# Wheat yield potential in controlled-environment vertical farms

Senthold Asseng[a], Jose R. Guarin[a], Mahadev Raman[b], Oscar Monje[c], Gregory Kiss[d], Dickson D. Despommier[e], Forrest M. Meggers[f], and Paul P. G. Gauthier[g,h,1]

[a]Agricultural & Biological Engineering Department, University of Florida, Gainesville, FL 32611; [b]Arup, Edison, NJ 08837; [c]AECOM, Air Revitalization Lab, Kennedy Space Center, Merritt Island, FL 32899; [d]Kiss + Partners, Brooklyn, NY 11201; [e]Department of Environmental Health Sciences, Columbia University, New York, NY 10027; [f]School of Architecture, Princeton University, Princeton, NJ 08544; [g]Department of Geosciences, Princeton University, Princeton, NJ 08544; and [h]Princeton Environmental Institute, Princeton University, Princeton, NJ 08544

Edited by Dieter Gerten, Potsdam Institute for Climate Impact Research, Potsdam, Germany, and accepted by Editorial Board Member Hans J. Schellnhuber June 19, 2020 (received for review February 11, 2020)

**Scaling current cereal production to a growing global population will be a challenge. Wheat supplies approximately one-fifth of the calories and protein for human diets. Vertical farming is a possible promising option for increasing future wheat production. Here we show that wheat grown on a single hectare of land in a 10-layer indoor vertical facility could produce from 700 ± 40 t/ha (measured) to a maximum of 1,940 ± 230 t/ha (estimated) of grain annually under optimized temperature, intensive artificial light, high $CO_2$ levels, and a maximum attainable harvest index. Such yields would be 220 to 600 times the current world average annual wheat yield of 3.2 t/ha. Independent of climate, season, and region, indoor wheat farming could be environmentally superior, as less land area is needed along with reuse of most water, minimal use of pesticides and herbicides, and no nutrient losses. Although it is unlikely that indoor wheat farming will be economically competitive with current market prices in the near future, it could play an essential role in hedging against future climate or other unexpected disruptions to the food system. Nevertheless, maximum production potential remains to be confirmed experimentally, and further technological innovations are needed to reduce capital and energy costs in such facilities.**

wheat | yield | vertical farm

The world population of 7.8 billion in 2020 will increase to more than 9 billion by 2050 and likely peak at approximately 11 billion by the end of the century (1). While one in nine people worldwide currently face hunger (2), this projected increase in population and food demand will require a >60% increase in global grain production (3). It is suggested that through a combination of pathways, including reducing food demand, increasing food production, reducing food waste, and sustaining the productive capacity, the projected food demand in 2050 could be met (4, 5). However, many agricultural areas are already degraded by erosion, and large amounts of fertilizers and pesticides are polluting groundwater and aquatic systems (6, 7). New approaches for more sustainable food production are needed to significantly reduce the environmental impact of future crop production (8, 9). While all these factors pose enormous challenges for agriculture, the difficulty is exacerbated by observed and projected changes in climate, leading to declines in crop yields in many regions of the world (10).

Wheat is one of the most important crops from a worldwide perspective, supplying 20% of calories and protein in the human diet (11). Wheat grown in the field requires at least one-half of the year to mature, so only one harvest is produced per year. Annual wheat yields range from <1 t/ha/y when water or nutrients are limiting to >10 t/ha/y in cooler, well-watered (via high rainfall or irrigation), and mostly long-season (8 to 11 mo) growing environments (Fig. 1*A*). When wheat is grown in a controlled indoor environment at a constant warm temperature, the phenological development of the crop is faster (12). This was originally explored for future plant growth systems deployed in spacecraft or surface habitats on the Moon or Mars. For example, Monje and Bugbee (13) showed that a wheat growing season at 23 °C lasts just 70 d from planting to maturity (Fig. 1*B*). With artificial lighting increasing the intensity and duration of light beyond what can be captured from the sun in a field, the short indoor growth cycle produced mean grain yields of 14 ± 0.8 t/ha per harvest at 11% grain moisture based on a 1-$m^2$ edge-protected experimental area (13) (Fig. 1*B*). This yield compares well with other reported wheat yields from the field, but theoretically five such crops could be harvested in a single year, resulting in the same indoor space yielding 70 ± 4 t/ha/y of grain (14 t/ha at 11% grain moisture × 5 harvests a year). This cumulative annual yield would be well above the current global average wheat yield of 3.2 t/ha/y, as well as the highest country-wide average wheat yield of ∼9 t/ha/y in Ireland and the 2017 world record wheat yield of 17 t/ha/y for a farmer's field in New Zealand (14) (Fig. 2).

