



**HAL**  
open science

## **PlantACT! – how to tackle the climate crisis**

Heribert Hirt, Salim Al-Babili, Marilia Almeida-Trapp, Martin Antoine,  
Manuel Aranda, Dorothea Bartels, Malcolm Bennett, Ikram Blilou, Damian  
Boer, Alix Boulouis, et al.

► **To cite this version:**

Heribert Hirt, Salim Al-Babili, Marilia Almeida-Trapp, Martin Antoine, Manuel Aranda, et al..  
PlantACT! – how to tackle the climate crisis. *Trends in Plant Science*, 2023, 28 (5), pp.537-543.  
10.1016/j.tplants.2023.01.005 . hal-04037738

**HAL Id: hal-04037738**

**<https://hal.inrae.fr/hal-04037738>**

Submitted on 4 Apr 2024

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License

*This is a PDF file of an article that is not yet the definitive version of record. This version will undergo additional copyediting, typesetting and review before it is published in its final form, but we are providing this version to give early visibility of the article. Please note that, during the production process, errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain. The final authenticated version is available online at: <https://doi.org/10.1016/j.tplants.2023.01.005>*

*For the purpose of Open Access, the author has applied a CC BY public copyright licence to any Author Accepted Manuscript version arising from this submission.*

## PlantACT! - How to tackle the climate crisis

<sup>1</sup>Agata Daszkowska-Golec, <sup>2</sup>Alain Gojon, <sup>3</sup>Alix Boulouis, <sup>4</sup>Anne Krapp, <sup>5</sup>Andreas P.M. Weber, <sup>6</sup>Antonio Molina, <sup>7</sup>Bernd Müller-Röber, <sup>8</sup>Ben Field, <sup>9</sup>Catherine Walshe, <sup>10</sup>Crisanto Gutierrez, <sup>11</sup>Chris Bowler, <sup>12</sup>Damian Boer, <sup>13</sup>Detlef Weigel, <sup>14</sup>Dorothea Bartels, <sup>15</sup>Edith Heard, <sup>16</sup>Eric Gomès, <sup>17</sup>Eva María Gómez Álvarez, <sup>18</sup>Fabien Chardon, <sup>19</sup>Hatem Rouached, <sup>20</sup>Hannes Kollist, <sup>21</sup>Ive De Smet, <sup>22</sup>Ido Nir, <sup>23</sup>Jonathan Jones, <sup>24</sup>José Pardo-Tomás, <sup>25</sup>Xenie Johnson, <sup>26</sup>Jose R. Dinneny, <sup>27</sup>Laurent LAPLAZE, <sup>28</sup>Livia Merendino, <sup>29</sup>Malcolm Bennett, <sup>30</sup>Martin Antoine, <sup>31</sup>Michel Havaux, <sup>32</sup>Michael Hodges, <sup>33</sup>Michaël Nicolas, <sup>34</sup>Michael Wrzaczek, <sup>35</sup>Nathalie Leonhard, <sup>36</sup>Pedro Luis Rodriguez Egea, <sup>37</sup>Peter Schlögelhofer, <sup>38</sup>Jean-Philippe Reichheld, <sup>39</sup>Sophie Brunel-Muguët, <sup>40</sup>Stanislav Kopriva, <sup>41</sup>Scott Hayes, <sup>42</sup>Stanislav Kopriva, <sup>43</sup>Vincent Colot, <sup>44</sup>Wigge Philip, <sup>45</sup>Alice Stra, <sup>46</sup>Amal Khalaf Alghamdi, <sup>47</sup>Catherine H. Gardener, <sup>48</sup>Clara Stanschewski, <sup>49</sup>Izamar Olivas Orduna, <sup>50</sup>Jose L. Moreno Ramirez, <sup>51</sup>Katja Froehlich, <sup>52</sup>Kirti A. Singh, <sup>53</sup>Kyle J. Lauersen, <sup>54</sup>Maged M. Saad, <sup>55</sup>Manuel Aranda, <sup>56</sup>Marilia Almeida-Trapp, <sup>57</sup>Matthew F. McCabe, <sup>58</sup>Mauricio Lopez-Portillo Masson, <sup>59</sup>Mark Tester, <sup>60</sup>Brande Wulff, <sup>61</sup>Ikram Blilou, <sup>62</sup>Salim Al-Babili, <sup>63</sup>Jean Colcombet, <sup>64</sup>Iain M. Young, <sup>65</sup>Heribert Hirt

<sup>1</sup>Institute of Biology, Biotechnology and Environmental Protection, Faculty of Natural Sciences, University of Silesia in Katowice, Katowice, Poland Email: [agata.daszkowska@us.edu.pl](mailto:agata.daszkowska@us.edu.pl)

<sup>2</sup>Institut des Sciences des Plantes de Montpellier (IPSiM), Université de Montpellier, Centre National de la Recherche Scientifique (CNRS), Institut National de Recherche pour l'Agriculture, l'Alimentation, et l'Environnement (INRAE), Institut Agro, Montpellier, France Email: [alain.gojon@inrae.fr](mailto:alain.gojon@inrae.fr)

