

Perspective

Technologies to deliver food and climate security through agriculture

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2 **Agriculture is a major contributor to environmental degradation and climate change. At the same**
3 **time, a growing human population, with changing dietary preferences, is driving ever increasing**
4 **demand for food. The need for urgent reform of agriculture is widely recognised and has resulted**
5 **in a number of ambitious plans. However, there is credible evidence to suggest that these are**
6 **unlikely to meet the twin objectives of keeping the rise in global temperature within the 2.0 °C**
7 **target set out in the Paris Agreement, and delivering global food security. Here, we discuss a**
8 **series of technological options to bring about change in agriculture for delivering food security and**
9 **providing multiple routes to the removal of CO₂ from the atmosphere. These technologies include**
10 **the use of silicate amendment of soils to sequester atmospheric CO₂, agronomy technologies to**
11 **increase soil organic carbon, and high yielding resource efficient crops to deliver increased**
12 **agricultural yield thus freeing land that is less suited for intensive cropping for land use practices**
13 **that will further increase carbon storage. Such alternatives include less intensive regenerative**
14 **agriculture, afforestation and bioenergy crops coupled with carbon capture and storage**
15 **technologies.**

16
17 There is considerable urgency surrounding the development of new approaches to global agriculture
18 that enable both food and climate security^{1,2}. An influential blue-print for reform of global
19 agriculture published two decades ago included advocating a change in diet away from meat and
20 dairy consumption, halting agricultural expansion, increasing crop resource use efficiency, closing of
21 yield gaps, and reducing food loss and waste³. These key recommendations are repeated in
22 numerous subsequent reports^{1,4} and could help deliver future food security and environmental
23 sustainability. Adherence to such reforms is required if the global agrifood system is not to
24 undermine efforts to meet the Paris climate change targets⁵. Unfortunately, progress on the core
25 elements of this blueprint has been limited. Global dietary trends are currently opposite to those
26 required⁶. Global croplands are expected to continue to expand⁷. Closing yield gaps remains a
27 persistent issue in underperforming land, especially in low- and middle-income countries (LMIC)⁸.
28 Meantime, increasing agricultural resource efficiency⁹ and reducing food loss and waste are major
29 challenges¹⁰. Moreover, current rates of improvement in average crop yields per hectare are
30 insufficient to meet the 60% increase in demand forecast for mid-century, a situation that will likely
31 be exacerbated by climate change¹¹. Clearly, there needs to be additional practical measures in
32 order to bring about the required level of change to the agrifood system¹².

33 Here, we outline a complementary series of technological options for sustainable, productive and
34 resilient agriculture, which provide multiple routes for removing CO₂ from the atmosphere to
35 directly mitigate climate change. We highlight three key requirements. Firstly, the transformation of
36 land management and agronomic practice, in particular using innovative soil amendments, which
37 simultaneously increase soil fertility, and capture CO₂ which is stored in organic and inorganic forms.
38 Secondly, engineering crops to both increase yield and resource-use-efficiency, and to maximally
39 exploit the new agronomic practice and deliver its objective of carbon sequestration. Thirdly, to use
40 the land made available by increased yield (or reduced demand) for further carbon sequestration
41 either by re/afforestation or bioenergy with carbon capture and storage (Figure 1).

42 Whilst large-scale long-term research development and demonstration programmes are required to
43 evaluate these technologies in different agricultural systems across the world, we suggest that each
44 of them is feasible. Alongside the assessment of the operational challenges and implementation risk,
45 societal and cultural issues have to also be taken into account¹³, especially because modern
46 technology-driven agriculture is often seen as a problem. However, because they are designed to
47 combat climate change, the agricultural technologies proposed below have the potential to turn a
48 problem into a solution.

