PERSPECTIVE
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Technologies to deliver food and climate security through agriculture

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Agriculture is a major contributor to environmental degradation and climate change. At the same time, a growing human population with changing dietary preferences is driving ever increasing demand for food. The need for urgent reform of agriculture is widely recognized and has resulted in a number of ambitious plans. However, there is credible evidence to suggest that these are unlikely to meet the twin objectives of keeping the increase in global temperature within the target of 2.0 °C above preindustrial levels set out in the Paris Agreement and delivering global food security. Here, we discuss a series of technological options to bring about change in agriculture for delivering food security and providing multiple routes to the removal of CO_2 from the atmosphere. These technologies include the use of silicate amendment of soils to sequester atmospheric CO_2, agronomy technologies to increase soil organic carbon, and high-yielding resource-efficient crops to deliver increased agricultural yield, thus freeing land that is less suited for intensive cropping for land use practices that will further increase carbon storage. Such alternatives include less intensive regenerative agriculture, afforestation and bioenergy crops coupled with carbon capture and storage technologies.

There is considerable urgency surrounding the development of new approaches to global agriculture that enable both food and climate security[1,2]. An influential blueprint for reform of global agriculture published two decades ago[3] included advocating a change in diet away from meat and dairy consumption, halting agricultural expansion, increasing crop resource use efficiency, closing of yield gaps and reducing food loss and waste. These key recommendations are repeated in numerous subsequent reports[1,4] and could help deliver future food security and environmental sustainability. Adherence to such reforms is required if the global agrifood system is not to undermine efforts to meet the Paris climate change targets[5]. Unfortunately, progress on the core elements of this blueprint has been limited. Global dietary trends are currently the opposite of those that are required[6]. Global croplands are expected to continue to expand[7], and closing yield gaps remains a persistent issue in underperforming land, especially in low- and middle-income countries[8]. Meanwhile, increasing agricultural resource efficiency[9] and reducing food loss and waste are major challenges[10]. Moreover, current rates of improvement in average crop yields per hectare are insufficient to meet the 60% increase in demand forecast by 2050, a situation that will likely be exacerbated by climate change[11]. Additional practical measures are needed to bring about the required level of change to the agrifood system[12].

In this Perspective we outline a complementary series of technological options for sustainable, productive and resilient agriculture, that provide multiple routes for removing CO_2 from the atmosphere to directly mitigate climate change. We highlight three key requirements. First, the transformation of land management and agronomic practice, in particular using innovative soil amendments that simultaneously increase soil fertility and capture CO_2, which is stored in organic and inorganic forms. Second, engineering crops to increase both efficiency of resource use and yield, and to maximally exploit the new agronomic practice and deliver its objective of carbon sequestration. Third, to use the land made available by increased yield (or reduced demand) for further carbon sequestration in less intensive regenerative agriculture, by reforestation or afforestation, or for bioenergy with carbon capture and storage (Fig. 1).

Large-scale long-term research development and demonstration programmes are required to evaluate these technologies in different agricultural systems across the world. Alongside the assessment of the operational challenges and implementation risk, societal and cultural issues also have to be taken into account[13], in particular because modern technology-driven agriculture is often seen as a problem. However, because they are designed to combat climate change, the agricultural technologies proposed below have the potential to turn a problem into a solution.

Soils innovation

Increasing soil organic carbon. Land management and agronomy are already reducing and reversing soil degradation and increasing soil carbon with measures such as contour ploughing, reduced tillage, cover crops and buffer strips along areas of ephemeral drainage. The impact of these practices, initiated almost 50 years ago, has been revealed by the relatively new technologies of eddy-covariance measurement of carbon balance between the landscape and atmosphere and mass isotope analysis of soils (for example, in ref. [14]). A major advance of the last few decades, now used across the Americas, was the introduction of transgenic herbicide-tolerant crops. This has enabled farms to control weeds without the need for tillage. Analyses reveal that there was a net accumulation of $1.6\,\mathrm{MgC\,ha^{-1}\,yr^{-1}}$ from the atmosphere for no-till crops but a net loss of $0.2\,\mathrm{MgC\,ha^{-1}\,yr^{-1}}$ for tilled crops[14]. At this rate, complete conversion of the approximately 90 Mha in corn–soy rotation in the US would sequester 21.7 TgC annually, and this figure would be expected to increase. In the past 60 years, Midwest maize production has increased almost threefold. This has increased not only

