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Perspective

The future potential of controlled environment agriculture

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Abstract

The production of high-quality food needs to increase to feed the growing global population. Controlled environment agriculture (CEA) systems in a vertical farm setting—in which several layers are stacked above each other, thus increasing the area for growth—can substantially boost productivity for crops, algae, mushrooms, fish, insects, and cultured meat. These systems are independent of climate, weather, and region, offering reduced environmental impact, although they come with high energy demands. An easy-to-understand, quantitative performance assessment of the theoretical potential for these 6 CEA systems is proposed here. It compares them against the world's main food production system: field production of maize, wheat, rice, and soybean. CEA could play a pivotal role in the global food supply if efficiencies in energy, control of growth environments, and waste stream utilization are vastly improved. Technological advancements, targeted policy support and public engagement strategies will be necessary to significantly reduce production costs and increase public acceptance.

Food security is becoming an increasingly pressing issue (1, 2). Climate change is reducing both crop production areas and crop yields globally at a time when the world's population—which now exceeds 8.2 billion (1)—continues to grow. One in 10 people experiences hunger (3) and a further 1 in 5 experience "hidden hunger," or deficits in micronutrients (4), particularly in poor regions, but also in food deserts in urban and rural areas of wealthier countries where access to affordable and/or nutritious food is limited.

There is a clear need to improve agricultural performance. Most of our global food is produced from just a few sources. Over half comes from four field-based crops (wheat, rice, maize, and soybean), around 9% from meat, and around 3.5% from fish (Figure 1). Nearly all of this is supplied by conventional food production systems that detrimentally impact the environment. Land clearing and intensive field-based agriculture cause biodiversity loss as well as high greenhouse gas emissions (5, 6). Widespread herbicide and pesticide use pollutes soils and drinking water, and excessive application of fertilizer containing both phosphorus (a limited resource) (7), and nitrogen, results in eutrophication and destruction of freshwater reservoirs and marine ecosystems (8–10). Agricultural irrigation accounts for two-thirds of global freshwater withdrawal (2, 5), putting extreme stress on this increasingly limited resource (11). Meat and fish are particularly unsustainable food sources, given the often heavy use of antibiotics and the high methane emissions from cattle (5). Current agricultural practices, which also involve much long-haul transport of food stuffs, threaten the United Nations Sustainable Development Goals and the Farm to Fork Strategy of the European Union (12), and risk overstepping many of the planetary boundaries (13). These challenges are exacerbated by regional dietary

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shifts (14), increasing societal concern for animal welfare, and economic and geopolitical crises.

These damaging impacts must be urgently reduced, yet at the same time food production must increase. Controlled environment agriculture (CEA) is well placed to support conventional agriculture in providing the type of food security needed to feed humankind in the future. CEA is a method of farming in which temperature, humidity, light, atmospheric carbon dioxide (CO_2) concentration, nutrient supply, and pests are all regulated within an enclosed indoor facility. These systems often feature vertically stacked layers, maximizing the available growing area with each additional layer (15). CEA systems have so far been developed mostly for crops, but they have also been adapted to less common food sources like algae, mushrooms, insects, and cultured meat, which will become increasingly important as protein sources. By securing the constant availability and production of nutritious and safe food in local, weather- and climate-independent indoor units, these CEA systems could alleviate many of the pressures that global food production systems are facing. They can be built virtually anywhere in the world and could cover fluctuating regional food demands in a targeted and controlled way.

Most CEA systems have high energy demands (16, 17), and so they could not substitute field agriculture, at least at current electricity costs and without a holistic integration of renewable energy sources. CEA systems need to be appropriately evaluated for their potential to improve on conventional food production performance and impact. However, such an evaluation has never been done. Here, we present the first scientific quantitative framework for evaluating CEA systems in terms of their potential for productivity, resource use and environmental impact. We employ 11 key performance indicators (KPIs) to objectively assess the potential of CEA for 6 food systems in comparison with the current performance of field-based agriculture of wheat, maize, rice, and soybean—the world's main food systems (3) (Figure 1). While a comparison of a CEA system with a field-based counterpart might be of interest, if any of these CEA systems are to produce food more efficiently at a scale relevant to global food supply, it must compete with the main source of food production, and not with peripheral, current niche production systems (i.e. in terms of production volume), like field grown mushrooms, algae, and insects. Hence, the comparison of the CEAs here is deliberately done with the 4 major cereal crops as the main source for human carbohydrate and protein consumption (3).