Crop simulation models that capture the eco-physiological interactions of a wheat crop—here the DSSAT-NWheat model—can closely reproduce a wide range of observed biomass growth and yield under different field conditions like those at three sites in Australia, The Netherlands, and China (15) (Fig. 1*A*). Here we show that DSSAT-NWheat also closely simulates the growth and

AGRICULTURAL SCIENCES

SUSTAINABILITY SCIENCE

## Significance

Wheat is the most important food crop worldwide, grown across millions of hectares. Wheat yields in the field are usually low and vary with weather, soil, and crop management practices. We show that yields for wheat grown in indoor vertical farms under optimized growing conditions would be several hundred times higher than yields in the field due to higher yields, several harvests per year, and vertically stacked layers. Wheat grown indoors would use less land than field-grown wheat, be independent of climate, reuse most water, exclude pests and diseases, and have no nutrient losses to the environment. However, given the high energy costs for artificial lighting and capital costs, it is unlikely to be economically competitive with current market prices.

Author contributions: S.A., M.R., O.M., G.K., D.D.D., F.M.M., and P.P.G.G. designed research; S.A., J.R.G., M.R., O.M., G.K., F.M.M., and P.P.G.G. performed research; M.R., O.M., and G.K. contributed new reagents/analytic tools; S.A., J.R.G., M.R., and P.P.G.G. analyzed data; and S.A., J.R.G., M.R., O.M., G.K., D.D.D., and P.P.G.G. wrote the paper.

The authors declare no competing interest.

This article is a PNAS Direct Submission. D.G. is a guest editor invited by the Editorial Board.



[1]To whom correspondence may be addressed. Email: paul.pg.gauthier@gmail.com.

This article contains supporting information online at https://www.pnas.org/lookup/suppl/doi:10.1073/pnas.2002655117/-/DCSupplemental.

First published July 27, 2020.