<sup>3</sup>UMR7141 "Chloroplast Biology and Light Sensing in Microalgae", Institut de Biologie Physico-Chimique, 13, rue Pierre et Marie Curie, 75005 Paris, France Email: [boulouis@ibpc.fr](mailto:boulouis@ibpc.fr)

<sup>4</sup>Anne Krapp, Institut Jean-Pierre Bourgin, National Research Institute for Agriculture, Food and the Environment (INRAE), AgroParisTech, Université Paris-Saclay, Versailles, 78000, France Email: [anne.krapp@inrae.fr](mailto:anne.krapp@inrae.fr)

<sup>5</sup>Andreas P.M. Weber, Professor, Institute of Plant Biochemistry, Heinrich Heine University Düsseldorf, Universitätsstraße 1, 40225 Düsseldorf, Germany Email: [aweber@hhu.de](mailto:aweber@hhu.de)

<sup>6</sup>Antonio Molina, Professor, Department of Biotechnology and Plant Biology, Universidad Politécnica de Madrid (UPM), Spain Email: [antonio.molina@upm.es](mailto:antonio.molina@upm.es)

<sup>7</sup>Bernd Müller-Röber, University Potsdam, Institute for Biochemistry and Biology, Molecular Biology, Karl-Liebknecht-Str. 24-25, 14476 Potsdam-Golm, Germany Email: [bmr@uni-potsdam.de](mailto:bmr@uni-potsdam.de)

<sup>8</sup>Ben Field, Aix-Marseille Univ, CEA, CNRS, BIAM, UMR7265, 13009 Marseille, France Email: [ben.field@univ-amu.fr](mailto:ben.field@univ-amu.fr)

<sup>9</sup>Catherine Walshe, Lancaster Environment Centre, Lancaster University, LA1 4YW Email: [c.walsh4@lancaster.ac.uk](mailto:c.walsh4@lancaster.ac.uk)

<sup>10</sup>Crisanto Gutierrez, Centro de Biología Molecular Severo Ochoa, 1, 28049 Madrid Email: [cgutierrez@cbm.csic.es](mailto:cgutierrez@cbm.csic.es)

<sup>11</sup>Chris Bowler, Ecole normale supérieure, 46 rue d'Ulm, 75005 Paris, France Email: [cbowler@biologie.ens.fr](mailto:cbowler@biologie.ens.fr)

<sup>12</sup>Damian Boer, PhD Student, Laboratory of Plant Physiology, Department of Plant Sciences, Wageningen University and Research, Wageningen, Netherlands Email: [damian.boer@wur.nl](mailto:damian.boer@wur.nl)

<sup>13</sup>Detlef Weigel, Professor, Max Planck Institute for Biology Tübingen, Max-Planck-Ring 5, 72076 Tübingen, Germany Email: [detlef.weigel@tuebingen.mpg.de](mailto:detlef.weigel@tuebingen.mpg.de)

<sup>14</sup>Dorothea Bartels, Professor, University of Bonn, Molecular Physiology, Kirschallee 1, D-53115 Bonn, Germany Email: [dbartels@uni-bonn.de](mailto:dbartels@uni-bonn.de)

<sup>15</sup>Edith Heard, EMBL Heidelberg, Meyerhofstr. 1, D-69117 Heidelberg, Germany Email: [edith.heard@embl.org](mailto:edith.heard@embl.org)

<sup>16</sup>Eric Gomès, EGFV, Univ. Bordeaux, Bordeaux Sciences Agro, INRAE, ISVV, F-33882 Villenave d'Ornon, France Email: [eric.gomes@inra.fr](mailto:eric.gomes@inra.fr)

<sup>17</sup>Eva María Gómez Álvarez, Plant Lab, Institute of Life Sciences, Scuola Superiore Sant'Anna, 56127 Pisa, Italy Email: [Eva.Gomez@santannapisa.it](mailto:Eva.Gomez@santannapisa.it)

<sup>18</sup>Fabien Chardon, Université Paris-Saclay, INRAE, AgroParisTech, Institut Jean-Pierre Bourgin (IJPB), 78000, Versailles, France Email: [fabien.chardon@inrae.fr](mailto:fabien.chardon@inrae.fr)