The 11 KPIs reflect the maximum theoretical potential based on experimental evidence, modeled reference values reported in the literature or values calculated in this paper (Data S1; Data S2) and should not be regarded as the current commercial performance for any of these systems. As a metric of production and nutritional value, the first set of KPIs measures economic yield (agricultural production per unit of growth area), energy harvest, and protein yield. A further set measures arable land use, fertilizers, and water demand, the currently limiting factors for traditional agriculture (7, 18, 19). We also included energy use and a set of KPIs to estimate direct environmental impact, such as greenhouse gas emissions, pesticide use or antibiotic use, and nutrient loss (Matrix 1).

The 6 selected CEA systems are at different stages of development. The matrix reflects the theoretical maximum performance of each and shows that all have the potential to increase yield and nutritional value—and reduce resource use and external environmental impact—by orders of magnitude. However, all have today much greater energy demands. In the following sections, we summarize the opportunities and challenges for each in reaching their maximum performances.

KPIs - Adjusted for a 10 layer-vertical farm system	Field crops	CEA Crops	CEA Algae	CEA Mushrooms	CEA Insects	CEA Fish	CEA Cultured meat
Average world annual yield (t/ha of land)	4.5	1,900	1,900	23,040	32,140	12,410	42
Energy harvest (Gcal/ha/year)	16.3	7,000	6,000	33,000	170,000	17,000	125
Protein (kg/ha/year)	767	228,000	330,000	4,800,000	13,500,000	2,500,000	8,300
Land use (million ha of land)	697	2	2	0.1	0.1	0.3	74
Water use (L/kg food)	1,785	0.14	33	50	0.01	2,500	52
Energy use (kWh/kg food)	2.3	650	12	4	17	42	26
Global food miles (trillion tkm)	7.3	~ 0	~ 0	~ 0	~ 0	~ 0	~ 0
GHG emission (eCO2/kg food)	3.3	~ 0	~ 0	~ 0	8	3	2
Pesticides/antibiotics (kg/ha/year)	1.6	~ 0	~ 0	~ 0	~ 0	~ 0	~ 0
N leaching and run-off (kg/ha)	5.4	~ 0	~ 0	~ 0	~ 0	NA	~ 0
P leaching and run-off (kg/ha)	0.1	~ 0	~ 0	~ 0	~ 0	NA	~ 0

% Change			Positive	Negative
0%	to	10%		
10%	to	100%		
100%	to	10000%		
10000%	to	100000%		
		>100000%		

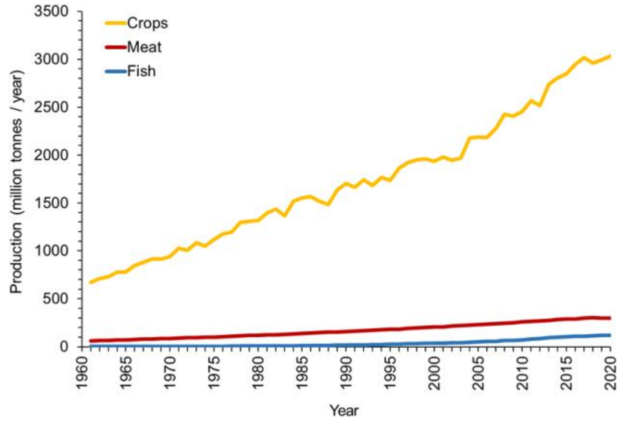

Fig. 1. World food production (million tonnes/year) for crops (yellow line), only considering wheat, maize, rice, and soybean; meat (red line), only considering cattle, pigs, and chicken; and fish (blue line), only considering those from open ocean fisheries and aquaculture, from 1961 to 2020. Crop weight is shown at 12% to 14% grain moisture, meat weight as fresh or chilled, and fish weight as live weight (3).