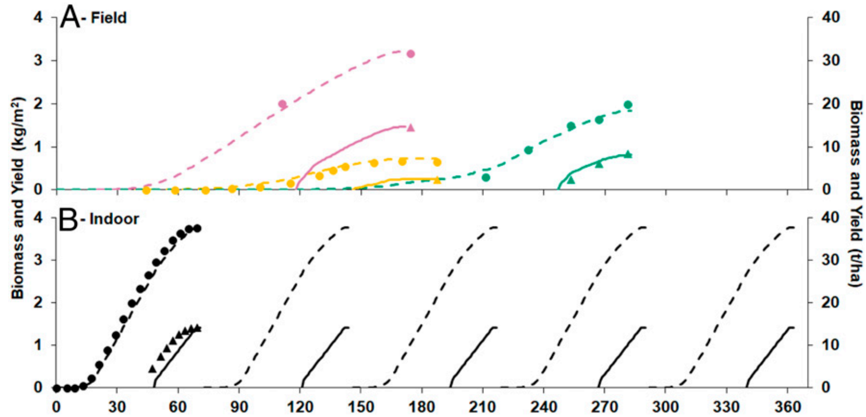


**Fig. 1.** Comparison of crop model simulations with observed wheat growth and yield in 1 y. (*A*) Observed (symbols) and simulated (lines) values for total biomass (circles, dashed lines) and yield (triangles, solid lines) for wheat grown in fields at Merredin, Australia (yellow); Wageningen, The Netherlands (green); and Xiangride, China (purple) (15). (*B*) Observed (symbols) and simulated (lines) values for total biomass (circles, dashed lines) and yield (triangles, solid lines) for an indoor experiment with 20 h of 1,400 μmol/m²/s light (50 MJ/m²/d, with 1 J = 1 W/s) at 330 ppm atmospheric $CO_2$ and five successive replicate harvests (13). Yields and total biomass (yield plus straw) are shown at 11% grain moisture. Simulations were done with the DSSAT-NWheat crop model.

yield of a fast-growing wheat crop under indoor conditions (Fig. 1*B* and *SI Appendix*, Fig. S1*A*). To consider model uncertainty, we repeated the simulation with another, simpler crop model, SIMPLE (16), and found similar results (*SI Appendix*, Fig. S1 *B* and *C*). Thus, both models can be used together to further explore the yield potential of wheat grown indoors.

In the indoor experiment reported by Monje and Bugbee (13), the wheat was grown under 20 h per day of light at an intensity of 1,400 μmol/m²/s, totaling 50 MJ/m²/d (with 1 J = 1 Ws), and an atmospheric $CO_2$ concentration of 330 ppm. However, wheat can utilize light for photosynthesis and growth for up to 24 h per day (17, 18) with an almost linear crop growth response up to 2,000 μmol/m²/s (19, 20). It is also known that wheat responds positively to elevated atmospheric $CO_2$ concentrations (13, 21) if other growth factors, such as nutrients, are not limiting. Using the crop models, we simulated the effect of maximizing light (up to 2,000 μmol/m²/s) and atmospheric $CO_2$ concentrations (1,200 ppm) in an indoor experiment assuming no nutrient limitations. A reduced nutrient concentration in the grain in high-productivity crops and under an elevated $CO_2$ concentration was also considered for calculating nutrient demand (*SI Appendix*, Tables S4 and S5). The cumulative simulated yield for five harvests per year was 114 ± 13 t/ha/y (with ± mean of the 10th and 90th percentiles of ensemble simulations) (Fig. 2).

The harvest index is a measure of how efficiently photosynthate is partitioning into the edible part of the plant. For cereals, the harvest index is calculated as the grain mass divided by the total above-ground biomass. In the pilot indoor experiment of Monje and Bugbee, the harvest index was noticeably low at 0.38 (13), as cereals grown at high N inputs can exhibit lower rates of carbon remobilization from vegetative tissues during grain filling (22). Under field conditions, the maximum harvest index for wheat has been shown theoretically and confirmed in field experiments to be ∼0.64 (23, 24). The harvest index may be influenced by genetic and environmental factors affecting source–sink relationships (25); for example, targeted breeding of germplasm suited to indoor growth conditions or cooler temperatures during grain filling might raise the harvest index. Assuming that the