- <sup>19</sup>Hatem Rouached, Plant Mineral nutrition: sensing, signaling, and transport, Plant & Soil Sciences Building, College of Agriculture & Natural Resources, Michigan State University, USA Email: [rouached@msu.edu](mailto:rouached@msu.edu)
- <sup>20</sup>Hannes Kollist, Institute of Technology, University of Tartu, Nooruse 1, Tartu 50411, Estonia Email: [hannes.kollist@ut.ee](mailto:hannes.kollist@ut.ee)
- <sup>21</sup>Ive De Smet, 1 Department of Plant Biotechnology and Bioinformatics, Ghent University, B-9052 Ghent, Belgium, 2 VIB Center for Plant Systems Biology, B-9052 Ghent, Belgium Email: [Ive.DeSmet@psb.vib-ugent.be](mailto:Ive.DeSmet@psb.vib-ugent.be)
- <sup>22</sup>Ido Nir, Department of Biology, Stanford University, Stanford, CA 94305, USA Email: [idonir@stanford.edu](mailto:idonir@stanford.edu)
- <sup>23</sup>Jonathan Jones, The Sainsbury Laboratory, Norwich, United Kingdom Email: [jonathan.jones@tsl.ac.uk](mailto:jonathan.jones@tsl.ac.uk)
- <sup>24</sup>José Pardo-Tomás, IMF-CSIC: Carrer Egipcíacques, 15. 08001 Barcelona, Spain Email: [jose.pardo@csic.es](mailto:jose.pardo@csic.es)
- <sup>25</sup>Xenie Johnson, CEA, CNRS, UMR 7265, BIAM, CEA Cadarache, Aix-Marseille Université, Saint-Paul-lez-Durance, France Email: [Xenie.JOHNSON@cea.fr](mailto:Xenie.JOHNSON@cea.fr)
- <sup>26</sup>Jose R. Dinneny, Department of Biology, Stanford University, Stanford, United States Email: [dinneny@stanford.edu](mailto:dinneny@stanford.edu)
- <sup>27</sup>Laurent LAPLAZE, Université de Montpellier, IRD, CIRAD, Montpellier, France Email: [laurent.laplace@ird.fr](mailto:laurent.laplace@ird.fr)
- <sup>28</sup>Livia Merendino, Université Paris-Saclay, CNRS, INRAE, Univ Evry, Institute of Plant Sciences Paris-Saclay (IPS2), 91405 Orsay, France Email: [livia.merendino@u-psud.fr](mailto:livia.merendino@u-psud.fr)
- <sup>29</sup>Malcolm Bennett, Future Food Beacon and School of Biosciences, University of Nottingham, Nottingham LE12 5RD, UK Email: [Malcolm.Bennett@nottingham.ac.uk](mailto:Malcolm.Bennett@nottingham.ac.uk)
- <sup>30</sup>Martin Antoine, IPSiM, Univ Montpellier, CNRS, INRAE, Institut Agro, Montpellier, France Email: [antoine.martin@cnrs.fr](mailto:antoine.martin@cnrs.fr)
- <sup>31</sup>Michel Havaux, Aix-Marseille University, CEA, CNRS UMR7265, BIAM, CEA/Cadarache, F-13108 Saint-Paul-lez-Durance, France Email: [michel.havaux@cea.fr](mailto:michel.havaux@cea.fr)
- <sup>32</sup>Michael Hodges, Université Paris-Saclay, CNRS, INRAE, Université Evry, Institute of Plant Sciences Paris-Saclay (IPS2), 91190 Gif sur Yvette, France Email: [michael.hodges@universite-paris-saclay.fr](mailto:michael.hodges@universite-paris-saclay.fr)
- <sup>33</sup>Michaël Nicolas, Department of Plants Physiology, Wageningen University and Research, Wageningen, Netherlands Email: [michael.nicolas@wur.nl](mailto:michael.nicolas@wur.nl)
- <sup>34</sup>Michael Wrzaczek, Department of Plant Molecular Signalling, Institute of Plant Molecular Biology, Biology Centre CAS Branisovska 1160/31, 370 05 Ceske Budejovice, Czech Republic Email: [michael.wrzaczek@umbr.cas.cz](mailto:michael.wrzaczek@umbr.cas.cz)
- <sup>35</sup>Nathalie Leonhardt, Laboratoire de Biologie du Développement des Plantes (LBDP), Institut de Biosciences et Biotechnologies d'Aix-Marseille (BIAM), UMR 7265 CNRS-CEA-Université Aix-Marseille II, CEA Cadarache Bat 156, 13108 St Paul lez Durance, France Email: [nathalie.leonhardt@cea.fr](mailto:nathalie.leonhardt@cea.fr)
- <sup>36</sup>Pedro Luis Rodriguez Egea, Instituto de Biología Molecular y Celular de Plantas Consejo Superior de Investigaciones Científicas- Univ. Politécnica Avd de los Naranjos.Edificio CPI, 8 ES-46022 Valencia.Spain Email: [prodriguez@ibmcp.upv.es](mailto:prodriguez@ibmcp.upv.es)
- <sup>37</sup>Peter Schloegelhofer, Professor, Max Perutz Labs, Dr. Bohrgasse 9, Room 5.623 1030, Vienna, Austria Email: [peter.schloegelhofer@univie.ac.at](mailto:peter.schloegelhofer@univie.ac.at)
- <sup>38</sup>Jean-Philippe Reichheld, Laboratoire Ge´nome et De´veloppement des Plantes, Université´ Perpignan Via Domitia, 66860 Perpignan, France Email: [jpr@univ-perp.fr](mailto:jpr@univ-perp.fr)
