands on which to cultivate new crops. Likewise, any further conversion of forests into agricultural land via deforestation threatens biodiversity, contributing a major source of CO_2 emissions and further jeopardizing planetary health. To increase food production using current agricultural practices would require more chemical fertilizers and pesticides, with major negative environmental, climate, and human health-related impacts. With most of the land suitable for agriculture already in use, fertile agricultural land is increasingly becoming the preserve of wealthy nations and/or industry, heightening economic disparities between the global north and south.

Plants require sunlight, nutrient-rich soils, and water for optimal growth. Although mildly higher temperatures can prolong the growing seasons in some regions, extreme temperatures inhibit crop growth and impact yields through decreased fertility. Furthermore, changing weather patterns alter the timing of rainfall as well as the distribution of pests and diseases. To cope with these challenges, short-term agronomic solutions include changing farming practices, such as rotating crops to match water availability and/or adjusting sowing dates to temperature and rainfall patterns (Table 1). Plant scientists can also contribute by identifying microbes and plant traits for generating (in the medium to longer term) crop varieties showing increased resistance to heat and drought, enhanced water use efficiency (Box 2) and, in general, improved resilience to the changes in environmental conditions (Table 1).

Tackling climate change requires the use of cropping systems, either ones already available but not broadly used or novel ones yet to be developed, as well as the development of crop varieties suitable for these new agrosystems. Introducing adaptable and new crop systems could lead to diversification of agricultural production, with positive effects on ecosystems and biodiversity. This strategy promises to enhance crop resilience to biotic and abiotic stresses, but can also improve carbon sequestration and storage. In addition, plant breeding can provide crops better adapted to climate change. The development of new plant species and varieties that are commercially sustainable and resistant to different risks involves the preservation of multiple varieties, landraces, rare breeds, and closely related wild relatives of domesticated species.

The current focus of crop adaptation is the expression of traits related to resistance to drought, heat, salinity, and flooding. Different regions need crops adapted to different stressors: in some regions, crops that are resilient to drought and/or extreme temperatures are required, while in others flooding or disease resistance is the priority. Moreover, breeding efforts should consider the need for more diverse and resilient agroecosystems and should benefit from local knowledge related to the adaptation and selection process. Crop varieties that meet these conditions could

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contribute to efficient adaptation strategies to cope with climate change. In this context, the PlantACT! initiative will alert, engage in, and work on solutions to reduce agriculture-based GHG emissions and facilitate a more equitable and sustainable global food production system.

Plants, soil, and microbes as actors for mitigation

Soil was long considered as solely an inert growth substrate. If the chemical and physical properties were not suitable, herbicides, fertilizers, and pesticides had to be added to the soil to provide stable yields. This notion has now changed following recognition that, besides the physical and chemical structure of soils, a diverse living community of soil organisms is essential for crop production. Soil microorganisms form beneficial symbiotic associations with plants and help plant roots in nutrient uptake and control of diseases. Soil microorganisms also play a role in soil water- and nutrient-holding capacity, and can contribute to mitigating climate change by maintaining or increasing soil carbon content. In the future, holistic approaches to the soil–