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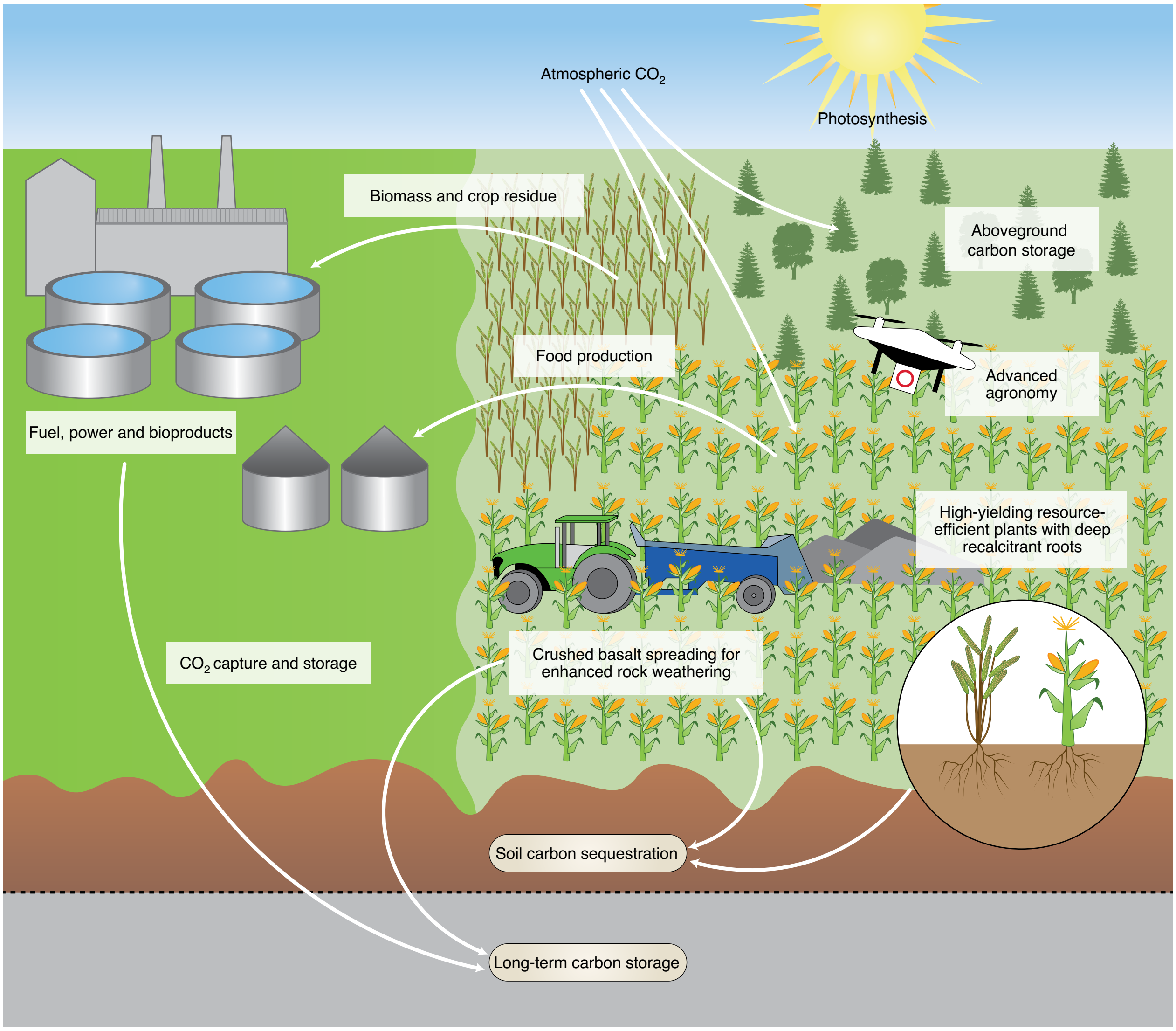

