SI Appendix

Wheat yield potential in controlled-environment vertical farms

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SI Appendix Materials and Methods

DSSAT-NWheat crop simulation model

DSSAT-NWheat is a dynamic crop simulation model that calculates the phenology, growth, carbon partitioning, water and nitrogen uptake and grain yield of a wheat crop in daily timesteps, driven by daily solar radiation, maximum and minimum temperature and rainfall. The NWheat model was recently transferred from the Agricultural Production Systems Simulator (APSIM) to the Decision Support System for Agrotechnology Transfer (DSSAT) platform (*1*) and has been tested with detailed wheat field experimental data from a wide range of growing environments (*2-14*), including elevated atmospheric CO_2 conditions (*2, 15*). Using a crop simulation model allowed to expand the indoor experiment by Monje and Bugbee (*16*) to growing conditions further maximizing yield and to calculate water and nutrient use.

Indoor experiment

The Monje and Bugbee (*16*) indoor experiment was used for crop modeling because it had detailed estimates of biomass (Fig. 1), LAI (Fig. S1a) and grain yield growth (Fig. 1) over time, which were suitable for detailed model testing. Report +/- SD reported for this yield by Monje and Bugbee (*16*) were added to the experimental yield in Figure 2. In addition, the 1 m^2 Monje and Bugbee (*16*) experiment had edge protection to represent a crop canopy. Hence, these results were scalable to larger areas. The HI of 0.38 was measured using biomass and grain yield, including the root biomass (~5% of total biomass), at crop maturity.

The default parameter for radiation use efficiency (RUE) in NWheat is 3.8 g per MJ of intercepted light (at 350 ppm CO_2; note the NWheat model does not include respiration losses and carbon for roots is generated based on a Root:Shoot ratio, i.e., not based on carbohydrates from photosynthesis). This RUE parameter in NWheat was adjusted for indoor conditions to 7.3 g per MJ of intercepted light (at 330 ppm CO_2) based on RUE measurements by Monje and Bugbee (*16*). The higher RUE under indoor conditions is due to high diffuse light with deep canopy penetration, in contrast to limited diffuse light with low canopy penetration under field conditions.

When increasing CO_2 from 330 ppm to 1200 ppm under high light growing conditions, RUE in the Nwheat model was increased by 13% (Table S3) based on measurements (*16*), which is less than reported from field experiments with lower light intensities. Therefore, RUE was increased to 8.25 g per MJ of intercepted light for simulations at 1200 ppm CO_2.

The NWheat cultivar parameters for the cultivar used by Monje and Bugbee (*16*), cv. Veery-10, are shown in Table S1.

Table S1. Crop cultivar coefficients for DSSAT-NWheat v4.6.

Cultivar	VSEN[i]	PPSEN[j]	P1[k]	P5[l]	Phint[m]	GRNO[n]	MXFIL[o]	STMMX[p]	MXNUP[q]
Veery-10	1.00	1.20	350	500	100	20	1.60	3.00	4.20

[i] VSEN: Sensitivity to vernalization; [j] PPSEN: Sensitivity to photoperiod; [k] P1: Thermal time from seedling emergence to end of juvenile phase; [l] P5: Thermal time (base 0 ˚C) from beginning of grain filling to maturity; [m] PHINT: Interval between successive leaf appearances (degree days); [n] GRNO: Coefficient of kernel number per stem weight at the beginning of grain filling (kernels g^{-1} stem); [o] MXFIL: Potential kernel growth rate (mg $kernel^{-1}$ per day); [p] STMMX: Potential final dry weight of a single tiller (excluding grain) (g $stem^{-1}$); [q] MXNUP: maximum nitrogen uptake per day (g/m^2).

SIMPLE model

To consider model uncertainty, all simulations were repeated with another simpler crop model, SIMPLE (*17*). Also for the SIMPLE model, the RUE response to elevated CO_2 was reduced to the measured response observed in the experiment. Similar results were achieved when comparing the additional model with the observations (Fig. S1b,c). Both models were applied in all simulations and the mean of the results from both models are reported for the simulation experiments. To quantify model uncertainty, RUE (+/-10%) and light intensity (1800, 1900, and 2000 $\mu mol/m^2/s$) were varied in both models and the +/- 25^{th} percentile was calculated as the uncertainty range of the simulations.

Table S2. Crop cultivar and species coefficients for the SIMPLE model.

Cultivar	TSUM[i]	HI[j]	I50A[k]	I50B[l]	RUE[m]	CO2_RUE[n]
Veery-10	1600	0.38	200	200	1.50	0.008

[i] TSUM: Thermal time (base 0 ˚C) requirement from sowing to maturity in daily mean temperature; [j] HI: Harvest index; [k] I50A: Thermal time requirement for sowing fraction of light interception to reach 50%; [l] I50B: Thermal time requirement from 50% light interception to maturity; [m] RUE: Radiation use efficiency (above ground biomass + below ground, if harvestable product is below ground); [n] CO2_RUE: Relative increase in RUE per 1 ppm elevated CO2 above 350 ppm.

Bugbee and Salisbury (*18*) reported a 3.8 g/m^2 grain yield from an earlier 1 m^2 indoor wheat experiment. This experiment had unprotected edges with additional light entering from the sides, thus increasing crop growth. As a consequence, the observed yields in this experiment were not representing a crop canopy, and hence, not representative and scalable for our study. Therefore, the Bugbee and Salisbury (*18*) yields were not used here. Later indoor experiments had edge protection, like the one from Monje and Bugbee (*16*) used here, or an experimental area of up to 20 m^2 (*19*), and yields from these experiments were more comparable with each other.

In addition to the factors considered in this study, additional options exist for manipulating the growing environment to further enhance photosynthesis and growth. For example, growing plants at 75kPa (similar to growing plants at 3000 m elevation in the mountains) reduces O_2 and CO_2 partial pressures, which in combination with reduced boundary layer resistance and increased gas diffusion rates can increase photosynthetic efficiency (*20*). Varying the artificial light wavelengths has also been shown to potentially increase photosynthesis in some plants (*21*).