- <sup>39</sup>Sophie Brunel-Muguet, EVA, Normandie Université, UNICAEN, INRAE, UMR 950 Ecophysiologie Végétale, Agronomie et nutritions N, C, S, SFR Normandie Végétal (FED 4277), Esplanade de la Paix, 14032 Caen, France Email: [sophie.brunel-muguet@inrae.fr](mailto:sophie.brunel-muguet@inrae.fr)
- <sup>40</sup>Stanislav Kopriva, Institute for Plant Sciences, Cologne Biocenter, University of Cologne, Zùlpicher Straße 47b, 50674 Cologne Email: [skopriva@uni-koeln.de](mailto:skopriva@uni-koeln.de)
- <sup>41</sup>Scott Hayes, PhD, Laboratory of Plant Physiology, Department of Plant Sciences, Wageningen University and Research, Wageningen, Netherlands Email: [scott.hayes@wur.nl](mailto:scott.hayes@wur.nl)
- <sup>42</sup>Stanislav Kopriva, Institute for Plant Sciences, Cologne Biocenter, University of Cologne, Zùlpicher Straße 47b, 50674 Cologne Email: [skopriva@uni-koeln.de](mailto:skopriva@uni-koeln.de)
- <sup>43</sup>Vincent Colot,, Institute of Biology of the Ecole Normale Supérieure, Email: [vincent.colot@ens.psl.eu](mailto:vincent.colot@ens.psl.eu)
- <sup>44</sup>Wigge Philip, Leibniz-Institut fuer Gemuse- und Zierpflanzenbau, Großbeeren 14979, German Email: [wigge@igzev.de](mailto:wigge@igzev.de)
- <sup>45</sup>Alice Stra, Biological and Environmental Sciences and Engineering Division (BESE), King Abdullah University of Science and Technology (KAUST), Thuwal, 23955-6900, Saudi Arabia Email: [alice.stra@kaust.edu.sa](mailto:alice.stra@kaust.edu.sa)
- <sup>46</sup>Amal Khalaf Alghamdi, Biological and Environmental Sciences and Engineering Division (BESE), King Abdullah University of Science and Technology (KAUST), Thuwal, 23955-6900, College of Science, King Saud University (KSU), Riyadh, Saudi Arabia Email: [amal.alghamdi@kaust.edu.sa](mailto:amal.alghamdi@kaust.edu.sa)
- <sup>47</sup>Catherine H. Gardener, Biological and Environmental Sciences and Engineering Division (BESE), King Abdullah University of Science and Technology (KAUST), Thuwal, 23955-6900, Saudi Arabia Email: [catherine.gardener@kaust.edu.sa](mailto:catherine.gardener@kaust.edu.sa)
- <sup>48</sup>Clara Stanschewski, Biological and Environmental Sciences and Engineering Division (BESE), King Abdullah University of Science and Technology (KAUST), Thuwal, 23955-6900, Saudi Arabia Email: [clara.stanschewski@kaust.edu.sa](mailto:clara.stanschewski@kaust.edu.sa)
- <sup>49</sup>Izamar Olivas Orduna, Biological and Environmental Sciences and Engineering Division (BESE), King Abdullah University of Science and Technology (KAUST), Thuwal, 23955-6900, Saudi Arabia Email: [izamar.olivasorduna@kaust.edu.sa](mailto:izamar.olivasorduna@kaust.edu.sa)
- <sup>50</sup>Jose L. Moreno Ramirez, Biological and Environmental Sciences and Engineering Division (BESE), King Abdullah University of Science and Technology (KAUST), Thuwal, 23955-6900, Saudi Arabia Email: [jose.morenoramirez@kaust.edu.sa](mailto:jose.morenoramirez@kaust.edu.sa)
- <sup>51</sup>Katja Froehlich, Biological and Environmental Sciences and Engineering Division (BESE), King Abdullah University of Science and Technology (KAUST), Thuwal, 23955-6900, Saudi Arabia Email: [katja.froehlich@kaust.edu.sa](mailto:katja.froehlich@kaust.edu.sa)
- <sup>52</sup>Kirti A. Singh, Biological and Environmental Sciences and Engineering Division (BESE), King Abdullah University of Science and Technology (KAUST), Thuwal, 23955-6900, Saudi Arabia Email: [kirti.bhatt@kaust.edu.sa](mailto:kirti.bhatt@kaust.edu.sa)
- <sup>53</sup>Kyle J. Lauersen, Bioengineering Program, Biological and Environmental Sciences and Engineering Division (BESE), King Abdullah University of Science and Technology (KAUST), Thuwal, 23955-6900, Saudi Arabia Email: [kyle.lauersen@kaust.edu.sa](mailto:kyle.lauersen@kaust.edu.sa)
- <sup>54</sup>Maged M. Saad, Biological and Environmental Sciences and Engineering Division (BESE), King Abdullah University of Science and Technology (KAUST), Thuwal, 23955-6900, Saudi Arabia Email: [maged.saad@kaust.edu.sa](mailto:maged.saad@kaust.edu.sa)
- <sup>55</sup>Manuel Aranda, Red Sea Research Center (RSRC), Biological and Environmental Sciences and Engineering Division (BESE), King Abdullah University of Science and Technology (KAUST), Thuwal, 23955-6900, Saudi Arabia Email: [manuel.aranda@kaust.edu.sa](mailto:manuel.aranda@kaust.edu.sa)