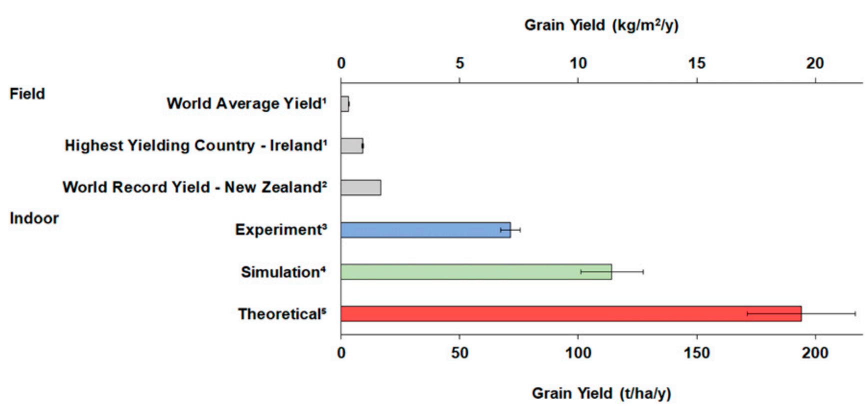


**Fig. 2.** Annual field and indoor wheat yields. Observed wheat yields from the field (gray bars) and an indoor controlled environment pilot experiment (blue bar), and simulated mean yields from two crop models for wheat cultivars with a low harvest index (green bar) and a theoretical high harvest index (red bar) grown in an indoor controlled environment. Error bars show SEM for the field, SD of the indoor experiment, and ± the mean of the 10th and 90th percentiles of the indoor simulations. Yields are shown at 11% grain moisture. [1]10-y average yield, 2008–2017 (2). [2]Guinness World Record, 2017 (14). [3]Observed 70-d season indoor experiment with 20 h of 1,400 μmol/m²/s light daily (50 MJ/m²/d) and 330 ppm atmospheric $CO_2$ concentration, scaled up to 1 ha and multiplied by 5 harvests/y (13). [4]Simulated 1-ha indoor experiment using the DSSAT-NWheat and SIMPLE models with 70-d seasons and 5 harvests/y with constant light and 1,200 ppm atmospheric $CO_2$. The average of simulations with 1,800, 1,900, and 2,000 μmol/m²/s light (77, 81, and 86 MJ/m²/d, respectively) and ±10% RUE is shown. [5]Simulated 1-ha indoor experiment using the DSSAT-NWheat and SIMPLE models with 70-d seasons and 5 harvests/y with constant light, 1,200 ppm atmospheric $CO_2$ and a theoretical harvest index of 0.64 (24). The average of simulations with 1,800, 1,900, and 2,000 μmol/m²/s light (77, 81, and 86 MJ/m²/d, respectively) and ±10% RUE is shown.

maximum harvest index from the field could be attained in an indoor crop, the wheat grain yield would theoretically be 194 ± 23 t/ha/y (based on simulation results of 39 t/ha × 5 harvests annually, with ± mean of the 10th and 90th percentiles of ensemble simulations) (Fig. 2). The theoretical yield of 39 ± 5 t/ha per single harvest simulated here is more than double of any reported wheat grain yield from the field, but whether this can actually be achieved needs to be demonstrated in indoor experiments.

Vertical farming, involving positioning several growth trays or platforms above one another in layers, has proven highly efficient for growing lettuce and other leafy herbs (26). For wheat, approximately 1 m of height per layer would be required to accommodate 0.5 m of crop canopy height if a double semidwarf cultivar were used, as in the Monje and Bugbee indoor experiment (13), with another 0.5 m to accommodate the artificial lighting, the root system (hydroponic or aeroponic) and conveyor structure. A 1-ha, 10-layer indoor wheat facility developed as a vertical farm (27) or plant factory (28) (*SI Appendix*) could produce up to 1,940 ± 230 t/ha/y (194 t/ha/y × 10 layers), approximately 600 times the current average global yield in the field (Fig. 2).