However, both approaches, lowering partial pressure and changing the light wavelengths, have not been proven to be effective for densely grown, high yielding, indoor wheat canopies and were therefore not further explored with the crop models.

Model testing

In addition to total biomass and yield growth dynamics (Fig. 1 in main paper), the simulated leaf area index (LAI) was compared with the observations from Monje and Bugbee (*16*) shown in Fig. S1a. Observed and simulated biomass and fSolar from the SIMPLE model are shown in Fig. S1b, c, respectively. Observed fSolar was calculated from the observed LAI using the equation: $fSolar = 1 - e^{(-k*LAI)}$, where k is the light extinction coefficient for wheat (0.6 in SIMPLE).

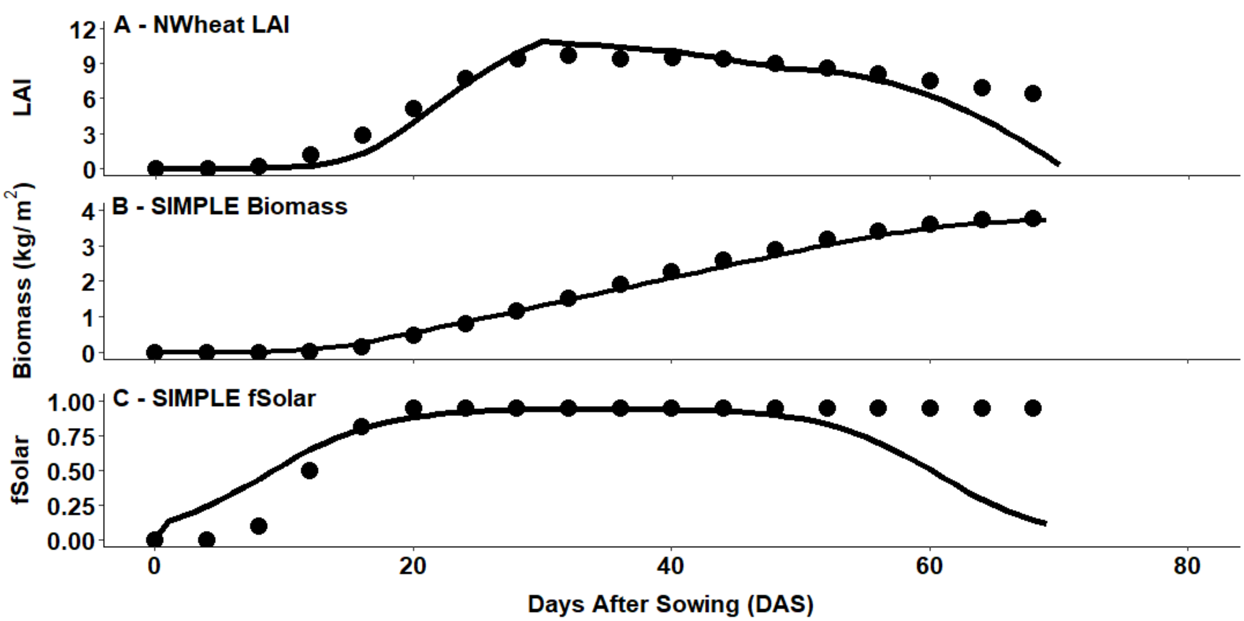

Fig. S1. Observed (circles) and simulated (solid line) (A) LAI, (B) biomass, and (C) fSolar for the indoor experiment with 20 h 1400 µmol/m^2/s light (50 MJ/m^2/d) and 330 ppm atmospheric CO_2 concentration (*16*) using the (A) NWheat and (B, C) SIMPLE crop models. Observations from Monje and Bugbee (16).

Indoor parameter

Table S3. Model factors considered for increasing yields above experimental achievements based on increasing the amount of daily light and radiation-use efficiency (RUE). Note: light in the DSSAT-NWheat and SIMPLE models is an input (light radiation in $MJ/m^2/d$).

Environmental factor	Factor adjustment in model
Increased light duration from 20 h to 24 h[1]	20% increase in daily light radiation from 50 to 60 $MJ/m^2/d$
24 h light + **Increased light intensity**[2] **from 1400 μmol/m²/s to 1800, 1900, and 2000 μmol/m²/s**	29, 36, and 43% increase in daily light radiation from 60 to 77, 81, and 86 $MJ/m^2/d$
24 h light + Increased light intensity + **Elevated CO_2 concentration from 330 ppm to 1200 ppm**[3]	13% increase in RUE
Combined factor effects for simulated yield (Fig. 2)	24 h light plus 29-43% increase in daily light radiation and 13% increase in RUE

[1] (*22, 23*).
[2] (*18, 24*).
[3] (*16*).

Yields, water and nutrient requirements

Table S4. Summary of yields, water and macro-nutrient uptake, and water and macro-nutrient costs for wheat growing scenarios.

Wheat growing scenario	Yield at 11% grain moisture (kg/ha/y)	Water use[6] (ML/ha/y)	Water cost[7] ($/ha/y)	Nutrient uptake[8] (kg/ha/y)			Nutrient cost[10] ($/ha/y)		
				N	P[9]	K[9]	N	P	K
World average yield[1]	3,217	2	239	106	21	26	50	11	12
Highest yielding country – Ireland[1]	9,222	6	572	303	61	76	142	32	35
World record yield – New Zealand[2]	16,791	10	993	552	110	138	259	58	64
Experiment[3]	71,445	38	3,822	2,350	470	588	1,102	247	272
Simulation[4]	114,235	43	4,300	3,725	745	931	1,746	391	431
Theoretical[5]	194,130	43	4,300	3,725	745	931	1,746	391	431