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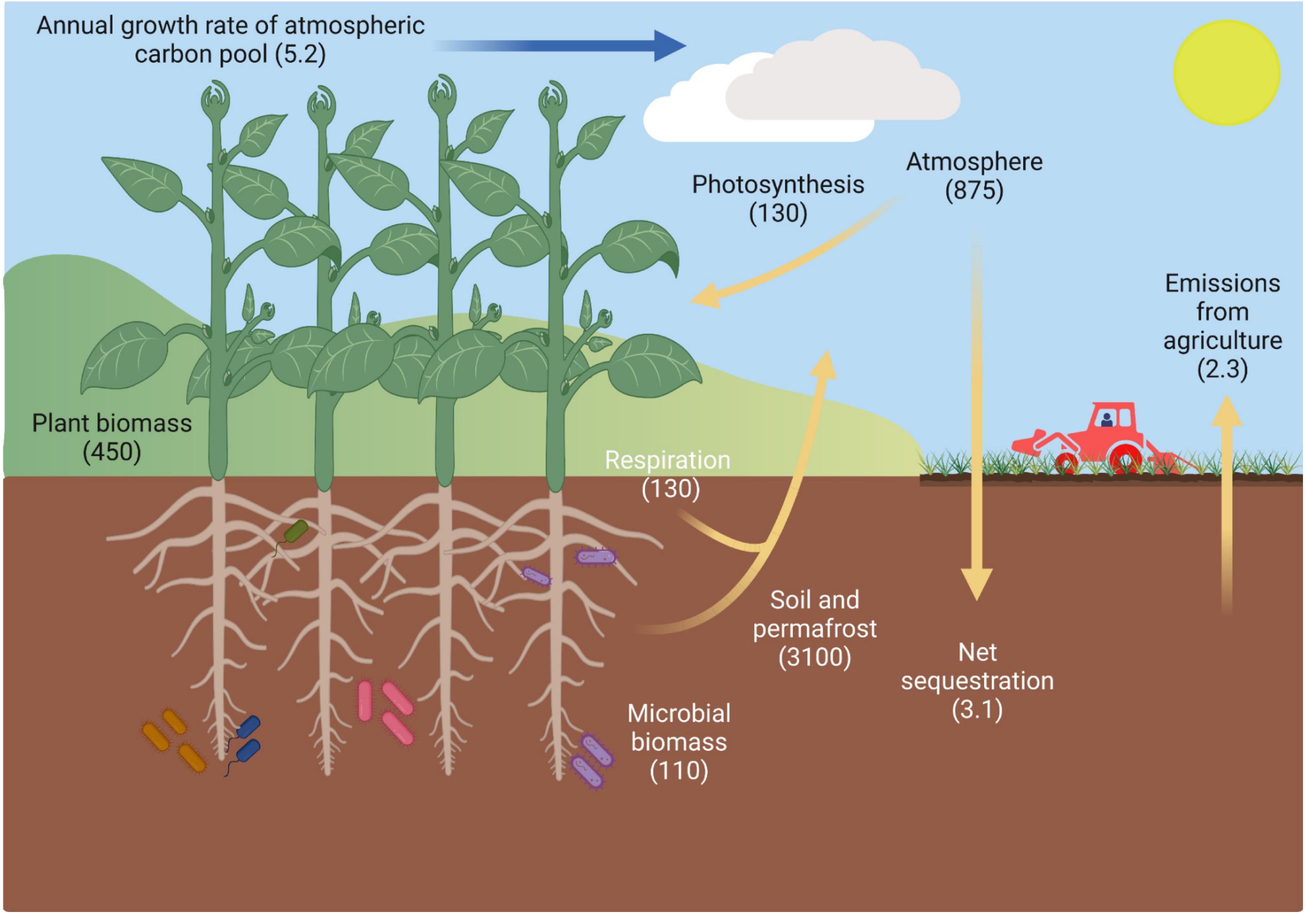

Figure 1. Schematic representation of the terrestrial carbon cycle. Annual growth rate of atmospheric carbon pool (blue arrow) is the differential of emissions from fossil fuels (9.6 gigatons of carbon, Gt C), land use change (1.2 Gt C), and uptake of carbon into terrestrial (3.1 Gt C) and oceanic (2.9 Gt C) carbon pools. Only land-based carbon fluxes are shown here. Data for carbon emissions from agriculture have been taken from the Food and Agriculture Organization of the United Nations (FAO) (www.fao.org/3/cb3808en/cb3808en.pdf). The FAO data include greenhouse gases other than CO_2, converted to CO_2 equivalents. Figure adapted from [25] with data from [4] and [11]. Figure created with BioRender.com.

Box 1. Reducing methane emissions from rice production

Methane is the second most important GHG after CO_2 and is >20 times more potent than CO_2. Rice paddy fields emit 10 g methane/m^2 (www.ipcc-nggip.iges.or.jp/EFDB), and this forms 15–20% of anthropogenic methane emissions. Methane arises from the decomposition of organic matter in anoxic conditions by soil methanogenic archaea. Changes in agronomical practices are already available to significantly reduce methane production in rice agrosystems (short-term solution). This includes water management practices such as alternate wetting and drying, or aerobic rice, that act to conserve water. However, transitioning from irrigated rice systems often leads to a yield penalty and greater inter-annual yield variability because of reduced access to water, weed competition, and changes in nutrient availability [21]. To tackle this, plant scientists (working together with agronomists, hydrologists, microbial ecologists, and agro-socioeconomists) could contribute by developing (medium-term) solutions that include new crop varieties for water-saving and low methane rice agrosystems. Traits include early vigor to deal with weed competition, and root traits to improve water and nutrient acquisition in aerobic conditions [22], but also the use of perennial rice varieties.

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plant–microbe ecosystem must be considered to achieve sustainable solutions related to climate change [19,20]. In this context, agriculture is not the only target of this approach, but landscaping and land restoration of unused land could provide novel solutions to climate change (Box 3). PlantACT! supports the idea that soil restoration could play a key role in improving agriculture and carbon capture as well as long-term carbon sequestration.

Concluding remarks

Given the complexity of the effects of climate change at all levels of planetary life, it is highly unlikely that exclusive disciplinary thinking will provide solutions that will hold up to their promises. Current thinking needs to be readjusted at the institutional, funding, and subject levels to enable multidisciplinary scientific approaches (see Outstanding questions). The present-day scientific culture of exclusive scientific exchange in specific fields needs to be broken down, and new forms of

Table 1. Strategies to avoid adverse impact of agriculture on climate change, to adapt to the consequences of climate change, and to mitigate climate change