49

50 **Soils innovation**

51 *Increasing soil organic carbon:* Land management and agronomy are already reducing and reversing
52 soil degradation, and increasing soil C, with contour ploughing, reduced tillage, cover crops and
53 buffer strips along areas of ephemeral drainage. The impact of these practices, initiated almost 50
54 years ago, was revealed by the relatively new technologies of eddy-covariance measurement of
55 carbon balance between the landscape and atmosphere and mass isotope analysis of soils (eg ref
56 14). A major advance of the last few decades, now used across the Americas, was the introduction
57 of transgenic herbicide tolerant crops. This has allowed farms to control weeds without the need for
58 tillage. Analyses reveal that in no-till there was a net accumulation of 1.6 Mg C ha⁻¹yr⁻¹ from the
59 atmosphere but a net loss of 0.2 Mg C ha⁻¹yr⁻¹ for tilled¹⁵. At this rate, complete conversion of the ca.
60 90 Mha in corn-soy rotation in the US would be sequestering 21.7 Tg C annually and this could be
61 expected to rise. In the past 60 years Midwest maize production has increased almost 3-fold. The
62 increase is not just in grain, but also in stem, leaf and root biomass providing more residue for the
63 soil. Today, all but the grain remains on the field after harvest with burning of stubble eliminated, so
64 providing very significant soil C input. A similar reversal has been calculated for sugarcane
65 production in Brazil, due to the elimination of burning and the current practice of leaving leaf and
66 plant tops on the field at harvest, which amount to several tons of organic C input to the soil¹⁴. We
67 envisage continued improvements in agronomic practice that work together with, and optimise, the
68 proposed plant and soil interventions set out below.

69 There is a potential for breeding crops that further increase and stabilise soil carbon. For example,
70 the drive to achieve cellulosic fuels identified genetic traits that make stem biomass more easily
71 digestible, but equally revealed how plant cell walls could be made more resilient to
72 decomposition¹⁶. Breeding for these traits would favour yet greater accumulation of carbon in the
73 soil. Another innovation would be to engineer new crop varieties with increased sink capacity to
74 store photosynthate in enhanced root systems capable of synthesising specific stable carbon
75 compounds¹⁷.

76 Amendment of soil with added sources of organic carbon, such as green manures, biochars, and
77 organic fertilisers produced from waste streams increases the content of stored carbon, and has
78 been proposed as a climate change mitigation option¹⁸, with recent international initiatives
79 promoting this, such as the “4p1000” led by the French Government¹⁹, and the FAO’s Recsoil
80 (Recarbonisation of global soil) programme²⁰. Natural soil contains vast numbers of organisms and
81 an enormous range of bacterial and fungal species, which recycle nutrients, transform soil carbon

82 and form symbioses with each other and with the inhabiting plants. A key advance will be to fully
83 understand how each component of the soil microbiome and the physical and chemical properties
84 of soil work together to enable healthy plant growth, and how the resulting chemical, physical and
85 biological properties determine suitability for different plant types. Then it may be possible to co-
86 design plant-microbe-soil ecosystems, specifically adapted for particular crops, climates, geographic
87 areas, nutrient availability and soil types, as well as remediation of damaged soils²¹⁻²³.

88 *Enhanced rock weathering for carbon sequestration:* Enhanced rock weathering (ERW) is a Carbon
89 Dioxide Removal (CDR) technology based on amending soils with crushed calcium- and magnesium-
90 rich silicate rocks to accelerate natural CO₂ sequestration processes²⁴, whilst delivering co-benefits
91 for crop production and soil health²⁵⁻²⁷. Basalt, an abundant fast-weathering rock with suitable
92 mineral chemistry, is a prime rock for implementing ERW within agriculture because it releases
93 plant-essential inorganic nutrients. CDR and storage via ERW of crushed basalt applied to soils
94 occurs as rainwater replete with dissolved CO₂ percolates through soil, interacts with roots and
95 microbes, and reacts with base cations (Ca²⁺, Mg²⁺, Na⁺, K⁺) to produce HCO₃⁻ ions (alkalinity). The
96 HCO₃⁻ ions that form are either transported to the ocean, where the carbon is sequestered on
97 timescales of >10⁵ years, or precipitated as pedogenic carbonates, which are typically stable on
98 timescales of ~10⁴ years²⁸ (Figure 1)

99 Quantification of potential co-benefits is necessary to generate evidence for catalysing early
100 adoption and accelerating development pathways into standard agricultural practices. Emerging
101 evidence from small-scale field trials²⁹⁻³¹ and experiments³² is supportive. The capacity of ERW to
102 increase soil pH and resupply depleted soil silica pools could by themselves boost crop yields, given
103 soil acidification resulting from intensification of agriculture. Acidified soils constrain crop
104 production by limiting nutrient uptake on ca. 200 million hectares of managed lands^{25,33}.
105 Considerable unrealised potential exists for extending ERW practices, by spreading basalt on
106 grasslands, rangelands and pastures, whose productivity is often limited by soil acidification and
107 nutrient-depletion, including silica. Thus there are possibilities for co-deployment of ERW not only in
108 agriculture but in the various land reclamation options discussed below.

109 Further research is required to assess costs of CO₂ drawdown with ERW, environmental risks, e.g.,
110 accumulation of potentially toxic metals, and responses of soil organic carbon stocks. Options for
111 meeting the demand for silicate rock in a sustainable, publically acceptable, manner must also be
112 assessed, including opportunities for utilizing rock-dust by-products of the mining industry to
113 facilitate ERW scalability without additional mining, and building a circular economy²⁷.