Indoor wheat farming is costly now and is likely to remain so in the future. Despite the very high potential yields, running a 1-ha, 10-layer indoor wheat facility is unlikely to be cost-recovering under normal market conditions (Fig. 3 and *SI Appendix*, Tables S6 and S7 and Fig. S2). In the field, most cereal production systems are already not economically viable, when considering the large amounts of subsidies spent globally on agricultural production each year (29). Even in efficient agricultural production systems without subsidies, profit margins per unit area for wheat are usually low (30). For indoor wheat production, the energy consumption to produce the constant light, maintain temperature and air quality, and run nutrient and watering systems is high. In fact, more than one-half of current costs are for electricity powering the artificial lighting (Fig. 3*A* and *SI Appendix*). In addition, maximizing yield is not the most energy cost-effective scenario (31), and using less light, with consequently lower yields (1,120 ± 100 t/ha/y, roughly 350 times the global average, with ± mean of 10th and 90th percentiles of ensemble simulations), can lead to improved energy efficiency and lower costs (*SI Appendix*, Tables S6 and S7). However, solar plus storage energy systems are already providing emission-free electricity of ~$0.02/kWh (https://www.utilitydive.com/news/los-angeles-solicits-record-solar-storage-deal-at-199713-cents-kwh/558018/), and future improvements in the efficiency of producing light and automation of labor will further reduce costs. Indoor single-layer greenhouse-based wheat farms in which sunlight supplements the artificial lighting could be more economical in some cases, but a detailed investigation of this option is beyond the scope of this study (32). Other sustainable energy sources could also be considered as they may provide a more efficient use of space, but this is also beyond the scope of the present study. The commodity price for wheat has varied in the past and increased temporally in 2008 and again in 2010 by threefold to fourfold due to global food supply issues (2). Such crises may become more frequent or consequential if climate change reduces future yields in the field (33). Lower costs and higher returns could conceivably reduce the cost:return ratio from 46:1 today to ~6:1 in the future (Fig. 3*B*), but this still would not be commercially viable.

Food security, currently challenged by >800 M undernourished people (2), an increasing demand (3) and population growth (1), can affect national security and even have repercussions internationally. For example, the 2008 wheat price hike led to widespread food riots (34) in more than 20 developing countries around the world, and the 2010 wheat price hike has been suggested to have sparked the Arab Spring uprisings (35). Therefore, the demonstrated potential to reliably produce large amounts of wheat indoors, close to users and consumers, independent of



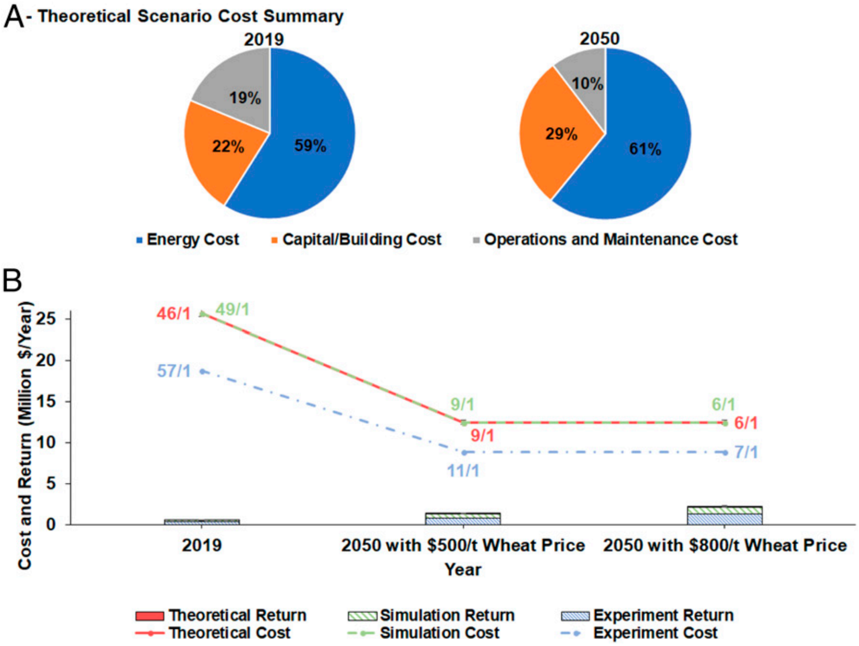


**Fig. 3.** Annual cost and return for indoor wheat farming. (*A*) Pie charts showing 2019 (*Left*) and 2050 (*Right*) breakdown of costs as percentages for a 1-ha, 10-layer indoor wheat growing scenario with an adapted high harvest index cultivar (the theoretical scenario in Fig. 2 and *SI Appendix*, Table S4) and capital and building costs financed at 5% per year. A breakdown of the costs for simulation and experiment scenarios is provided in *SI Appendix*, Fig. S2. (*B*) Total annual cost of wheat production (lines) and annual returns (stacked bars) for a 1-ha, 10-layer facility for theoretical (red), simulation (green), and experimental (blue) indoor wheat growing scenarios (as shown in Fig. 2 and *SI Appendix*, Table S4), assuming wheat prices of $200/t in 2019 (2) and $500/t and $800/t in 2050 (based on a likely increase in the future price and premium price for pesticide-free production). The 2050 cost is the same for the $500/t and $800/t wheat price scenarios. Data point labels are cost/return ratios for each scenario. Error bars show SEM when larger than symbols.