<sup>56</sup>Marilia Almeida-Trapp, Core labs, King Abdullah University of Science and Technology (KAUST), Thuwal, 23955-6900, Saudi Arabia Email: [marilia.trapp@kaust.edu.sa](mailto:marilia.trapp@kaust.edu.sa)

<sup>57</sup>Matthew F. McCabe, Hydrology, Agricultural and Land Observation, Water Desalination and Reuse Center, Biological and Environmental Science and Engineering Division, King Abdullah University of Science and Technology, Thuwal, Saudi Arabia Email: [matthew.mccabe@kaust.edu.sa](mailto:matthew.mccabe@kaust.edu.sa)

<sup>58</sup>Mauricio Lopez-Portillo Masson, Laboratory for Genome Engineering and Synthetic Biology, Division of Biological Sciences, 4700 King Abdullah University of Science and Technology, Thuwal 23955-69 Email: [mauricio.lopezportillomasson@kaust.edu.sa](mailto:mauricio.lopezportillomasson@kaust.edu.sa), Saudi Arabia.

<sup>59</sup>Mark Tester, Biological and Environmental Sciences and Engineering Division (BESE), King Abdullah University of Science and Technology (KAUST), Thuwal, 23955-6900, Saudi Arabia Email: [mark.tester@kaust.edu.sa](mailto:mark.tester@kaust.edu.sa)

<sup>60</sup>Brandt Wulff, Biological and Environmental Sciences and Engineering Division (BESE), King Abdullah University of Science and Technology (KAUST), Thuwal, 23955-6900, Saudi Arabia Email: [brandt.wulff@kaust.edu.sa](mailto:brandt.wulff@kaust.edu.sa)

<sup>61</sup>Ikram Blilou, Biological and Environmental Sciences and Engineering Division (BESE), King Abdullah University of Science and Technology (KAUST), Thuwal, 23955-6900, Saudi Arabia Email: [ikram.blilou@kaust.edu.sa](mailto:ikram.blilou@kaust.edu.sa)

<sup>62</sup>Salim Al-Babili, Biological and Environmental Sciences and Engineering Division (BESE), King Abdullah University of Science and Technology (KAUST), Thuwal, 23955-6900, Saudi Arabia Email: [Salim.Babili@KAUST.EDU.SA](mailto:Salim.Babili@KAUST.EDU.SA)

<sup>63</sup>Jean Colcombet, Institute of Plant Sciences - Paris-Saclay (IPS2) Bâtiment 630, rue de Noetzlin, Plateau du Moulon 91405 Orsay, France Email : [jean.colcombet@universite-paris-saclay.fr](mailto:jean.colcombet@universite-paris-saclay.fr)

<sup>64</sup>Iain M. Young, Biological and Environmental Sciences and Engineering Division (BESE), King Abdullah University of Science and Technology (KAUST), Thuwal, 23955-6900, Saudi Arabia Email: [iain.young@kaust.edu.sa](mailto:iain.young@kaust.edu.sa)

<sup>65</sup>Heribert Hirt, Biological and Environmental Sciences and Engineering Division (BESE), King Abdullah University of Science and Technology (KAUST), Thuwal, 23955-6900, Saudi Arabia Email: [heribert.hirt@kaust.edu.sa](mailto:heribert.hirt@kaust.edu.sa)

## Abstract

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 to up to 25 % of total GHG emissions, plant scientists are at center stage to find possible solutions to a transition to sustainable agriculture and land use. In this article, the PlantACT! initiative of plant scientists lays out a road map in which areas and how plant scientists can contribute to find immediate, mid-term and long-term solutions and what changes are necessary in the way to work out these solutions at the personal, institutional and funding level.

## I. The climate emergency

Humanity is facing an unprecedented challenge from climate change [1]. The CO<sub>2</sub> 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 not possible any more, achieving climate neutrality is more important than ever, by reducing net CO<sub>2</sub> emissions to zero through a 45% reduction in emissions within 10 years [1]. This represents a disruptive goal which demands new thinking, solutions and commitments.

The atmospheric temperature increase caused by rising carbon dioxide concentrations will not decrease significantly even after zero carbon emissions (peak carbon) have been achieved [3]. The climate effects of atmospheric CO<sub>2</sub> at peak carbon will remain irreversible for at least 1,000 years, if not counteracted by a net reduction in atmospheric CO<sub>2</sub>. In reality, anthropogenic climate change is irreversible over the next 10 generations at least, unless rapid measures are taken to sequester carbon dioxide 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 Gt C per year. The vast majority of this assimilated carbon is returned to the atmospheric CO<sub>2</sub> 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 of atmospheric CO<sub>2</sub> concentration. Net anthropogenic annual carbon emissions are leading to an estimated 5.2 Gt C increase in atmospheric CO<sub>2</sub> in 2022 [4] [Figure 1). All paths towards the 1.5°C goal depend on a rapid reduction of the carbon footprint of agriculture, forestry and land use, combined with the use of bioenergy with carbon capture and storage [5-7].