Matrix 1

Comparison of the theoretical CEA potential with the benchmark of the representative global field crop KPIs, with blue representing positive changes and red negative changes in orders of magnitude from 0% to >100,000%. CEA theoretical potential for all systems was calculated for a 10-layer system facility built on 1 ha of land, except for CEA mushrooms in which a 10-m-high bioreactor was used placed on a single layer of 1 ha. Each layer has 1 ha of growth area stacked above each other. All the values shown for field crops are based on published data. All assessments for the CEA systems are based on specific examples of current cultivars, species, and/or cultivation technologies within a defined setup and time frame or are the result of a modeling study or theoretical assessments (Data S1). These numbers should be regarded as reference values representing the theoretical potential of CEA, not as indicators of its current commercial performance (Data S1). Quantities of field crops (wheat, maize, rice, and soybean combined) for yield, energy harvest, protein, water use, and greenhouse gas emissions are shown as the weighted mean. Land use and global food miles are the sum of the values for the 4 crops, while the application of disease control measures (pesticides and antibiotics) and nitrogen (N) and phosphorus (P) loss are expressed as the averaged mean. The numbers in the matrix have been rounded to the nearest value for simplicity. For the exact values, refer to Data S1 and Data S2.

CEA of crops

This technology has already been commercialized for fast-growing, high-value products such as leafy green crops, fruits, microgreens, and berries (15, 16, 20, 21). However, very high energy demands, particularly for LED lighting (17), means that it is currently not commercially viable for the 4 main field grain crops (Matrix 1; Figure 1). Current experimental crop production units require around 650 kWh of energy per kilogram of grain, mostly for lighting, based on modeled data (16).

There is much scope to reduce CEA's energy requirements (17). Some strategies include applying light in sync with the physiological demands of the plants, which can reduce electricity consumption (17). Maximizing productivity, yield, and energy efficiency can be achieved by dynamically optimizing all factors that influence plant growth (15). These factors include LED light, temperature, humidity, atmospheric CO_2 concentration, ventilation, water, and nutrients (15). Through continuous feedback loops, the entire growth environment can be constantly optimized to match plant growth needs (22).

A recent study showed that fully controlled growth conditions could enable several wheat harvests per year (16), and estimated production could reach 1,900 t/ha/year in a 10-layer system, versus 4.5 t/ha/year in the field, a 42,000% increase in productivity (Data S1; Data S2). At top efficiency, only 0.14 L of water per kilogram of grain would leave the controlled environment, as most of the transpired water can be recovered. Field-based crops require approximately 1,800 L/kg of grain production (Matrix 1). This makes crop CEA ideal for water-scarce areas. Nutrient losses are near zero as compared to traditional agriculture because losses can be controlled (15, 18). And, because CEA crops are not grown in soil, soil-borne, health-threatening contaminants like cadmium (23) and arsenic (24) are eliminated. Additionally, pests and diseases can be physically excluded from the facility, eliminating the need for herbicides and pesticides.

In comparison with field-based food production, the hidden monetary and environmental cost savings in CEA resulting from avoiding pollution of the external environment will presumably be high, according to the latest report released by the Food System Economics Commission, which shows that the accumulated hidden costs of food production have reached trillions of dollars (25). CEA of crops might be incorporated strategically in areas where access to fresh produce is limited such as in urban food deserts (26), or in regions under extreme climates, like deserts, where agriculture presence is negligible but solar energy is abundant.

CEA of microalgae

Controlled environment microalgae production has the potential to generate highly nutrient-dense biomass from phototrophic aquatic microorganisms (27), but it is currently limited to high-value food products such as the antioxidant and red pigment astaxanthin, derived from *Haematococcus pluvialis* (28). Large-scale implementation is currently particularly costly (29) because of light needed for autotrophic and photoheterotrophic systems (30) and inefficient technologies for the isolation of highly nutritious biomass fractions, such as proteins (31). Energy demands are like the level of that for crops, but the theoretical photosynthetic efficiency of microalgae is about 2 to 4 times higher than that of crops grown in the field (32, 33), which translates to 10 to 50 times faster growth (34). In a 10-layer system, average yields could reach 1,900 t/ha/year of dry biomass, based on the 100 t/ha/year achieved in open bioreactor systems and the theoretical potential of 280 t/ha/year if maximum photosynthetic efficiency is realized (32, 33, 35). Protein yield could reach 330 t/ha/year protein, depending on the algae species (36, 37), which is comparable to CEA crops (Matrix 1).