[1]10-year average yield, 2008-2017 (*25*).
[2]Guinness World Records, 2017 (*26*).
[3]Observed indoor experiment with 70-day season for 5 harvests/y, 20 h with 1400 μmol/m^2/s light (50 MJ/m^2/d), and 330 ppm atmospheric CO_2 concentration (*16*).
[4]Simulated 1 ha, 1-layer indoor experiment with 70-day season for 5 harvests/y, average of 24 h with 1800, 1900, and 2000 μmol/m^2/s light (77, 81, and 86 MJ/m^2/d) and +/- 10% RUE, and 1200 ppm atmospheric CO_2 concentration using the DSSAT-NWheat and SIMPLE models.
[5]Simulated 1 ha, 1-layer indoor experiment with 70-day season for 5 harvests/y, average of 24 h with 1800, 1900, and 2000 μmol/m^2/s light (77, 81, and 86 MJ/m^2/d) and +/- 10% RUE, and 1200 ppm atmospheric CO_2 concentration using the DSSAT-NWheat and SIMPLE models with a theoretical harvest index of 0.64 (*27, 28*). Water and nutrient uptake and costs are the same as in the simulation scenario because total biomass is the same, but harvest index differs.
[6]Water use for field scenarios based on yield-ET relationship (*29*); for the indoor experiment based on Monje and Bugbee (*30*); for the simulation and theoretical scenarios based on potential evapotranspiration rates after Penman-Monteith (*31*), scaled to elevated atmospheric CO_2 concentrations with indoor measurements from Monje and Bugbee (*30*). ML is million liters.
[7]Water cost based on higher range of agricultural water costs in United States ($100/ML) (*32*).
[8]N uptake for indoor scenarios are simulated cumulative N uptake from DSSAT-NWheat, and N uptake for field scenarios are based on yield-N uptake relationship from indoor scenarios.
[9]P and K amounts estimated based on N amounts and average NPK relationship, where P = 0.2*N and K = 0.25*N (*33*).
[10]Nutrient costs from University of Kentucky Cooperative Extension Service (*34*).

Table S5. Summary of calculated micro-nutrient uptake based on the concentration of nutrients in plant tissue from Bugbee and Salisbury (*18*) and adjusted for mature tissue.

Wheat growing scenario	Total biomass at 11% moisture[6] (kg/ha/y)	Total nutrient uptake[7] (kg/ha/y)										Total nutrient cost[8] ($/ha/y)									
		Ca	Mg	S	Fe	B	Mn	Zn	Cu	Mo	Si	Ca	Mg	S	Fe	B	Mn	Zn	Cu	Mo	Si
World average[1]	9,356	23	7	7	0.3	0.1	0.1	0.1	0.02	0.00	1	2	8	1	0.03	0.06	0.00	0.04	0.04	0.04	5
Highest yielding country – Ireland[1]	26,820	67	20	20	1	0.3	0.4	0.2	0.1	0.00	3	5	22	2	0.08	0.18	0.00	0.10	0.11	0.13	14
World record yield – New Zealand[2]	48,833	122	37	37	1	1	1	0.4	0.1	0.01	5	9	41	3	0.15	0.32	0.01	0.19	0.19	0.23	26
Experiment[3]	207,784	519	156	156	6	2	3	2	1	0.03	22	36	173	13	1	1	0.02	1	1	1	109
Simulation[4]	333,661	834	250	250	9	4	5	3	1	0.04	35	58	278	21	1	2	0.04	1	1	2	175
Theoretical[5]	333,661	834	250	250	9	4	5	3	1	0.04	35	58	278	21	1	2	0.04	1	1	2	175

[1]10-year average yield, 2008-2017 (*25*).
[2]Guinness World Records, 2017 (*26*).
[3]Observed indoor experiment with 70-day season for 5 harvests/y, 20 h with 1400 μmol/m^2/s light (50 MJ/m^2/d), and 330 ppm atmospheric CO_2 concentration (*16*).
[4]Simulated 1 ha, 1-layer indoor experiment with 70-day season for 5 harvests/y, average of 24 h with 1800, 1900, and 2000 μmol/m^2/s light (77, 81, and 86 MJ/m^2/d) and +/- 10% RUE, and 1200 ppm atmospheric CO_2 concentration using the DSSAT-NWheat and SIMPLE models.
[5]Simulated 1 ha, 1-layer indoor experiment with 70-day season for 5 harvests/y, average of 24 h with 1800, 1900, and 2000 μmol/m^2/s light (77, 81, and 86 MJ/m^2/d) and +/- 10% RUE, and 1200 ppm atmospheric CO_2 concentration using the DSSAT-NWheat and SIMPLE models with a theoretical harvest index of 0.64 (*27, 28*).
[6]Total biomass for field scenarios estimated by dividing reported yields by 0.38 HI from indoor experiment and multiplying by additional 10% for roots; experiment, simulation, and theoretical total biomass estimated by multiplying above-ground biomass by additional 10% for roots.
[7]Nutrient uptake for field, simulation and theoretical scenarios estimated from nutrient concentration in plant tissue from Bugbee and Salisbury (*18*) reduced by 75% based on difference of NPK concentrations between Table S4 and Bugbee and Salisbury (1988).
[8]Nutrient costs based on prices from USGS Mineral Commodity Summaries (*35*).

Indoor cost analysis

In order to evaluate the capital, operational and maintenance costs of indoor wheat farming, a conceptual design was developed for a large-scale facility with 10 ha of planted area. The facility comprises ten planted zones, each 100 m long, 10 m wide and 10 layers high, separated by access lanes and including adequate space for planting, harvesting, processing and administrative activities. The entire building is 135 m by 135 m in plan and 12.75 m high (see Fig. S3). These dimensions are comparable to 'big box' retail stores and warehouses so typical US construction costs for those building types have been assumed.

Construction costs for the planted zones were built up from component costs for the LED lighting, plant boxes, irrigation systems, air handling and conveying systems. Costs were estimated by comparison to equipment performing similar functions in other contexts. Planting, harvesting and bailing equipment costs were derived from equipment used in field agriculture.