## **II. Agriculture as a Contributor to Climate Change**

Agriculture is both a victim and culprit of global climate change as 20-25% of GHGs are released through agricultural activities. Apart from CO<sub>2</sub>, significant amounts of methane and nitrous oxide are emitted from agriculture which represent more potent greenhouse

gases than CO<sub>2</sub> (>30 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 organic and mineral nitrogen fertilizer use. However, both gases have a shorter lifespan than CO<sub>2</sub>: methane and N<sub>2</sub>O remain in the atmosphere for 12 and 114 years compared to 300-1,000 years for CO<sub>2</sub> [9]. Hence, unlike CO<sub>2</sub>, reductions in both of these other greenhouse gases would deliver rapid benefits (Box 1).

The N fertilizer supply chain currently contributes >2% greenhouse gas (GHG) emissions [10]. Global use of synthetic N fertilizers is predicted to increase 50% by 2050 [11]. When N fertilizers are applied, significant amounts of N<sub>2</sub>O are generated through microbial conversion in the soil [10]. In the short term, the most effective strategy is reducing the amount of N applied [12] to avoid over-fertilization through improvements in agronomy, extension advice and management practices. In the short to medium term, a switch to agro-systems utilizing legume crops able to naturally fix nitrogen 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.

The majority of CO<sub>2</sub> 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<sub>2</sub> 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 of beef. Increasingly shifting away from animal to alternative protein sources would provide major benefits [17]. In the short term, reducing demand for soya-based 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.

Given the central importance of food, a reduction of greenhouse-gas emissions from agriculture is a major challenge and will require the implementation of a range of techniques and tools, from 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.

### **III. 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 of 70-100% in food production 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<sub>2</sub> emissions and further jeopardizes 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 (Table 1) showing increased heat- and drought-resistance, enhanced water-use efficiency (Box 2) and, in general, improved resilience to the changes in environmental conditions.

Tackling climate change requires the use of cropping systems, either already available but not broadly used or novel ones 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 better climate change-adapted crops. 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 contribute to efficient adaptation strategies to cope with climate change. In this context, the PlantACT! initiative (Plants for climate ACTion!) will alert, engage and work on solutions to reduce agriculture-based GHG emissions and facilitate a more equitable and sustainable global food production system.

#### **IV. Plants, soil and microbes as actors for mitigation**



Soil was long considered solely as an inert growth substrate. If the chemical and physical properties were not suitable, herbicides, fertilizers and pesticides had to be added to 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 of the soil-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 (Box3). 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.

## **V. Conclusions**

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 both at the institutional, funding, as well as subject levels to enable multidisciplinary scientific approaches. The present-day scientific culture of exclusive scientific exchange in specific fields needs to be broken down and new forms of interdisciplinary conferences and communication need to be established (e.g. ideas labs, 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, introducing genes into elite crop varieties takes 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 to Sub-Saharan Africa where population growth will be highest this century. Moreover, land in many countries is limited, but less 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 inter-disciplinary 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 inter-disciplinary interactions and solutions by stimulating new forms of working and funding (Box 4).

### **Acknowledgements**

The work of HH was supported by baseline grant BAS/1/1062-01-01 from King Abdullah University of Science and Technology, Thuwal, KSA. APMW acknowledges funding under Germany's Excellence Strategy EXC-2048/1, Project ID 390686111 and the European Union H2020 project 862087-GAIN4CROPS