Microalgae are versatile systems, growing in fresh, brackish, or salt water (27), freeing biomass production from the constraints of conventional agriculture. In bioreactors, all growth conditions can be controlled, including light for photosynthesis. Atmospheric CO_2 fixation at high photosynthetic rates makes microalgae biomass production carbon negative (38) and nutrient losses are avoided. Pesticides are unnecessary in bioreactors, and open ponds can sustain high productivity levels without pesticide use, even in the presence of contamination (39, 40). Additionally, after biomass recovery, most water can be reused in the cultivation system (40). In heterotrophic systems, algae grow in the dark and use organic compounds as a source of carbon and energy, instead of light, which can reduce upscaling costs due to higher biomass productivity or if waste streams are utilized (30).

CEA of mushrooms

Cultivation of mushrooms in bioreactors is currently carried out on small scales. At maximum efficiency of experimentally tested submerged cultures (41), yields could be higher than yields from field agriculture, becoming the second most productive CEA system per unit area and time (Matrix 1). However, energy demands are high (Matrix 1). Energy costs are associated with stirring, aeration, and maintaining constant temperature and humidity (42). Additionally, downstream processing to obtain protein isolates remains costly. However, energy could be reduced by directly producing vegan (41) or hybrid foods without isolating the protein fraction.

CEA of mushrooms takes advantage of the complex array of secreted and intracellular enzymes that mushrooms use to degrade and exploit even the most recalcitrant materials (43), including straw, peelings, pulps, pomaces, and brewer's spent grains (44). Mushroom cultivation converts organic waste and by-products of agriculture and food processing into valuable food and feed (44). Some edible mushrooms can convert a range of structurally different substrates, making it possible to match each mushroom species to almost any organic waste (44). Mushrooms may be grown in surface or submerged cultures to produce fruiting bodies, mycelial pellets, and aerial mycelium with high nutritional value (45). Fungal mycelia are rich in protein, fiber, β-glucans, vitamins, and bioactive and medicinal compounds (45–47).

An ideal system is one that relies exclusively on organic waste as the sole source of carbon, nitrogen, and minerals, which can then be converted into mushroom biomass. These mushroom cultures could yield up to 23,000 t/ha/year of dry matter in large-scale, 10-m-high bioreactors (Matrix 1). Remarkably, this system would only require 0.13 million ha of land to produce about 3,000 million tons of dry matter per year, versus 697 million ha of land required for the 4 main grain crops (Matrix 1).

CEA of insects

It has the potential to produce more protein per unit area than CEAs of any other foods, though at a higher energy cost than protein derived from the field. However, insects as a food source may not gain universal public acceptance (48).

Insect CEA exploits the fact that organisms such as the larvae of black soldier flies and mealworms can use organic substrates with little need for external energy (49). Based on the commercial data available, black soldier fly larvae (BSFL) could produce about 32,000 t/ha/year of dry matter and 13,500 t/ha/year of protein in a 10-layer system of 1 ha per layer (Matrix 1). Additionally, industrial insect farming generates frass, a mixture of excrement, chitinous exuviae, and feed leftovers, which could be used as fertilizers for crops (50). Insect CEA efficiently converts agricultural by-products (49), food, and industrial organic waste into feed for aquaculture and livestock at a large scale (51), an important link for a circular economy. However, there is a need to standardize feedstock for BSFL, so that the nutrient quality of that BSFL-based feed is maintained (51). Insect CEA, when coupled with other systems, can utilize unused portions of crops, algae, mushrooms, and fish as feed, while frass can serve as nutrient source for crops, mushrooms, and algae.

Insects can turn ecologically hazardous waste, such as the empty fruit bunches massively produced by the palm oil industry, into valuable protein, lipid, chitin, and frass (52). Furthermore, BSFL can aid in the bioconversion and detoxification of agricultural by-products contaminated with toxic plant secondary metabolites, like gossypol found in cottonseed press cake (53). Mealworms can even biodegrade polystyrene waste (54).

CEA of fish

Current farming of fish and other heterotrophic aquatic organisms under fully controlled conditions uses fresh or saline water tanks in a closed-loop production. These systems are called recirculating aquaculture systems (RASs), and they might include biofloc technology, a symbiotic system of aquatic animals and microorganisms, or integrated multitrophic aquaculture, in which various organisms are farmed at the same time (55). In a theoretical 10-layer system with high stocking densities and optimal feed-to-fish efficiency, edible biomass and protein productivity would increase by over 100,000% in comparison with field crops, based on conservative estimations (Matrix 1; Data S1), though a high density of fish farming may raise animal welfare concerns. However, fish from CEA sources are safer. Consumption of fish from traditional sources poses health concerns when lead or mercury are present in the open water systems (56, 57). As fish CEA systems are land based, the problem of pollutant accumulation in farmed fish is reduced or eliminated.