Land acquisition costs were based on average US agricultural land prices and it is assumed that an overall site area of three times the building plan area will be required for accommodating the building as well as material handling, transportation and logistics activities. Typical US site development costs have been assumed.

The building is assumed to be well insulated and energy analysis of the facility indicates that energy use for lighting is the dominant factor in overall energy costs. Energy cost is therefore only minimally affected by climatic zone.

Of the other operational costs, staffing is the most significant. It is estimated that 65 employees will be required to cover a range of functions at an average hourly rate of $29.51, which includes all payroll and overhead costs. These costs assume a unionized US workforce and could be much lower in other global locations.

The costs associated with water, CO_2, nutrients, pH control, ethylene removal and facility maintenance were found to be small in relation to energy and staff costs and have a minor impact on the overall economic analysis.

Conventional harvesting and baling machinery will be oversized for the 10 layers of indoor growing wheat. However, costs associated with such machines have been used as a conservative assumption. We also considered the cost for a conveyor system, as the most efficient way to move crops in 10 layers, however, other systems might also be feasible. Costs for special equipment has been considered in the calculations, including ventilation, removing ethylene and moisture, and cooling or warming. Creating appropriate temperature gradients and requirements for drying before harvest have been considered at a concept design level and we conclude that they should be feasible in the context of a conveyor system., But the details will need to be worked out in the design of an actual facility.

Diseases need to be kept out of an indoor farm and if successful would avoid any pesticide use (*36*). If a disease outbreak occurs and the entire crop is lost, such a system could be cleaned up rather quickly and restarted. If one indoor crop is lost due to a disease outbreak, four out of the original five harvests per year can still be achieved. In contrast, if a crop is destroyed by a disease in the field, the entire year harvest of this crop will be lost.

A back-up energy supply could be important for the resilience of such facilities. If the primary energy source is solar, then back-up battery storage will likely be sufficient to provide security of supply. However, for other energy sources, additional back-up systems might be required which are not considered in our calculations.

A detailed spreadsheet model was developed to carry out the full cost analysis with the ability to adjust each parameter so that the sensitivity of the overall cost to various scenarios and assumptions could be tested. This study uses costs relevant to the US. These costs may vary in different countries.

An example of cost calculations for theoretical indoor wheat growing scenario of 24 h with 2000 μmol/m^2/s light (86 MJ/m^2/d) and 1200 ppm CO_2 concentration is given below.

For access to the cost analysis spreadsheets please email Mahadev Raman: Mahadev.Raman@arup.com.

"Energy & Production" sheet:

	Wheat Trust Environmental Control, Energy and Production			
1.0	**Input Data**	**Value**	**Units**	
	Scenario Number	10		
	Scenario Type	Theoretical		
	Length of wheat plot	100	m	
	Width of wheat plot	10	m	
	Light intensity	2000	µmol/m²/s	
	Light source efficiency	2	µmol/joule	
	Radiant energy produced	4.68	µmol/joule	
	Hours of operation per day	24	hours	
	Unlit proportion of growth cycle	11	%	Accounts for senescence and other darkness periods.
	Ambient CO2 concentration	400	ppm	
	CO2 concentration in facility	1200	ppm	
	Supply air temperature	21.5	C	
	Return air temperature	24.5	C	
	Winter outside air temperature	10	C	
	Summer outside air temp	25	C	

Heating Season	4	months	
Cooling Season	4	months	
Pressure loss in vent system	400	Pa	
Air velocity through plants	0.5	m/s	
Fan efficiency	80	%	
COP for Heating	4		
COP for Cooling	3.2		
Efficiency of heat recovery	60	%	
Wheat yield	20.3	$kg/m^2/year$	Simulated wheat yield from NWheat crop model.
Transpiration efficiency	224	kg water transpired per kg wheat yield	Calculated from simulated yield and ET relationship.
Biomass ratio	0.6	kg biomass (without grain) per kg wheat yield	Based on simulated biomass and yield.
Calorific value of wheat/biomass	17.2	MJ/kg	
Wheat price	0.20	$/kg	
Hay price	0.16	$/kg	
Energy cost	0.02	$/kWh	
Yield from field agriculture	0.32	$kg/m^2/year$	https://farmdocdaily.illinois.edu/2018/07/international-benchmarks-for-wheat-production.html

2.0 Lighting Energy Calculations per Plot

Area of wheat plot	1000	m^2	
Lighting electricity load	1000	W/m^2	
PAR energy produced	427	W/m^2	
Total lighting energy flow	1000	kW	
Radiated energy	427	kW	Radiated energy needs to be removed from the wheat plot.
Convected energy	573	kW	Assumed to be captured and removed at source.
Energy converted to biomass	17	kW	
Energy absorbed by transpiration	325	kW	
Net energy to air system	85	kW	

3.0 Vent System Calculations per Plot

Temp difference across plot	3	K
Air flow required	22.5	m^3/s
Air flow per unit length	0.225	$m^3/s/m$
Area of air supply diffuser	0.450	m^2/m
Temp rise from convected heat	20.2	K
Temperature of exhaust	44.7	C
Heat to temper outside air	326	kW
Heat recovery available	525	kW
Additional heat required	0	kW
Cooling required	99	kW

Vent system consumption	11.2	kW	

4.0 Summary of Growing Zone Energy Results/Plot

Lighting consumption	7796400	kWh/year	
Heating energy consumption	0	kWh/year	
Cooling energy consumption	89261	kWh/year	
Ventilation energy consumption	98505	kWh/year	
Total energy consumption	7984166	kWh/year	
Energy/unit area of plot	7984	kWh/m²/year	
Total energy cost for plant zone	160	$/m²/year	

5.0 Building and Process Dimensional Information

Number of planted zones	10		
Number of planted layers	10		
Clearance at seedling end	10	m	
Clearance at harvesting end	15	m	
Space between beds	3.00	m	
Width of center aisle	5.00	m	
Space between beds and wall	3.00	m	
Additional building width	0.00	m	
Height of plant including roots	0.5	m	
Height of conveyor mechanism	0.45	m	
Height of lighting zone	0.15	m	
Staff facilities	3	% of zone area	Ancillary spaces
Administration	2	% of zone area	
Inventory and Logistics	5	% of zone area	
Building M&E Systems	5	% of zone area	
Min depth of ancillary spaces	10	m	
Storey height of ancillary spaces	4.5	m	
Maintenance plinth height	0.25	m	
Roof structure and finish depth	1.5	m	
Base building annual energy use	52	kWh/m²	From Energy Tool model for NY climate.