### **References**

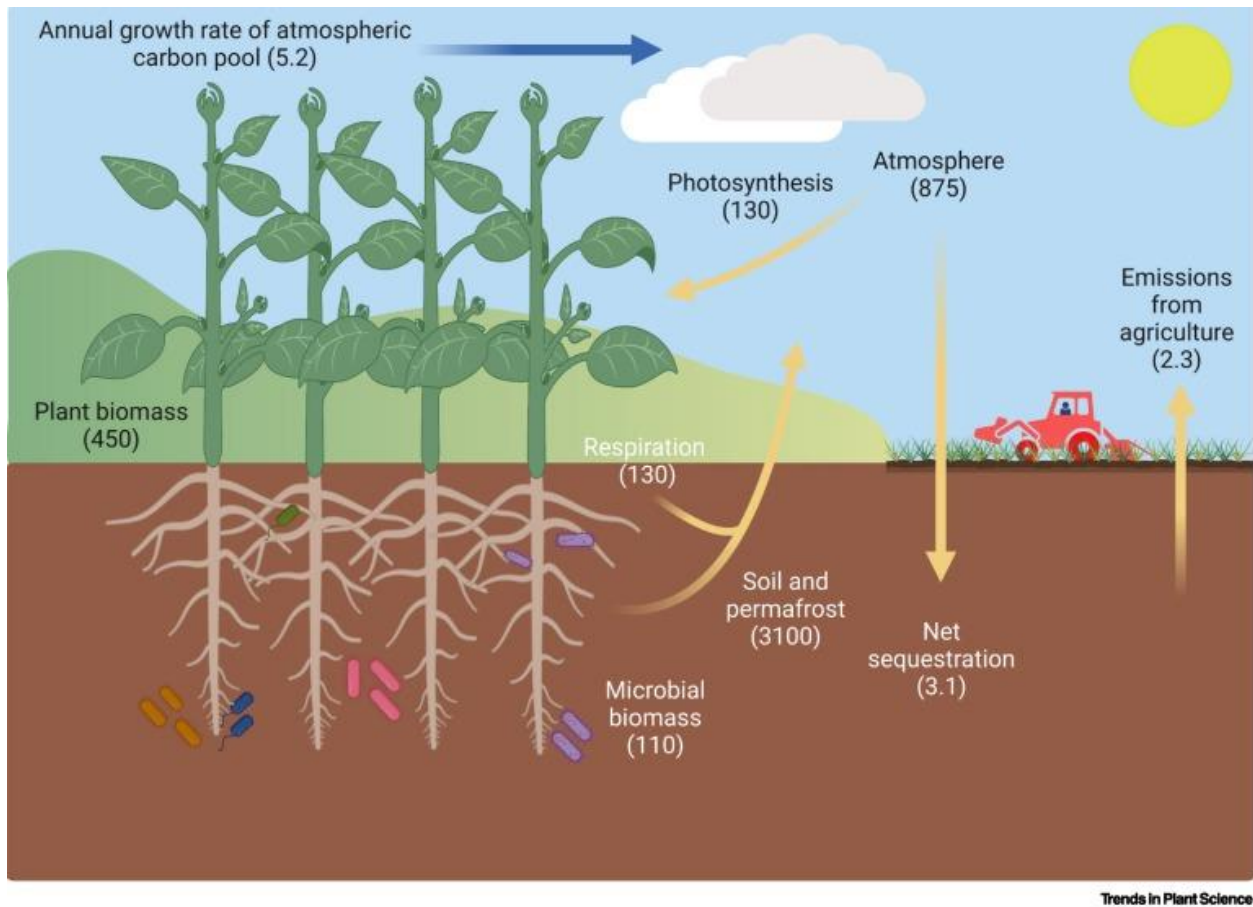
1. IPCC 2022 Climate Change 2022: Impacts, Adaptation and Vulnerability. <https://www.ipcc.ch/report/ar6/wg2/>
2. Ourbak, T. & Tubiana, L. Changing the game: the Paris Agreement and the role of scientific communities. *Clim Policy* 1–6 (2017).
3. Solomon S, Plattner GK, Knutti R, Friedlingstein P. (2009) Irreversible climate change due to carbon dioxide emissions. *Proc Natl Acad Sci U S A* 106(6):1704-9.
4. Friedlingstein P., et al. (2022) Global Carbon Budget 2022 *Earth Syst. Sci. Data*, 12, 3269–3340.
5. Fajardy, M., Köberle, A., Dowell, N. M. & Fantuzzi, A. (2019) *BECCS deployment: a reality check*. 1–16 <https://www.imperial.ac.uk/media/imperial-college/grantham->

institute/public/publications/briefing-papers/BECCS-deployment---a-reality-check.pdf

6. Searchinger, T. D., Wiersenius, S., Beringer, T. & Dumas, P. (2018) Assessing the efficiency of changes in land use for mitigating climate change. *Nature* **564**, 249–253.
7. Leifeld, J. & Menichetti, L.(2018) The underappreciated potential of peatlands in global climate change mitigation strategies. *Nat Commun* **9**, 1071.
8. Smith P., Reay D. & Smith J (2021) Agricultural methane emissions and the potential for mitigationPhil. Trans. R. Soc. A.3792020045120200451.
9. Forster, P., et al. (2007). Changes in atmospheric constituents and in radiative forcing. Cambridge University Press, Cambridge, UK.
10. Menegat S, Ledo A, Tirado R. (2022) Greenhouse gas emissions from global production and use of nitrogen synthetic fertilisers in agriculture. *Sci Rep.* 12(1):144905.
11. FAO 2018. The future of food and agriculture—Alternative pathways to 2050. 60 p. Licence: CC BY-NC-SA 3.0 IGO. .
12. Sutton M.A., et al. (2013) Our Nutrient World: The challenge to produce more food and energy with less pollution. Global Overview of Nutrient Management. Centre for Ecology and Hydrology, Edinburgh on behalf of the Global Partnership on Nutrient Management and the International Nitrogen Initiative.
13. Stagnari, F., Maggio, A., Galieni, A. *et al.* (2017) Multiple benefits of legumes for agriculture sustainability: an overview. *Chem. Biol. Technol. Agric.* **4**, 2.
14. Hamont, O. (2019) Plant scientists can't ignore Jevons paradox anymore. *Nature Plants* **6**, 720-722.
15. P.R. Shukla, J. Skea, R. Slade, R. van Diemen, E. Haughey, J. Malley, M. Pathak, J. Portugal Pereira (eds.) Technical Summary, 2019. In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems.