Fish CEA incurs high capital costs and demands a relatively high amount of energy to move water, filter sediments, and separate dissolved and solid nutrient-rich materials from uneaten feed and excrement (58). Nitrogen and phosphorus emission losses could be high (Data S1). There are increasing efforts to couple fish CEA with CEA of crops and algae via aquaponics to eliminate nitrogen and phosphate losses, and to use insects and/or organic by-products as sustainable feed. A model estimated that RAS in combination with macroalgae could reduce dissolved inorganic nitrogen and dissolved inorganic phosphorus by at least 66% and 31%, respectively (59). A proper harvesting strategy could reduce these emissions even more (59).

CEA of cultured meat

This refers to lab-grown meat or meat-based products using large-scale cell-culture technology (60). Animal cells proliferating and maturing in bioreactors eventually differentiate into meat-like components.

This technology is at a very early stage. It requires significant energy input (61) in the form of electricity, heat, or gas, and to produce media components (62) (Matrix 1). Together with substantial challenges to scaling up production, commercial cultured meat production is currently unviable. However, the overall energy consumption for cultured meat, encompassing both industrial and feed energy, has been calculated to be roughly one-third of the energy needed for animal beef production (62). This indicates that its potential is significant. Under ideal conditions, the estimated productivity for yield, energy harvest and protein could surpass by over 600% that of field crops (Matrix 1; Data S1). Moreover, 1 kg of cultured beef could be produced with 52 L of water (63), roughly 3% of what 1 kg of field crops requires (Matrix 1), because water can be presumably recycled largely within closed cultured meat bioreactors (62, 63). Cultured meat is an ethical and secure protein source. By eliminating the need for animal husbandry and slaughter, antibiotics, and additives, it assuages some animal welfare, environmental, and health concerns. Consumers may also accept cultured meat more than other novel sources of protein, such as algae or insects.

Discussion

Aside from the increase in productivity per unit time and area, the major advantages across all CEA systems include a significantly improved utilization of natural resources for water and nutrients, minimal food miles, zero pesticide, herbicide, and antibiotic use, and minimal to zero nutrient loss to the environment, except in the case of CEA fish (Matrix 1). CEA systems are also independent of weather, climate, and region, which all alleviate ecological pressures exerted by current traditional agricultural practices. CEA systems could therefore become a pillar of future food security, supporting traditional agricultural systems in periods when regional production declines, for example in case of sudden extreme weather events.

CEA could also tackle food insecurity. However, generalizing the feasibility of its implementation to all countries at risk from food insecurity would be currently overly optimistic. Food insecurity risk drivers are variable, ranging from armed conflicts or displacements due to climate change, which can cause drought or floods with extreme temperatures, dramatically affecting agriculture. For these reasons, we envision that CEA (of the most adequate food source for the region) could be best implemented in countries that are at peace with unsuitable agricultural land and agriculture being impacted by climate change, soil degradation, and urbanization, and also countries that want to reduce biodiversity loss and environmental damage from agriculture might implement such systems. Other factors could also play an important role, such as the presence or lack of specialized workforce and the degree of acceptance to the technology and the food produced.

For example, Kenya shows a modest threat to its food security scores, and it is projected to worsen in 2025 (64). Kenya has recently established some CEA farms and a specialized local working force (65). CEA farms can successfully cultivate tilapia, the most popular fish in Kenya, or classical CEA vegetables such as tomato and leafy greens, which are local staples. Further, Kenya is positioned as a leader in geothermal energy production in Africa as a sustainable, cost efficient energy source, which is projected to increase in coming years (66). As a result, prices in Kenya for electricity production might become affordable for successful CEA commercial operations. Hence, Kenya could be a good candidate for CEAs, provided political, economic, social, and infrastructure stability.

Densely populated urban areas of rich countries such as Singapore or the United Arab Emirates have supported the adoption of CEA farms to decrease their reliability on imports. Singapore has set a “30 by 30” strategy in which it aims to supply 30% of its nutritional demands through local production by 2030 (67). Singapore plans to ramp up the production of leafy greens, herbs, and berries. As the wealthiest country in Asia with virtually no agricultural land, meeting the 30 by 30 goals can only be done through urban farming in vertical farming settings. Similarly, Dubai will be soon home to the largest vertical farm in the world, and it is set to replace 1% of the food imports within the United Arab Emirates in the next years (68).