6.0 Building Dimensions

Planting zone length	125	m	
Planting zone width	135	m	
Planting zone height	11	m	
Plan area planted per zone	10000	m²	
Floor plan area per zone	16875	m²	
Total planted area in building	100000	m²	

Ancillary spaces required	15	% of zone floor plan area
Total ancillary space required	2531	m^2
Number of ancillary stories	2	
Plan area of ancillary space	1266	m^2
Calculated depth of ancillary spaces	9.4	m
Actual depth of ancillary spaces	10	m
Building Length	135	m
Building Width	135	m
Building Height	12.75	m
Total Building Plan Area	18225	m^2

7.0	**Annual Energy and Production Statistics**		
	Total wheat production	2026647	kg/year
	Value of production	**405,329**	\$/year
	Total hay produced	1139989	kg/year
	Value of hay	**182,398**	\$/year
	Base building energy use	948	MWh
	Production energy use	798417	MWh
	Total energy use	799364	MWh
	Cost of energy	**15,987,286**	\$/year

“Capital Costs” sheet:

				User Input	Do Not Edit			
	Wheat Trust Capital Costs							
1.0	**Production Systems**	$/$m^2$						
	Planting Boxes	40	+					+ Price from Paul Gauthier.
			*					*\$500 for washer plus dryer moves 2m^2 of surface and has water, vent and movement controls built in.
	Conveyor Systems	100						
	Lighting	600	~					~\$150 for 265W LED grow lamp. So, \$0.6 per Watt.
	Irrigation, pH Control and Nutrient Delivery	50	*					
	CO2 Delivery System	30	*					
	Ethylene Removal System	30	*					
	Ventilation and Temperature Control	50	*					
		900	x	100000	m^2	=	\$ 90,000,000	
2.0	**Materials Handling and Logistics**	\$/zone						
	Seedling Handling	14000	+					+ A Northern FTF-603PTS crop Seeder costs \$2000 and is 1.5m wide.
	Reaping & Threshing Machinery	50000	*					*John Deere Combine at \$500,000 can harvest 600,000m^2 per day.

	Bailing and Packaging Machinery	5000	~					~John Deere 459 baler at $50,000 can produce 20 bales an hour at 40 m² per bale.
		69000	x	10	zones	=	$ 690,000	
3.0	**Base Building**	$/m²						
	Foundation	50	x	18225	m²	=	$ 911,250	RS Means suggest that the base cost for a warehouse was $104.84/sf in 2018.
	Structure	350	x	18225	m²	=	$ 6,378,750	So, allowing for inflation, this would give about $1200/m² excluding fit-out.
	M&E Systems	450	x	18225	m²	=	$ 8,201,250	https://www.rsmeans.com/model-pages/warehouse.aspx
	Cladding	800	x	6885	m²		$ 5,508,000	JLL cost benchmarks for office fit-out suggest $120.18/sf to $216.07/sf, depending on quality and complexity, in 2018.
	Roof	50	x	18225	m²	=	$ 911,250	https://www.constructiondive.com/news/jll-releases-cost-benchmark-guide-for-office-buildouts/519920/
	Fit-out Costs for Ancillary Areas	1300	x	2531	m²	=	$ 3,290,625	
							$ 25,201,125	
						or	$ 1,382.78	/m²

5.0	**Total Facility Cost**		
	Production Systems	$ 90,000,000	
	Materials Handling and Logistics	$ 690,000	
	Base Building	$ 25,201,125	
		$ 115,891,125	
	Total Planted Area	100000	m²
	Cost per m² of Planted Area	$ 1,159	/m²
	Building Floor Area (Main Floor plus Mezzanine)	19491	m²
	Cost per m² of Building	$ 5,946	/m²

6.0	**Site Acquisition and Development**								
	Land Area	=	3	x	Plan Area	=	54675	m²	On average, agricultural land is valued at $3140/acre, or $0.776/m².
	Land plus Site Preparation Costs					=	$ 40	/m²	https://downloads.usda.library.cornell.edu/usda-esmis/files/pn89d6567/qb98mj07s/rv042w81z/AgriLandVa-08-02-2018.pdf
									Site preparation can cost up to $40/m².
	Total Site Costs					=	**$ 2,187,000**		https://blog.parkenterpriseconstruction.com/commercial-site-work-costs-guide

“Operations & Management” sheet:

Wheat Trust Operating and Maintenance Costs

			User Input	Do Not Edit		
1.0	**Types of Employee and their costs**					
	Role	Number	Annual Salary	Total		
	Plant Manager	1	150000	$ 150,000		
	Building Maintenance	2	75000	$ 150,000		
	Agricultural Systems Maintenance	8	50000	$ 400,000		
	Administration and Accounts	4	50000	$ 200,000		
	Planting and Harvesting	45	35000	$ 1,575,000		Three shifts of 15
	Transportation and Logistics	5	75000	$ 375,000		
		65		$ 2,850,000		This is the total salary bill.
	Total Employment Cost: salary x	1.4	=	**$ 3,990,000**	per year	This is the cost of salaries plus social security, healthcare and retirement benefits.
	Average hourly salary for 2080 hrs/year			$ 21.08	per hour	
	Average employment cost for 2080 hrs/year			$ 29.51	per hour	