day-to-day weather and climate trends while excluding pesticides and herbicides, recycling most water, and eliminating nutrient runoff (26), could be reason enough to develop and install some indoor wheat production facilities. For instance, the Middle East imports most of its wheat because of its limited agricultural land and water resources (2). Adding indoor vertical wheat to developing programs for achieving sustainable desert agriculture already in place (36, 37) could help stabilize the regional food supply. Unused desert areas potentially offer a vast energy supply for solar farms in this region (38). Indoor vertical wheat facilities could be particularly valuable in buffering the effects of climate-related events or other anomalies in food production in any country; however, the likelihood of such a system becoming sufficiently economically viable to displace conventional means of grain production is low (Fig. 3).

A number of research questions about growing wheat indoors remain unanswered. New research with controlled indoor wheat experiments should attempt to confirm the maximum production potential and its possible impact on nutritional value and baking quality. Indoor experiments should explore ways to reduce energy costs, manage disease-free growing conditions, and fully automate such facilities. Controlled environment research should be conducted to determine whether different light recipes can potentially increase photosynthesis (39); to manipulate the environmental conditions, like root zone water potential during grain filling; and to improve the harvest index of wheat (22). Future research could be directed toward a quantitative comparison and evaluation of different growth-environment options. Breeding programs using strategic crossing for biomass and harvest index traits should be developed to improve indoor wheat growth, yield, and grain quality under optimal indoor growing conditions (40).

It is worth mentioning that the proposed 10-layer facility is further scalable and adaptable. For example, 10 of the 10-layer units modeled here could be stacked to provide 100 wheat-growing layers for use in especially dense and land-scarce urban environments. Both the yield and the production costs would increase proportionally by roughly 10-fold, with some additional outlay for suitable infrastructure but with limited additional capital costs for roof and land. The envisaged 100-layer wheat facility could produce 19,400 ± 2,300 t/ha/y of wheat grain on 1 ha of land—6,000 times the current average global wheat yield.

Under specific circumstances, and if the energy cost and profitability issues can be resolved, indoor vertical wheat farming might be attractive; nonetheless, the outcomes described here may contribute only a relatively small fraction (yet to be determined) of the global grain production needed to achieve global food security in the near future.

## Materials and Methods

Two crop simulation models, DSSAT-NWheat (15) and SIMPLE (16), were tested with detailed data from an indoor wheat experiment reported by Monje and Bugbee (13). The wheat crop in this experiment was grown under 20 h/d of light at an intensity of 1,400 μmol/m$^2$/s and an atmospheric $CO_2$ concentration of 330 ppm. The two crop models were used to simulate growth and yield under no water or nutrient limitations with 1,800, 1,900, and 2,000 μmol/m$^2$/s for 24 h/d and with ±10% radiation use efficiency (RUE) to create a model ensemble. The theoretical highest harvest index for wheat, confirmed to be 0.64 in field observations (23, 24), was then applied to the simulated total biomass to estimate the possible maximum wheat grain yield under controlled indoor conditions. The mean of the simulation ensemble with model uncertainty, expressed as ± the mean of the 10th and 90th percentiles, is presented.

Building and operation costs and cost/return ratios were calculated for a 1-ha, 10-layer indoor vertical wheat production facility, expandable to 100 layers. Details are provided in *SI Appendix*.