Interestingly, among the countries scoring the highest on food security indexes (69), 3 belong to the Nordic European countries, Finland, Norway, and Sweden (Data S3), none of which are top-ranked worldwide for food production (3). They have relatively low electricity prices in Europe for nonhousehold consumers with high energy demands (70), such as current vertical farms (Data S4) (71). Norway faces unfavorable weather conditions for crops, and currently there is modest customer acceptance to produce from vertical farms (72). CEA presence could increase, provided sufficient policy and public support.

Iceland can produce its own diary and meat, but it relies on imports for fruits and vegetables (73). Being placed as the second country in Europe with the cheapest average electricity prices for nonhousehold consumers with high energy demands (Data S4), Iceland could benefit from the implementation of commercial CEA to guarantee the local supply of vegetables and fruits.

Many of the world’s largest food-producing countries, such as the United States and France, Spain, and Germany in the European Union, rely on unsustainable agricultural practices that contribute to excessive pesticide use, soil degradation, nutrient loss to the environment, and a decline in biodiversity (74). The implementation of CEA could reduce the current environmental damage arising from traditional agricultural practices in these countries (15).

CEA systems can contribute to a circular economy when by-products generated by one food system are reutilized as an energy source in another (15). NASA and other space agencies have developed circular bioregenerative life support systems for spacecrafts, or potentially for lunar and Martian habitats (75). The expertise on improving resource efficiency by combining by-products from different CEA systems could be adapted and further developed on terrestrial CEA systems (15, 76). For example, microalgae have been linked with aquaculture systems (77); the organic waste generated by fish can be utilized by the algae for growth.

At this early stage, CEA’s most notable drawbacks are its large energy consumption and high construction costs. The energetic requirements for CEA systems are in the form of light, kinetic, or chemical energy inputs, and they will depend on substantial improvement of energy efficiency and low-cost, renewable energy sources if they are to become commercially viable at large scale. CEA systems are potentially resource efficient (Matrix 1), but they will require more optimization by tailoring the performance of crops, algae, mushrooms, fish, insects, and cell-cultured meat to CEA, for example, via conventional breeding or using modern genetic techniques.

Our analyses (Matrix 1) make clear how productive less familiar food sources like insects and algae could be in generating protein, but engaging society and policy support will be essential to improve public acceptance of such CEA foods, which differ in type, taste, and structure from traditional food. Policymakers should also consider aiding for implementing CEA systems, not to compete with traditional agriculture, but rather to support an additional path towards food security. Additionally, life cycle assessments specific to regions or countries where CEA systems are to be implemented are necessary. Matrix 1 can provide, together with other essential KPIs for environmental performance and energy use, a framework for much needed life cycle assessments for these novel systems (61, 62, 78, 79).

According to the Food and Agriculture Organization of the United Nations, a sustainable food system provides food security and nutrition for all while safeguarding the economic, social, and environmental foundations without compromising the future of the next generations. CEA for an array of food systems is at its early stage and has an untapped potential, and could play a crucial role to support sustainable future food production. To realize CEA’s potential at a commercial scale, tax incentives and grants for interdisciplinary research and development should link systems expertise in crops, algae, mushrooms, fish, insects, and cultured meat with bioengineering, process logistics, architecture, and importantly, research and implementation of inexpensive energy efficiency systems. Investments in CEA startups on particularly unsuitable agricultural land and countries at current or projected risk from food insecurity mainly driven by climate instability should be assisted, simultaneously expanding environmental, dietary, and culinary education (48, 72).

Supplementary Material

Supplementary material is available at *PNAS Nexus* online.

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Author contributions

Conceptualization: V.C.B., A.V., T.B., W.K., T.W., M.R., M.H., H.Z., O.M., S.A. Investigation: V.C.B., A.V., T.B., W.K., T.W., M.R., M.H., H.Z., O.M., S.A. Visualization: V.C.B., S.A. Funding acquisition: S.A., T.B. Writing—original draft: V.C.B., A.V., T.B., W.K., T.W., M.R., M.H., H.Z., O.M., S.A. Writing—review & editing: V.C.B., S.A.

Data availability

The authors confirm that the data supporting the findings of this study are available within the article and the supplementary information.

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