2.0	**Nutrients, Carbon Dioxide, pH Control and Ethylene Removal**			
	Total Biomass Produced with 10% roots	3483299	kg/year	Fertilizer costs vary from $350 to $850 per short ton depending on the nutrients required:
	Nutrient Content of Biomass	2.00%		https://www.ers.usda.gov/data-products/fertilizer-use-and-price.aspx
	Nutrient Consumption	69666	kg/year	
	Price of Nutrients	$ 1.00	per kg	Calculated from simulated nutrient uptake and mineral commodity price.
	Total Cost of Nutrients	**$ 69,666**	per year	
	CO2 Concentration in growth zone	1200	ppm	
	Ambient CO2 Concentration	400	ppm	
	Air Flowrate	2699	kg/s	
	CO2 flowrate	2.2	kg/s	CO2 costs are examined here and are expected to drop over time:
	Price of CO2	$ 3.00	per tonne	https://hub.globalccsinstitute.com/publications/accelerating-uptake-ccs-industrial-use-captured-carbon-dioxide/2-co2-market
	Total Cost of CO2	**$ 204,259**	per year	
	pH Control	**$ 6,967**	per year	10% of the Nutrient cost is assumed for pH control chemicals.
	Ethylene Removal	**$ 20,426**	per year	A once-through ventilation system is assumed so any ethylene produced will be evacuated. 10% of the CO2 cost is assumed.

3.0	**Water**			
	Total Water Consumed	453600	m^3 per year	The cost of water for agricultural use varies from $5 to over $100 per $1000m^3$. The higher value is assumed here.
	Price of Water	$ 0.10	per m^3	https://www.oecd.org/unitedstates/45016437.pdf
	Total Cost of Water	**$ 45,360**	per year	

4.0	**Maintenance**		
	Cost of Production Systems	$ 90,000,000	
	Cost of Agricultural Machinery	$ 690,000	
	Cost of Building Systems	$ 8,201,250	
	Annual Maintenance Allowance	5.000%	of capital cost per year
	Cost of Remainder of Facility	$ 19,186,875	
	Annual Maintenance Allowance	0.50%	of capital cost per year
	Total Maintenance Cost	**$ 505,997**	

5.0	**Annual O&M Cost**		
	Employees	$ 3,990,000	
	Nutrients, CO2, pH, Ethylene	$ 301,318	
	Water	$ 45,360	
	Maintenance	$ 505,997	
		$ 4,842,675	per year

"Executive Summary" sheet:

Wheat Trust Executive Summary

	Scenario	**24**	**2000**		**Theoretical**					
1.0	**Wheat Production**			per m² growing area		per tonne of annual harvest	**Future scenario**			
	Total Growing Area	100000	m²	1	m²	49				
	Wheat Production	**2026647**	kg/year	20.27	kg/yr	1000				
	Hay Production	1139989	kg/year	11.40	kg/yr	563				
	Revenue from Wheat	405,329	$/year	4.05	$/yr	200	1,621,318	4x		
	Revenue from Hay	182,398	$/year	1.82	$/yr	90	729,593	4x		
	Total Revenue	**587,728**	$/year	5.88	$/yr	290	2,350,910	4x		
	Yield from modern field Agriculture	0.32	kg/m²/year	0.32	kg/m²/yr	0.32				
	Area of field for equivalent yield	6,333,272	m²	63.33	m²	3125				
	Diameter of Field Required	2,839	m	8.98	m	63				

	2019	2050
Cost/return	**45/1**	**6/1**
Return	587,728	2,350,910

2.0	**Energy**							
	Energy Consumption	799364	MWh/year	7.99	MWh/yr	394		
	Energy Cost	**15,987,286**	$/year	159.87	$/yr	7889	**7,993,643**	half
3.0	**Capital Costs**							
	Production Systems	$ 90,000,000					45,000,000	half
	Materials Handling and Logistics	$ 690,000					690,000	
	Base Building	$ 25,201,125					25,201,125	
	Site Acquisition and Development	$ 2,187,000					2,187,000	
		$ 118,078,125		1181	$	58263	**73,078,125**	
	Cost per year financed at 5%	**$ 5,903,906**					**3,653,906**	
	Area of Production Facility	18225	m^2	0.18	m^2	9		
	Site Area Needed for Facility	54675	m^2	0.55	m^2	27		
	Diameter of Production Site	264	m	0.83	m	5.9		
4.0	**Operations and Maintenance**							
	Employees	$ 3,990,000					500,000	
	Nutrients, CO2, pH, Ethylene	$ 301,318					301,318	
	Water	$ 45,360					-	
	Maintenance	$ 505,997					505,997	
		$ 4,842,675		48.43	$	2390	**1,307,315**	

"Power Production" sheet:

						User Input	Do Not Edit			
	Wheat Trust Power Production									
1.0	**Energy Demand**									
	Annual Energy Demand	=	799364	MWh						
2.0	**Energy Supply - Solar Photovoltaics**									
	Peak Solar Radiation Intensity	=	950	W/m^2						
	Equivalent hours at full output	=	1840	hours/year						
	Generation Efficiency	=	22%							
	Area of PV required	=	2078647	m^2						
	Land Use Efficiency	=	50%							
	Land Area Required for PV Array	=	4157293	m^2						
	Dimensions of PV Facility	=	2.04	km	x	2.04	km	or	2.30	km Diameter
3.0	**Cost of PV Generation Facility**									

Generation Capacity	=	434	MW	
Cost $/W	=	1.13		https://www.nrel.gov/docs/fy19osti/72133.pdf
Cost of PV Generator	=	**$ 491**	**million**	
Cost of energy storage $/W	=	0.91		https://www.nrel.gov/docs/fy19osti/71714.pdf
Cost of Energy Store	=	**$ 395**	**million**	

SI Appendix Results

Annual cost and return scenarios of indoor facility

Table S6. Simulation. 2019 and 2050 cost analysis for 1 ha, 10-layer simulation indoor wheat growing scenario (1200 ppm CO_2 and 24 h light) with varying light intensity from 400, 600, 800, 1000, 1200, 1400, 1600, 1800, 1900, and 2000 μmol/m²/s (17, 26, 34, 43, 51, 60, 69, 77, 81, and 86 MJ/m²/d, respectively) using the NWheat and SIMPLE models.