**Data Availability.** Pertinent data are provided in *SI Appendix*. Additional data are available on request.

**ACKNOWLEDGMENTS.** We thank Anna-Lisa Paul and Robert Ferl (University of Florida Space Plants Lab) for helpful discussions and information on indoor growing environments. We also thank Ray Wheeler (Kennedy Space Center) and Stephen Pacala, Dan Rubinstein, and Robert Socolow (Princeton University) for fruitful discussions at an early stage of this research. P.P.G.G. was funded by the Princeton Environmental Institute's Urban Grand Challenge Grant. M.R. was supported by Arup University's Global Research Fund.

1. M. Roser, H. Ritchie, and E. Ortiz-Ospina (2013) - "World Population Growth." Published online at OurWorldInData.org. Retrieved from: https://ourworldindata.org/world-population-growth. Accessed 22 March 2020.
2. Food and Agriculture Organization of the United Nations, Food and agriculture data (2019). http://www.fao.org/faostat/en/#home. Accessed August 15, 2019.
3. H. C. J. Godfray *et al*., Food security: The challenge of feeding 9 billion people. *Science* **327**, 812–818 (2010).
4. B. A. Keating, M. Herrero, P. S. Carberry, J. Gardner, M. B. Cole, Food wedges: Framing the global food demand and supply towards 2050. *Global Food Secur.-Agric. Policy Econ. Environ.* **3**, 125–132 (2014).
5. D. Gerten *et al*., Feeding ten billion people is possible within four terrestrial planetary boundaries. *Nat. Sustainability* **3**, 200–208 (2020).
6. D. Ferber, Keeping the Stygian waters at bay. *Science* **291**, 968–973 (2001).
7. M. D. Smith *et al*., Seafood prices reveal impacts of a major ecological disturbance. *Proc. Natl. Acad. Sci. U.S.A.* **114**, 1512–1517 (2017).
8. P. C. West *et al*., Leverage points for improving global food security and the environment. *Science* **345**, 325–328 (2014).
9. N. V. Fedoroff *et al*., Radically rethinking agriculture for the 21st century. *Science* **327**, 833–834 (2010).
10. J. R. Porter *et al*., *Climate Change 2014: Impacts, Adaptation and Vulnerability: Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, CB Field, Ed. *et al*. (Cambridge Univ. Press, Cambridge, UK, 2014).
11. D. Tilman, C. Balzer, J. Hill, B. L. Befort, Global food demand and the sustainable intensification of agriculture. *Proc. Natl. Acad. Sci. U.S.A.* **108**, 20260–20264 (2011).
12. A. Watson *et al*., Speed breeding is a powerful tool to accelerate crop research and breeding. *Nat. Plants* **4**, 23–29 (2018).
13. O. Monje, B. Bugbee, Adaptation to high $CO_2$ concentration in an optimal environment: Radiation capture, canopy quantum yield, and carbon use efficiency. *Plant Cell Environ.* **21**, 315–324 (1998).
14. Guinness World Records (2017) Highest wheat yield. Available at https://www.guinnessworldrecords.com/world-records/highest-wheat-yield. Accessed 22 March 2020.
15. S. Asseng, N. C. Turner, J. D. Ray, B. A. Keating, A simulation analysis that predicts the influence of physiological traits on the potential yield of wheat. *Eur. J. Agron.* **17**, 123–141 (2002).
16. C. Zhao *et al*., A SIMPLE crop model. *Eur. J. Agron.* **104**, 97–106 (2018).
17. B. G. Bugbee, F. B. Salisbury, *Controlled Ecological Life Support Systems: CELSS Workshop*, R. D. MacElroy, M. N. V. Prasad, D. T. Smernoff, Eds. NASA Technical Memorandum 88215 (NASA, Ames Research Center, 1986), pp. 447–486.
18. R. M. Wheeler, *et al*., Crop production for advanced life support systems—Observations from the Kennedy Space Center Breadboard Project. NASA Technical Memorandum 2003-211184 (NASA Biological Sciences Office, 2003).
19. B. G. Bugbee, F. B. Salisbury, Exploring the limits of crop productivity, I: Photosynthetic efficiency of wheat in high irradiance environments. *Plant Physiol.* **88**, 869–878 (1988).
20. B. G. Bugbee, F. B. Salisbury, Current and potential productivity of wheat for a controlled environment life support system. *Adv. Space Res.* **9**, 5–15 (1989).
21. B. A. Kimball, Crop responses to elevated $CO_2$ and interactions with $H_2O$, N, and temperature. *Curr. Opin. Plant Biol.* **31**, 36–43 (2016).
22. J. Yang, J. Zhang, Grain filling of cereals under soil drying. *New Phytol.* **169**, 223–236 (2006).
23. R. B. Austin *et al*., Genetic improvements in winter-wheat yields since 1900 and associated physiological changes. *J. Agric. Sci.* **94**, 675–689 (1980).
24. M. J. Foulkes *et al*., Raising yield potential of wheat, III: Optimizing partitioning to grain while maintaining lodging resistance. *J. Exp. Bot.* **62**, 469–486 (2011).
25. A. C. White, A. Rogers, M. Rees, C. P. Osborne, How can we make plants grow faster? A source-sink perspective on growth rate. *J. Exp. Bot.* **67**, 31–45 (2016).
26. P. Pinstrup-Andersen, Is it time to take vertical indoor farming seriously? *Global Food Secur.-Agric. Policy Econ. Environ.* **17**, 233–235 (2018).
27. D. Despommier, *The Vertical Farm: Feeding the World in the 21st Century*, (St. Martin's Press, 2010), p. 320.
28. R. R. Shamshiri *et al*., Advances in greenhouse automation and controlled environment agriculture: A transition to plant factories and urban agriculture. *Int. J. Agric. Biol. Eng.* **11**, 1–22 (2018).
29. Organisation for Economic Cooperation and Development, *Agricultural Policy Monitoring and Evaluation 2019*, (Organisation for Economic Cooperation and Development, 2019).
30. M. Monjardino, D. Revell, D. J. Pannell, The potential contribution of forage shrubs to economic returns and environmental management in Australian dryland agricultural systems. *Agric. Syst.* **103**, 187–197 (2010).