114

115 **Crop innovation**

116 *Increased yield potential:* Increases in crop yield potential will rely upon increased total biomass
117 given that harvest index is now maximized for the major food crops. Hence, increased
118 photosynthetic efficiency may be the only remaining option^{34,35}. For a long time, it was considered
119 that evolution and selection would have already optimized the process, with little prospect of
120 improvement. However, analysis has shown that efficiency in current crop cultivars falls far short of
121 theoretical³⁵. Photosynthesis is probably the most studied of all plant processes, yielding key
122 insights into how efficiency could be increased^{34,35}. This has culminated in demonstrated substantial
123 increases in photosynthetic efficiency, crop productivity and sustainability in replicated field trials<sup>36-
124 38</sup>. These advances are now being transferred to, and demonstrated in, key food crops³⁹. One such
125 innovation, designed to future-proof soybean against rising [CO₂] and temperature, has already been
126 demonstrated under field conditions⁴⁰. It is to be emphasised how crucial it is to increase plant
127 photosynthesis if climate and food security are to be delivered: with higher photosynthetic capacity
128 and higher consequent biomass production, it is then possible to consider how to optimise allocation
129 within the plant, to allow both high food yield and increased soil carbon storage in roots using the
130 approaches described above.

131 *Improved water use efficiency:* Realizing increased yield potential in farm fields requires that the
132 crop has adequate water. This portends two problems. First, rising temperature increases the drying
133 power of the atmosphere exponentially, so crops will require substantially more water in the future.
134 Secondly, success in increasing production potential would only be realized in higher yield with more
135 water. For example, the US corn/soy belt, the largest single area of global food production, is today
136 predominantly rainfed, but to meet future food demand would have to become predominantly
137 irrigated⁴¹. Will it be possible to meet future demand without stressing water resources yet further?
138 Photosynthesis and water use are inextricably linked because the leaf stomata control the influx of
139 CO₂ and the loss of water; adjusting stomatal function has hence been the focus for much
140 research⁴². Recently, up-regulation of a single gene has been shown to increase crop water use
141 efficiency⁴³ and similar gains may be achieved by manipulating stomatal numbers and distribution⁴⁴.
142 Increasing the rate of opening and closure of stomata when light levels change has been suggested
143 to be a target for increasing water use efficiency and biomass accumulation⁴⁵, recently borne out
144 experimentally⁴⁶.

145 Further efficiencies are offered by agronomic practices that improve soil pore and aggregate
146 structure, which increases the capacity of soil to both store and supply plant available water. All of
147 the soil amendments described above support soil structure development, which is intimately linked
148 to plant traits that contribute to photosynthate allocation below ground⁴⁷.

149 *Reduced N fertiliser requirement:* Fertiliser is the principle source of greenhouse gas emissions from
150 cereal farming⁴⁸, but achieving increased crop yield without increasing N fertilizer applications is a
151 challenge. A cereal yield of 10t/ha with an average 10% protein content requires a minimum
152 addition of 160 kg [N]/ha, and this assumes the crop assimilates all of the applied fertilizer and all of
153 this is translocated to the grain at crop maturation. For every additional tonne of yield an additional
154 16 kg [N]/ha will be required. New approaches to supporting plant N metabolism are urgently
155 needed. One approach is to develop N₂ fixing cereals by introducing the plant genetic elements that
156 allow invasion by nitrogen fixing bacteria⁴⁹. However, N₂ fixation is costly to the plant, accounting for
157 an estimated 50% of potential biomass in legumes. Losses would be greater where N comes from
158 free-living N₂ fixers in the microbiome. These losses could be offset by simultaneously increasing
159 photosynthetic efficiency, by the technologies noted above. Another novel approach may come from
160 understanding how plants respond to N availability, which could allow much more efficient N
161 use^{23,50}.

162 Improved agronomic practice currently plays the most important role in reducing fertiliser
163 applications, through precision placement within the field. GPS tracked harvesting provides high
164 spatial resolution datasets on variation in yield across fields, identifying where fertilizer is needed
165 most in subsequent planting, while unmanned aerial vehicles can routinely track colour to guide top-
166 dressing. This is increasingly supported by high-throughput high resolution probing of soil quality,
167 making most farm operations driven increasingly by big data, coupled with better agricultural
168 weather forecasting for timing farm operations. Robotics coupled with GPS could further
169 revolutionize the situation: allowing an operator to monitor multiple robots planting to more
170 optimal agronomies, weeding, harvesting and monitoring pests and diseases for targeted chemical
171 intervention, only where needed⁵¹. By contrast, on the non-mechanized small-holdings, which feed
172 much of sub-Saharan Africa, improvements can instead come from optimal placement of seed and
173 fertilizer, together with multi-cropping, as successfully being promoted, for example, by the “one-
174 acre fund”⁵².