2019 Costs (Million $/year)	Simulation Scenario – 24 h Light Intensity (μmol/m²/s)									
	400	600	800	1000	1200	1400	1600	1800	1900	2000
Energy Cost[1] ($M)	3.22	4.81	6.41	8.00	9.60	11.20	12.79	14.40	15.19	15.99
Capital Cost[2] ($M)	3.50	3.80	4.10	4.40	4.70	5.00	5.30	5.60	5.75	5.90
O & M[3] Cost ($M)	4.56	4.60	4.64	4.67	4.71	4.74	4.78	4.81	4.83	4.84
Total Cost ($M)	11.28	13.22	15.15	17.08	19.01	20.94	22.87	24.81	25.77	26.73
Return[4] ($M)	0.09	0.16	0.24	0.31	0.36	0.41	0.46	0.51	0.53	0.55
Cost/Return (-)	129.3	80.2	63.4	55.6	52.4	50.8	49.6	48.8	48.5	48.2
Energy Cost/Return[5] (-)	36.9	29.2	26.8	26.1	26.5	27.1	27.7	28.3	28.6	28.8

2050 Costs (Million $/year)	Simulation Scenario – 24 h Light Intensity (μmol/m²/s)									
	400	600	800	1000	1200	1400	1600	1800	1900	2000
Energy Cost[6] ($M)	1.61	2.41	3.20	4.00	4.80	5.60	6.40	7.20	7.60	7.99
Capital Cost[7] ($M)	2.45	2.60	2.75	2.90	3.05	3.20	3.35	3.50	3.58	3.65
O & M Cost[8] ($M)	1.07	1.10	1.13	1.16	1.19	1.22	1.25	1.28	1.29	1.31
Total Cost ($M)	5.13	6.11	7.08	8.06	9.04	10.02	11.00	11.98	12.47	12.95
Return[9] ($M)	0.35	0.66	0.96	1.23	1.45	1.65	1.85	2.03	2.13	2.22
Cost/Return (-)	14.7	9.3	7.4	6.6	6.2	6.1	6.0	5.9	5.9	5.8
Energy Cost/Return (-)	4.6	3.6	3.4	3.3	3.3	3.4	3.5	3.5	3.6	3.6

[1]At $0.02/kWh.
[2]Financed at 5%/y.
[3]Operations and maintenance.
[4]Wheat price at $200/t.
[5]Using cost of energy only.
[6]Half of 2019 energy costs.
[7]Half of 2019 production systems costs and financed at 5%/y.
[8]Employment costs reduced from $3,990,000/y to $500,000/y.

[9]Wheat prices four times higher than 2019 wheat prices.

Table S7. Theoretical. 2019 and 2050 cost analysis for 1 ha, 10-layer theoretical indoor wheat growing scenario (1200 ppm CO_2, 24 h light, and 0.64 harvest index) with varying light intensity from 400, 600, 800, 1000, 1200, 1400, 1600, 1800, 1900, and 2000 μmol/m^2/s (17, 26, 34, 43, 51, 60, 69, 77, 81, and 86 MJ/m^2/d, respectively).

2019 Costs (Million $/year)	Theoretical Scenario – 24 h Light Intensity (μmol/m^2/s)									
	400	600	800	1000	1200	1400	1600	1800	1900	2000
Energy Cost[1] ($M)	3.22	4.81	6.41	8.00	9.60	11.20	12.79	14.40	15.19	15.99
Capital Cost[2] ($M)	3.50	3.80	4.10	4.40	4.70	5.00	5.30	5.60	5.75	5.90
O & M Cost[3] ($M)	4.56	4.60	4.64	4.67	4.71	4.74	4.78	4.81	4.83	4.84
Total Cost ($M)	11.28	13.22	15.15	17.08	19.01	20.94	22.87	24.81	25.77	26.73
Return[4] ($M)	0.09	0.17	0.25	0.33	0.38	0.44	0.49	0.54	0.56	0.59
Cost/Return (-)	122.4	75.9	59.9	52.5	49.4	47.9	46.8	46.1	45.7	45.5
Energy Cost/Return[5] (-)	34.9	27.6	25.3	24.6	25.0	25.6	26.2	26.7	27.0	27.2

2050 Costs (Million $/year)	Theoretical Scenario – 24 h Light Intensity (μmol/m^2/s)									
	400	600	800	1000	1200	1400	1600	1800	1900	2000
Energy Cost[6] ($M)	1.61	2.41	3.20	4.00	4.80	5.60	6.40	7.20	7.60	7.99
Capital Cost[7] ($M)	2.45	2.60	2.75	2.90	3.05	3.20	3.35	3.50	3.58	3.65
Operations and Maintenance Cost[8] ($M)	1.07	1.10	1.13	1.16	1.19	1.22	1.25	1.28	1.29	1.31
Total Cost ($M)	5.13	6.11	7.08	8.06	9.04	10.02	11.00	11.98	12.47	12.95
Return[9] ($M)	0.37	0.70	1.01	1.30	1.54	1.75	1.96	2.15	2.25	2.35
Cost/Return (-)	13.9	8.8	7.0	6.2	5.9	5.7	5.6	5.6	5.5	5.5
Energy Cost/Return (-)	4.4	3.5	3.2	3.1	3.1	3.2	3.3	3.3	3.4	3.4

[1]At $0.02/kWh.
[2]Financed at 5%/y.
[3]Operations and maintenance.
[4]Wheat price at $200/t.
[5]Using cost of energy only.

[6]Half of 2019 energy costs.
[7]Half of 2019 production systems costs and financed at 5%/y.
[8]Employment costs reduced from \$3,990,000/y to \$500,000/y.
[9]Wheat prices four times higher than 2019 wheat prices.