Fig. 1 | Options for food security and climate change mitigation using soil and crop innovations and agricultural land reclamation. Photosynthesis by bioengineered resource-efficient, high-yielding crop varieties cultivated using advanced agronomic practices increase food production, and soil organic carbon storage is enhanced by deep recalcitrant roots (brown area). Reclaimed land is used for afforestation, which sequesters CO_2 into aboveground biomass, and for cultivation of similarly productive bioenergy crops. Biomass, crop residues and unavoidable wastes are processed for fuel, power and bioproducts, and released CO_2 is captured and processed for long-term geological storage (grey area). Co-deployment of basalt application supports high productivity throughout and enables further CO_2 sequestration through ERW, increasing inorganic carbon storage in the soil and soluble bicarbonate production, with long-term geological storage in oceans.

grain biomass, but also stem, leaf and root biomass, providing more residue for the soil. Today, all but the grain remains on the field after harvest, with burning of stubble eliminated, thereby providing very substantial carbon input to the soil. A similar reversal for sugarcane production in Brazil resulted from the elimination of burning and the current practice of leaving leaf and plant tops on the field at harvest. Greenhouse gas (GHG) flux measurements revealed a net sink of 15.5 tonnes CO_2-equivalent $ha^{-1} yr^{-1}$ by using this system[15]. We envisage continued improvements in agronomic practice that work together with and optimize the proposed plant and soil interventions set out below.

There is a potential for breeding crops that further increase and stabilize soil carbon. For example, the drive to develop cellulosic fuels has identified genetic traits that make stem biomass more easily digestible, but has also revealed how plant cell walls could be made more resilient to decomposition[16]. Breeding for these traits would favour increased accumulation of carbon in the soil. Another innovation would be to engineer new crop varieties with increased sink capacity to store photosynthate in enhanced root systems capable of synthesizing specific stable carbon compounds[17].

Amendment of soil with added sources of organic carbon, such as green manures, biochars and organic fertilizers produced from waste streams increases the content of stored carbon, and has been proposed as an option for climate change mitigation[18]. Recent international initiatives such as the 4p1000 initiative led by the French Government[19] and the Food and Agriculture Organization (FAO) recarbonisation of global soil (Recsoil) programme[20] have promoted this option. Natural soil contains vast numbers of organisms and an enormous range of bacterial and fungal species, which recycle nutrients, transform soil carbon and form symbioses with each other and with the inhabiting plants. A key advance will be to fully understand how each component of the soil microbiome and the physical and chemical properties of soil work together to enable healthy plant growth, and how the resulting chemical, physical and biological properties determine suitability for different plant types. It may then be possible to design plant–microbe–soil ecosystems, specifically adapted for particular crops, climates, geographic areas, nutrient availability and soil types, as well as for remediation of damaged soils[21–23].

Enhanced rock weathering for carbon sequestration. Enhanced rock weathering (ERW) is a CO_2 removal (CDR) technology based on amending soils with crushed calcium- and magnesium-rich silicate rocks to accelerate natural CO_2 sequestration processes[24], while delivering co-benefits for crop production and soil health[25–27]. Basalt, an abundant fast-weathering rock, is a prime rock for implementing ERW in agriculture because it releases plant-essential inorganic nutrients. CDR and storage via ERW of crushed basalt applied to soils occurs as rainwater with dissolved CO_2 percolates through soil, interacts with roots and microbes, and reacts with base cations (Ca^{2+}, Mg^{2+}, Na^+ and K^+) to produce HCO_3^- ions (alkalinity). The HCO_3^- ions that form are either transported to the ocean, where the carbon is sequestered on timescales of more than 10^5 years, or precipitated as pedogenic carbonates, which are typically stable on timescales of around 10^4 years[28] (Fig. 1).

Quantification of potential co-benefits is necessary to generate evidence for catalysing early adoption and accelerating development pathways into standard agricultural practices. Emerging evidence from small-scale field trials[29–31] and experiments[32] is supportive. The capacity of ERW to increase soil pH and resupply depleted soil silica pools alone could boost crop yields, given that soil acidification results from intensification of agriculture. Acidified soils constrain crop production by limiting nutrient uptake on about 200 million hectares of managed lands[25,33]. Considerable unrealized potential exists for extending ERW practices by spreading basalt on grasslands, rangelands and pastures, whose productivity is often limited by soil acidification and depletion of nutrients, including silica. Thus there are possibilities for co-deployment of ERW both in agriculture and in the various land-reclamation options discussed below.