16. Aleksandrowicz L, Green R, Joy EJ, Smith P, Haines A. The Impacts of Dietary Change on Greenhouse Gas Emissions, Land Use, Water Use, and Health: A Systematic Review. *PLoS One*. 2016 Nov 3;11(11):e0165797.
17. R. Gaillac, S. Marbach, (2021) The carbon footprint of meat and dairy proteins: A practical perspective to guide low carbon footprint dietary choices. *J. Cleaner Prod.*, 321, 128766,
18. Boerema A, Peeters A, Swolfs S, Vandevenne F, Jacobs S, Staes J, Meire P. (2016) Soybean Trade: Balancing Environmental and Socio-Economic Impacts of an Intercontinental Market. *PLoS One*. 11(5):e0155222.
19. Kell, D. B. Large-scale sequestration of atmospheric carbon via plant roots in natural and agricultural ecosystems: why and how. *Philosophical Transactions Royal Soc B Biological Sci* **367**, 1589–1597 (2012).
20. Schweitzer, H. *et al.* Innovating carbon-capture biotechnologies through ecosystem-inspired solutions. *One Earth* **4**, 49–59 (2021).
21. IPCC emission database: <https://www.ipcc-nggip.iges.or.jp/EFDB>
22. van Oort PAJ, Zwart SJ. (2018) Impacts of climate change on rice production in Africa and causes of simulated yield changes. *Glob Chang Biol*. 3:1029-1045.
23. Ndoye S., Burrige J., Bhosale R., Grondin A., & Laplaze L. (2022) Root traits for low input agroecosystems in Africa: lessons from three case studies. *Plant, Cell & Environment*, 45: 637– 649.
24. Bailey-Serres J, Parker JE, Ainsworth EA, Oldroyd GED, Schroeder JI. (2019) Genetic strategies for improving crop yields. *Nature*. 575:109-118.
25. Syed S, Buddolla V, Lian B. (2020) Oxalate Carbonate Pathway-Conversion and Fixation of Soil Carbon-A Potential Scenario for Sustainability. *Front Plant Sci*. 11:591297.
26. Jansson C, Faiola C, Wingler A, Zhu XG, Kravchenko A, de Graaff MA, Ogden AJ, Handakumbura PP, Werner C, Beckles DM. (2021) Crops for Carbon Farming. *Front Plant Sci*. 12:636709.

## Figures



**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 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 FAO (Food and Agriculture Organization of the United Nations, <https://www.fao.org/3/cb3808en/cb3808en.pdf>). The FAO data includes greenhouse gases other than CO<sub>2</sub>, converted to CO<sub>2</sub> equivalents. Adapted from [26] with data from [4] and [11] (created with BioRender.com).

### **Box 1. Reducing methane emissions from rice production.**

Methane is the second most important greenhouse gas after CO<sub>2</sub> and is >20 times more potent than CO<sub>2</sub>. Rice paddy fields emit 10g CH<sub>4</sub>/m<sup>2</sup> [21] 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 agro-systems (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 [22]. To tackle this, plant scientists (working together with agronomist, hydrologist, microbial ecologist and agro-socio-economists) 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 [23] but also the use of perennial rice varieties.

### **Box 2. Enhancing water use efficiency and carbon capture**

Carbon gain in photosynthesis is a water consuming process as fixing one molecule of CO<sub>2</sub> requires hundreds of molecules of H<sub>2</sub>O lost by transpiration. However, there is substantial natural variation of water use efficiency (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 aperture can lead to decreased CO<sub>2</sub> 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 C<sub>4</sub> plants (and/or C<sub>3</sub>-C<sub>4</sub> intermediates) can perform photosynthesis at lower stomatal aperture. Examples

from breeding for WUE has pointed to genes involved in stomatal patterning, abscisic acid homeostasis and CO<sub>2</sub> signaling [24].

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

Soil organic carbon (SOC) represents a major form of terrestrial C storage (Figure 1). 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<sub>2</sub> in an inorganic form that is highly stable. Fungi and bacteria associated to these plants (called oxalotrophs) can use oxalate as their sole carbon and energy sources. In a soil that is rich in Ca<sup>2+</sup> or Mg<sup>2+</sup>, these microbes can produce Ca<sup>2+</sup>- or Mg<sup>2+</sup>-carbonates which thereby increase the soil inorganic carbon (SIC) content [25]. These natural CO<sub>2</sub> trapping systems that are primarily found in arid and hyper-arid regions could provide novel and important C sequestration alternatives. Such systems do not compete with agricultural land and can fix carbon in the soil for decades to centuries.

### **Box 4. Re-designing 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 re-design 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 for 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 trans-disciplinary interactions and solutions by stimulating new forms of working and funding.

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

GHG Source	Avoid	Adapt	Mitigate
Methane	Reduce dependence on ruminant livestock protein Rice paddy-field management (Box 1)	Perennial crops Improve rice seedling early vigor (Box1)	Capture methane emissions at source
Nitrous Oxide	Reduce synthetic N fertilizer use N <sub>2</sub> -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	Reforestation Restoration of peat moss De-desertification
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)

Colors indicate estimated timeframes to implementation: ■ short-term (within a decade), ■ mid-term (one to several decades), ■ long-term (centennial).