175

176 **Agricultural land reclamation**

177 If the food produced per unit land area could be sustainably increased and be resilient to climate
178 change, total agricultural land area reduction could be realised. For example, it is estimated that the
179 Green Revolution saved 18-27 million hectares of land from cultivation⁵³. This then gives the

180 possibility for the land that is under pressure to be utilised for less intensive localised regenerative
181 farming practices that store soil carbon or restored to forests and grasslands that store carbon in
182 above- and below-ground biomass, and in soils⁵⁴. This rationale has become a major part of the
183 “natural climate solutions”^{55,56}. However, with the projected need for 60% more food by 2050, we
184 must be cognizant that it is likely a challenge to constrain agriculture to the land it is already using,
185 and this raises the questions, 1) what processes are most likely to reduce agricultural land; and 2)
186 what are the best strategies for using the land made available?

187 *Processes for agricultural land reduction:* Two types of changes in the agri-food system have been
188 suggested as a means to reduce agricultural land use. Firstly, reducing global meat consumption
189 alone would free up the vast land areas currently used to provide grazing and feed crops for
190 livestock. This forms a pivotal part of agrifood-related climate change mitigation proposals⁴. But
191 reducing meat consumption presents a major challenge: not only altering diets in high income
192 countries (HIC) but especially halting and reversing the dietary transition in LMIC. Because there is a
193 strong correlation between economic development and meat consumption⁷, it is unlikely that land
194 use that supports livestock will decrease in the near future without drastic changes in human
195 behaviour driven by health concerns and/or significant policy changes⁶.

196 Secondly, it has long been recognized that if the yield gap could be closed, large amounts of
197 agricultural land could be released. The yield gap is the difference between the maximum potential
198 yield, or that achieved by ‘best practices’ for a crop, versus that achieved on average. It can also be
199 described as the gap between yields achieved in HIC and LMIC, especially those whose food security
200 is challenged. For more than half a century much national investment and international aid has been
201 focused on this challenge. Most recently, it has been projected from modelling that closing the yield
202 gap could release 50% of agricultural land globally, but depending on substantial increases in yield
203 across Africa⁵⁷. Is this realistic? The facts suggest not with current technologies. While access to
204 seed, equipment and agrochemicals are important, closing the yield gap cannot be achieved without
205 substantial quantities of fertilizer and plant available water (see above). In the poorer countries of
206 Africa, even when farms can afford fertilizer at the required level, adequate road systems for
207 delivery are often lacking. The challenge of closing the yield gap is evident in the fact that African
208 farms on average achieved 27% of the maize yield of N. American farmers in 1962, declining to just
209 17% in 2018⁵⁸. Closing the yield gap is further threatened by climate change, which IPCC have
210 forecast, with high confidence, will be disproportionately worse for food production in Africa¹.

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

219 *Strategies for use of reclaimed land:* Land use has to be based upon active land management derived
220 from knowledge of ecology, biology and climate, recognising the complexity of ecosystems⁵⁹. The
221 most suitable land areas need to be selected for different functions, and refined indices of GHG
222 accounting that consider the best options for land use incorporated into decision making. For
223 example, a recent technoeconomic analysis shows that, where practical, bioenergy schemes,
224 especially when combined with carbon capture and storage (BECCS) would provide significantly
225 greater GHG mitigation than afforestation⁶⁰ (Figure 1).

226 Afforestation includes three options: restoration of natural forests; agroforestry in which trees are
227 interspersed with suitable crops; and tree plantations, for commercial use of timber⁶¹. The
228 implementation of the mix of these options depends upon numerous factors, particularly geography

229 and climate – the humid tropics represent the best option for natural forest regeneration with
230 maximum carbon storage potential. Specific management practices, such as planting of highly
231 productive trees, especially nitrogen fixers, and other chosen plant species, that could be used as
232 construction materials or as energy crops, could be more likely to have a significant effect in the
233 needed time-frame than natural regeneration. Especially important in predicting the carbon capture
234 potential of these interventions is to take into account the effects of climate change - particularly
235 the increased incidence of wild fires⁶².