Further research is required to assess costs of CO_2 drawdown, environmental risks (for example, accumulation of potentially toxic metals) and responses of soil organic carbon stocks with ERW. Options for meeting the demand for silicate rock in a sustainable, publicly acceptable manner must also be assessed, including opportunities for using rock dust by-products of the mining industry to facilitate ERW scalability without additional mining, thereby building a circular economy[27].

Crop innovation

Increased yield potential. Increases in crop yield potential will depend on increased total biomass, given that harvest index is now maximized for the major food crops. Increased photosynthetic efficiency may thus be the only remaining option[34,35]. For a long time, it was accepted that evolution and selection would have already optimized the process, with little prospect of improvement. However, analysis has shown that efficiency in current crop cultivars falls far short of the theoretical maximum[35]. Photosynthesis is probably the most studied of all plant processes, and these studies have yielded key insights into how efficiency could be increased[34,35]. This has culminated in demonstrated substantial increases in photosynthetic efficiency, crop productivity and sustainability in replicated field trials[36–38]. These advances are now being transferred to and demonstrated in key food crops[39]. One such innovation, designed to future-proof soybean against rising CO_2 concentration and temperature, has already been demonstrated under field conditions[40]. It should be emphasized how crucial it is to increase plant photosynthesis if climate and food security are to be delivered: with higher photosynthetic capacity and higher consequent biomass production, it will be possible to consider how to optimize allocation within the plant, to allow both high food yield and increased soil carbon storage in roots using the approaches described above.

Improved water use efficiency. Realizing increased yield potential in farm fields requires an adequate water supply for the crop. This suggests two possible problems. First, rising temperature increases the drying power of the atmosphere exponentially, so crops will require substantially more water in the future. Second, success in increasing production potential would only be realized in higher yield if more water is available. For example, the US corn–soy belt, the largest single area of global food production, is currently predominantly rainfed, but to meet future food demand it would have to become predominantly irrigated[41]. Will it be possible to meet future demand without stressing water resources even further? Photosynthesis and water use are inextricably linked, because the leaf stomata control the influx of CO_2 and the loss of water; adjusting stomatal function has thus been the focus for much research[42]. Recently, upregulation of a single gene has been shown to increase crop water use efficiency[43], and similar gains may be achieved by manipulating stomatal numbers and distribution[44]. Increasing the rate of opening and closing of stomata when light levels change has been suggested to be a target for increasing water use efficiency and biomass accumulation[45], recently borne out experimentally[46].

Further efficiencies are offered by agronomic practices that improve soil pore and aggregate structure, which increase the capacity of soil to both store and supply plant-available water. All of the soil amendments described above support soil structure development, which is intimately linked to plant traits that contribute to photosynthate allocation below ground[47].

Reduced nitrogen fertilizer requirement. Fertilizer is the principal source of GHG emissions from cereal farming[48], but achieving increased crop yield without increasing nitrogen fertilizer applications is a challenge. A cereal yield of 10 t ha^{-1} with an average of 10% protein content requires a minimum addition of 160 kg N ha^{-1}, and this assumes the crop assimilates all of the applied fertilizer and all of this is translocated to the grain at crop maturation. For every additional ton of yield, an additional 16 kg N ha^{-1} will be required. New approaches to supporting plant nitrogen metabolism are urgently needed. One approach is to develop nitrogen-fixing cereals by introducing plant genetic elements that allow invasion by nitrogen-fixing bacteria[49]. However, nitrogen fixation is costly to the plant, accounting for an estimated 50% of potential biomass in legumes. Losses would be greater where nitrogen comes from free-living nitrogen fixers in the microbiome. These losses could be offset by simultaneously increasing photosynthetic efficiency using the technologies noted above. Another novel approach may come from understanding how plants respond to nitrogen availability, which could allow much more efficient nitrogen use[23,50].