31. B. A. Keating *et al*., Eco-efficient agriculture: Concepts, challenges, and opportunities. *Crop Sci.* **50**, S109–S119 (2010).
32. D. D. Avgoustaki, G. Xydis, Indoor vertical farming in the urban nexus context: Business growth and resource savings. *Sustainability* **12**, 1965 (2020).
33. G. C. Nelson *et al*., Climate change effects on agriculture: Economic responses to biophysical shocks. *Proc. Natl. Acad. Sci. U.S.A.* **111**, 3274–3279 (2014).
34. J. Berazneva, D. R. Lee, Explaining the African food riots of 2007-2008: An empirical analysis. *Food Pol.* **39**, 28–39 (2013).
35. M. F. Bellemare, Rising food prices, food price volatility, and social unrest. *Am. J. Agric. Econ.* **97**, 1–21 (2015).
36. S. Kamel, C. Dahl, The economics of hybrid power systems for sustainable desert agriculture in Egypt. *Energy* **30**, 1271–1281 (2005).
37. M. D. Mbaga, The prospects of sustainable desert agriculture to improve food security in Oman. *Consilience: J. Sustainable Develop. Consilience* **13**, 114–128 (2014).
38. S. Griffiths, Strategic considerations for deployment of solar photovoltaics in the Middle East and North Africa. *Energy Strategy Reviews* **2**, 125–131 (2013).
39. P. M. Pattison, J. Y. Tsao, G. C. Brainard, B. Bugbee, LEDs for photons, physiology and food. *Nature* **563**, 493–500 (2018).
40. M. P. Reynolds *et al*., Strategic crossing of biomass and harvest index-source and sink-achieves genetic gains in wheat. *Euphytica* **213**, 257 (2017).