GHG source	Avoid		Adapt		Mitigate	
Estimated timeframes to implementation[a]	Short-term	Long-term	Mid-term	Long-term	Mid-term	Long-term
Methane	Rice paddy-filed management (Box 1)	Reduce dependence on ruminant livestock protein		Perennial crops Improve rice seedling early vigor (Box 1)		Capture methane emissions at source
Nitrous oxide	Reduce synthetic nitrogen (N) fertilizer use	N_2 fixation through legumes	Breeding for improved N-use efficiency Restore degraded soil fertility Novel crops			
Land use change	Replace soya-based animal feeds Sustainable intensification		Adopting plant-based diets Alternative plant-based protein sources		De-desertification	Reforestation Restoration of peat moss
Carbon dioxide		Reduce dependence on fossil fuels	Improved crop rotation schemes	Improved water use efficiency (Box 2) Enhanced temperature tolerance		Increased carbon capture through photosynthesis Enhanced storage of organic and inorganic carbon in soils (Box 3) Oxalogenic plants (Box 3)

[a] Short-term, within a decade; mid-term, one to several decades; long-term, centennial.

Box 2. Enhancing water use efficiency (WUE) and carbon capture

Carbon gain in photosynthesis is a water-consuming process, as fixing one molecule of CO_2 requires hundreds of molecules of H_2O lost by transpiration. However, there is substantial natural variation in WUE among plant species, and this holds great potential to improve this trait in crops. Improved WUE can be achieved by using microbes collected from plants able to cope with extremely low water availability and contributing to this phenotype (short-term solution), and by breeding water-saving crops (mid-term solution). Reducing water loss by narrowed stomatal apertures can lead to decreased CO_2 concentration inside the leaves and hence increased photorespiration, in particular at higher temperatures. To avoid a possible penalty on growth in WUE crops, carbon capture efficiency could be improved. Potential advantages of C4 plants (and/or C3–C4 intermediates) can perform photosynthesis at lower stomatal aperture. Examples from breeding for WUE has pointed to genes involved in stomatal patterning, abscisic acid homoeostasis, and CO_2 signaling [23].

Box 3. Building up soil inorganic carbon (SIC) in arid regions

Soil organic carbon (SOC) represents a major form of terrestrial C storage (see Figure 1 in main text). The importance of SIC is less appreciated. Oxalogenic plants that secrete oxalate and associate with microbes in the soil show great promise for capturing CO_2 in an inorganic form that is highly stable. Fungi and bacteria associated with these plants (called oxalotrophs) can use oxalate as their sole carbon and energy source. In a soil that is rich in Ca^{2+} or Mg^{2+}, these microbes can produce Ca^{2+} or Mg^{2+} carbonates which thereby increase the SIC content [24]. These natural CO_2-trapping systems that are primarily found in arid and hyper-arid regions could provide novel and important carbon sequestration alternatives. Such systems do not compete with agricultural land and can fix carbon in the soil for decades to centuries.

interdisciplinary conferences and communication need to be established (e.g., ideas laboratories, workshops, grass-root-level proposals that compete with each other for prizes). Information access to farmers, scientists, and decision-makers via open-access platforms is needed to find and evaluate different approaches and solutions. Solutions must be fact-checked not only in terms of global carbon but also in terms of social and societal impact. The time constraints for proposed solutions (e.g., launching breeding programs for crop adaptations and introducing genes into elite crop varieties take a decade) have to be considered and weighed against immediate solutions (e.g., changes in agricultural practices, ready microbe-induced crop resilience). Overall, one solution for all will not be possible. Solutions will need to be shaped and targeted differently to reflect geographical and local needs and contexts and will have to be continuously assessed for their impact. For example, solutions need to be targeted differently to the EU and US compared with Sub-Saharan Africa where population growth will be highest this century. Moreover, land in many countries is limited, but less so in Africa, where agriculture suffers from low yield and hence supporting intensification in a sustainable manner could have an immediate impact. Overall, if we want to preserve a livable planet, we must leave our well-trodden disciplinary paths and search for novel interdisciplinary solutions and approaches. Moreover, not only national but overarching transnational funding programs need to be implemented to develop or adapt solutions to local specificities. PlantACT! aims to urgently accelerate these new interdisciplinary interactions and solutions by stimulating new forms of working and funding (Box 4).

Box 4. Redesigning the way plant-based climate solutions are funded

The time required to develop plant-based climate solutions is rapidly running out. One major challenge is the research grant funding systems currently operating in many countries, which impose delays of up to 12 months between submission of an idea to eventually starting a project. There is an urgent need to redesign and accelerate the way plant-based climate solutions are assessed, initially tested, and then rolled out. New formats to catalyze trans-disciplinary research solutions are also urgently needed. The Belmont Forum (https://belmontforum.org) provides an example of how such a change can be designed, which involves funding organizations, international science councils, and regional consortia committed to international transdisciplinary research to provide knowledge for understanding, mitigating, and adapting to global environmental change. PlantACT! aims to urgently accelerate new transdisciplinary interactions and solutions by stimulating new forms of working and funding.

Outstanding questions

Can we convert agriculture from a positive to a negative GHG contributor?

What changes in scientific culture are necessary to develop climate solutions?

Which short-term and long-term solutions need to be developed and/or prioritized?

What changes in funding structures are required to support solutions on local and global scales?

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Declaration of interests

No interests are declared.

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