Improved agronomic practice currently has the most important role in reducing fertilizer applications through precision placement in the field. Global Positioning System (GPS)-tracked harvesting provides high-spatial-resolution datasets on variation in yield across fields, identifying where fertilizer is needed most in subsequent planting, while unmanned aerial vehicles can routinely track colour to guide top-dressing. This is increasingly supported by high-throughput high-resolution probing of soil quality, making most farm operations driven increasingly by big data, coupled with better agricultural weather forecasting for timing farm operations. Robotics coupled with GPS could further revolutionize the situation: enabling an operator to monitor multiple robots planting in more optimal agronomies, weeding, harvesting and monitoring pests and diseases for targeted chemical intervention only where needed[51]. By contrast, on the non-mechanized smallholdings that feed much of sub-Saharan Africa, improvements can come from optimal placement of seed and fertilizer, together with multi-cropping, as successfully being promoted by the One-Acre Fund[52].

Agricultural land reclamation

If the food produced per unit land area could be sustainably increased and be resilient to climate change, a reduction in total agricultural land area could be realized. For example, it is estimated that the Green Revolution saved 18–27 million hectares of land from cultivation[53]. This would allow for the possibility for the land that is under pressure to be used for less intensive localized regenerative farming practices that store soil carbon, or restored to forests and grasslands that store carbon in aboveground and belowground biomass and in soils[54]. This rationale has become a major part of the 'natural climate solutions'[55,56]. However, with the projected need for 60% more food by 2050, we must recognize that it will probably be challenging merely to constrain agriculture to the land it is already using, and this raises the questions: (1) what processes are most likely to reduce agricultural land? and (2) what are the best strategies for using the land made available?

Processes for agricultural land reduction. Two types of changes in the agrifood system have been suggested as means to reduce agricultural land use. First, reducing global meat consumption alone would free up the vast land areas currently used to provide grazing and feed crops for livestock. This forms a pivotal part of agrifood-related climate change mitigation proposals[4]. However, reducing meat consumption presents a major challenge: not only altering diets in high-income countries but especially halting and reversing the dietary transition in low- and middle-income countries . Because there is a strong correlation between economic development and meat consumption[7], it is unlikely that land use that supports livestock will decrease in the near future without drastic changes in human behaviour driven by health concerns and/or substantial policy changes[6].

Second, it has long been recognized that if the yield gap could be closed, large amounts of agricultural land could be released. The yield gap is the difference between the maximum potential yield, or that achieved by best practices for a crop, versus the yield achieved on average. It can also be described as the gap between yields achieved in high-income countries and in low-income countries, especially those whose food security is challenged. For more than 50 years, much national investment and international aid has been focused on this challenge. Most recently, it has been projected from modelling that closing the yield gap could release 50% of agricultural land globally, but this requires substantial increases in yield across Africa[57]. Is this realistic? The facts suggest not with current technologies. While access to seed, equipment and agrochemicals are important, closing the yield gap cannot be achieved without substantial quantities of fertilizer and plant-available water (see 'Improved water use efficiency'). In the poorer countries of Africa, even when farms can afford fertilizer at the required level, there are often no adequate road systems for delivery. The challenge of closing the yield gap is evident in the fact that African farms, on average, achieved 27% of the maize yield of North American farmers in 1962, declining to just 17% in 2018 (ref. [58]). Closing the yield gap is further threatened by climate change, which the Intergovernmental Panel on Climate Change have forecast, with high confidence, will be disproportionately worse for food production in Africa[1].

The Green Revolution was driven by the development of genetically advantaged seed. By passing from farmer to farmer, advantaged seed becomes widely dispersed even in the absence of other support infrastructure, as do new cultivation methods. The preceding sections show genetic and biotechnological approaches that promise advantaged seed with higher yield potential, improved water use efficiency, and possibly capacity to fix nitrogen and mine phosphorus. These developments offer the potential to help overcome some of the recognized economic and infrastructure barriers facing farmers and smallholders in low- and middle-income countries. A key further consideration will be how opportunities are perceived and the local conditions and preferences for change.

Strategies for use of reclaimed land. Land use must be on the basis of active land management derived from knowledge of ecology, biology and climate, recognizing the complexity of ecosystems[59]. The most suitable land areas need to be selected for different functions, and refined indices of GHG accounting that consider the best options for land use incorporated into decision making. For example, a recent technoeconomic analysis shows that, where practical, bioenergy schemes, especially when combined with carbon capture and storage (BECCS) would provide substantially greater GHG mitigation than afforestation[60] (Fig. 1).