236 A further important consideration is the time taken for any restoration intervention to have an
237 impact on carbon sequestration. A 140-year study, which documented the long timescale for carbon
238 accumulation in the transformation of land that had been arable for hundreds of years, pointed to
239 the importance of local environmental factors such as soil acidity and N accumulation⁶³. In another
240 study of woodland restoration on land once cleared from forest for cropping and then abandoned, it
241 was not until after 40 years that a semblance of the original pine-oak forest was achieved, and net
242 primary productivity reached a meagre 3.0 Mg C ha⁻¹ yr⁻¹. In cooler and drier locations an even
243 longer re-establishment must be expected.

244 An example of the complexities involved in restoration is seen in the US Midwest where land taken
245 out of production because of its erodibility has been largely left to restore the natural prairie. Prairie
246 species include perennials that produce surface roots and rhizome systems that help bind the soil,
247 prevent wind and water erosion, and deposit carbon to build the soil and its quality. In the absence
248 of the large grazers that once roamed prairie, and similarly steppe, maintenance requires annual
249 burning. However, there are highly productive grass perennials that might be as or more effective;
250 these include switchgrass, prairie cord-grass and Miscanthus. Miscanthus is of particular interest,
251 since when harvested post-senescence it remains productive without fertilization. In side-by-side
252 field trials net GHG reduction of 0.5, 1.0, and 2.0 Mg C ha⁻¹ yr⁻¹ with average annual yields of 3.6, 9.2,
253 and 17.2 Mg of dry biomass were achieved for native prairie, switchgrass, and Miscanthus, and this
254 was without burn management or addition of fertilizer⁶⁴. Crops such as switchgrass, Miscanthus, or
255 woody crops combusted for energy or processed to advanced biofuels when combined with both
256 ERW and CCS would offset fossil fuel GHG emissions while removing atmospheric CO₂ into soil and
257 deep geological carbon storage (Figure 1). Co-deployment of ERW with bioenergy crops and
258 afforestation helps maximise use of land, water and energy, while significantly reducing ERW costs
259 and enhancing the combined CDR potential of these methods²⁶.

260 **Conclusions**

261 In this article we have set out options for delivering a different form of agriculture, one designed to
262 meet both the food and climate emergencies: bioengineered resource efficient crop varieties
263 cultivated in silicate-amended C-rich healthy soils using advanced agronomic practice. It gives the
264 possibility of high yields supporting global food security and makes a significant contribution to
265 extracting atmospheric CO₂, an action required alongside emissions cuts to keep within the 2° C limit
266 set out in the Paris Agreement.

267 A principle advantage of our plan is that it does not rely on a single predominant reform, such as a
268 change in diet. It does not require huge and unpredictable changes in human culture, lifestyle or
269 economy, though it could be pursued in parallel with such goals. It offers a range of technologies, all
270 of which are feasible and deliverable. Some are ready now, and already being implemented, such as
271 increasing soil organic carbon or using precision agriculture. Others are at the testing and evaluation
272 stages, such as the use of silicates or BECCS. Others are longer term and require more research and
273 development, such as the genetic engineering of new crop varieties, although even here, research
274 on model plant species indicates that all of it is possible. Whilst integration of these technologies
275 into a full package of measures is the desired priority, not least because of the synergies between
276 them, it is not a necessity - each one can independently be considered for local and regional
277 circumstances that contribute to meeting the twin climate change and food security objectives. A

278 further advantage of such flexibility is that these options can be taken up in different ways in
279 countries with different farming systems and levels of agricultural productivity.

280 Discussion about agricultural reform has tended to focus upon the trade-offs between climate
281 change mitigation and intensive agriculture⁶⁵. In contrast, we advocate a series of emerging
282 agricultural technologies that eliminates this trade-off by delivering both simultaneously and
283 therefore allowing intensive agriculture to become an important player in climate change mitigation.

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441

442 Figure Legend

443

444 **Figure 1. Options for food security and climate change mitigation using soil and crop innovations, and**
445 **agricultural land reclamation.** Bioengineered resource efficient, high yielding crop varieties cultivated using
446 advanced agronomic practice give increased food production and soil C storage enhanced by deep recalcitrant
447 roots. Reclaimed land can be used for afforestation giving CO₂ sequestration in above ground biomass and for
448 cultivation of bioenergy crops. Biomass and crop residues and unavoidable wastes can be processed for fuel,
449 power and bioproducts and released CO₂ captured and stored. Co-deployment of basalt application supports
450 high productivity throughout and gives further CO₂ sequestration through enhanced rock weathering.