Afforestation includes three options: restoration of natural forests; agroforestry in which trees are interspersed with suitable crops; and tree plantations, for commercial use of timber[61]. The implementation of the mix of these options depends upon numerous factors, particularly geography and climate—the humid tropics represent the best option for natural forest regeneration with maximum carbon storage potential. Specific management practices, such as planting of highly productive trees, especially nitrogen fixers, and other chosen plant species, which could be used as construction materials or as energy crops, could be more likely to have a substantial effect in the needed timeframe than natural regeneration. Especially important in predicting the carbon capture potential of these interventions is the effects of climate change—particularly the increased incidence of wildfires[62].

A further important consideration is the time taken for any restoration intervention to have an impact on carbon sequestration. A 140-year study, which documented the long timescale for carbon accumulation in the transformation of land that had been arable for hundreds of years, pointed to the importance of local environmental factors such as soil acidity and nitrogen accumulation[63]. In another study of woodland restoration on land once cleared from forest for cropping and then abandoned, it was not until after 40 years that a semblance of the original pine–oak forest was achieved, and net primary productivity reached only $3.0\,\mathrm{Mg\,C\,ha^{-1}\,yr^{-1}}$. In cooler and drier locations, an even longer re-establishment must be expected.

An example of the complexities involved in restoration is seen in the United States Midwest, where land taken out of production because of its erodibility has been largely left to restore the natural prairie. Prairie species include perennials that produce surface roots and rhizome systems that help bind the soil, prevent wind and water erosion, and deposit carbon to build the soil and its quality. In the absence of the large grazers that once roamed the prairie, maintenance of prairie and similarly steppe requires annual burning. However, there are highly productive grass perennials that might be at least as effective; these include switchgrass, prairie cord-grass and *Miscanthus*. *Miscanthus* is of particular interest since when harvested post-senescence, it remains productive without fertilization. In side-by-side field trials, net GHG reductions of 0.5, 1.0 and $2.0\,\mathrm{Mg\,C\,ha^{-1}\,yr^{-1}}$ with average annual yields of 3.6, 9.2 and 17.2 Mg of dry biomass were achieved for native prairie, switchgrass and *Miscanthus*, respectively, and this was without burn management or addition of fertilizer[64]. Crops such as switchgrass, *Miscanthus*, or woody crops combusted for energy or processed to advanced biofuels when combined with both ERW and carbon capture and storage would offset fossil fuel GHG emissions while removing atmospheric CO_2 into soil and deep geological carbon storage (Fig. 1). Co-deployment of ERW with bioenergy crops and afforestation helps maximize use of land, water and energy while substantially reducing ERW costs and enhancing the combined CDR potential of these methods[26].

Conclusions

In this Perspective we have set out options for delivering a form of agriculture that is designed to meet both the food and climate emergencies: bioengineered resource-efficient crop varieties cultivated in silicate-amended carbon-rich healthy soils using advanced agronomic practice. This form of agriculture gives the possibility of high yields supporting global food security and makes a substantial contribution to extracting atmospheric CO_2, an action that is required alongside emissions cuts to keep within the 2 °C limit set out in the Paris Agreement.

A principal advantage of our plan is that it does not rely on a single predominant reform, such as a change in diet. It does not require huge and unpredictable changes in human culture, lifestyle or economy, though it could be pursued in parallel with such goals. It offers a range of technologies, some of which are ready now and are already being implemented, such as increasing soil organic carbon or using precision agriculture. Others are at the testing and evaluation stages, such as the use of silicates or BECCS. Others are longer term and require more research and development, such as the genetic engineering of new crop varieties, although even here, research on model plant species indicates that this is possible. While integration of these technologies into a full package of measures is the desired priority, not least because of the synergies between them, it is not a necessity—each one can be considered independently for local and regional circumstances that contribute to meeting the twin climate change and food security objectives. A further advantage of such flexibility is that these options can be taken up in different ways in countries with different farming systems and levels of agricultural productivity.

Discussion about agricultural reform has tended to focus on the trade-offs between climate change mitigation and intensive agriculture[65]. By contrast, we advocate a series of emerging agricultural technologies that eliminates this trade-off by delivering both simultaneously, thereby allowing intensive agriculture to have a key role in climate change mitigation.

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Author contributions

P.H., S.P.L., P.S., S.A.B. and D.J.B. wrote the paper.

Competing interests

The authors declare no competing interests.

Additional information

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