Annual cost and return for experimental, simulation and theoretical scenarios

Table S8. Summary of major costs for a 1-ha, 10-layer indoor wheat production facility in 2019.

Factor	2019 Indoor costs (Thousand \$/year)	
	Experiment[1]	Simulation & Theoretical[2, 3]
Base building, production systems, and materials handling and logistics[4]	4,895	5,645
Light[5]	9,096	14,813
Cooling/heating/ventilation[5]	66	359
CO_2	0	195
Ethylene removal	0	20
Water (cost will be lower if recycled)	38	43
Macro- and micro-nutrients	42	67

[1]Indoor experiment with 70-day season for 5 harvests/y, 20 h with 1400 μmol/m^2/s light (50 MJ/m^2/d), and 330 ppm atmospheric CO_2 concentration.
[2]Simulated indoor experiment with 70-day season for 5 harvests/y, average of 24 h with 1800, 1900, and 2000 μmol/m^2/s light (77, 81, and 86 MJ/m^2/d), and 1200 ppm atmospheric CO_2 concentration using the DSSAT-NWheat and SIMPLE models with a theoretical harvest index of 0.64 (*27, 28*).
[3]Simulation indoor scenario has same major costs as theoretical indoor scenario (Figure 2, Table S4) because the total biomass is the same, except harvest index differs. Nutrient cost could be higher in theoretical scenario due to higher nutrient demand from increased grain yield, but the increase in overall total cost would likely be minimal.
[4]Financed at 5%/y. Production systems include costs of planting boxes, conveyor system, lighting system, irrigation, pH control, nutrient, and CO_2 delivery systems, ethylene removal system, and temperature and ventilation control system. Materials handling and logistics include seedling handling, reaping and threshing machinery, and baling and packaging machinery.
[5]Cost for planting area only using energy price at \$0.02/kWh.

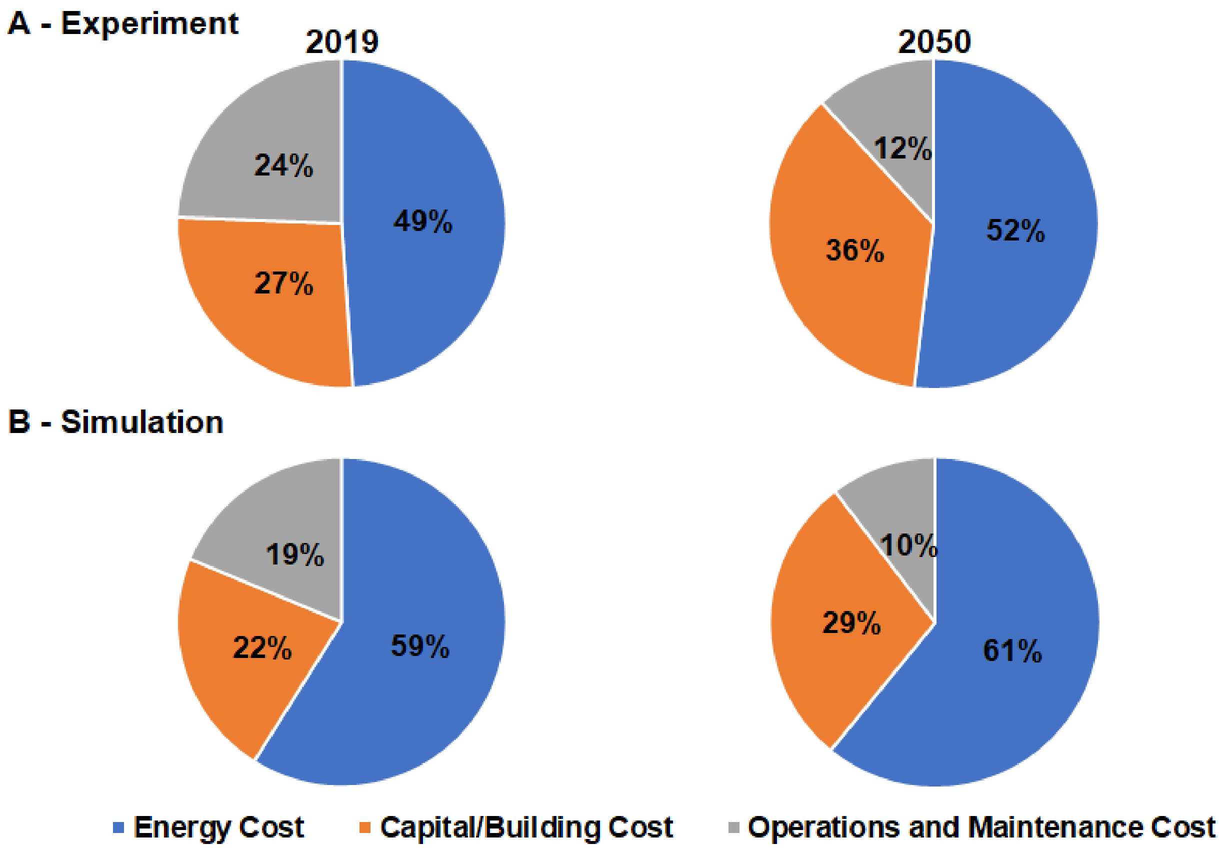

Fig. S2. Annual costs for indoor wheat farming. Pie charts show 2019 (left) and 2050 (right) cost analysis as categorized percentages for experiment (**A**) and simulation (**B**) 1 ha, 10-layer indoor wheat growing scenarios using the NWheat and SIMPLE models (Fig. 3B). Capital and building costs financed at 5% per year.

Comparison of annual global agricultural subsidies and proposed indoor wheat facility

Table S9. Cost comparison between annual global agricultural subsidies and proposed indoor wheat facilities for 2019 and 2050.

Description	2019	2050
Global Subsidies[1] ($M/y)	528,000	528,000
Total Cost per Facility[2] ($M/y)	25.77	12.47
Facilities per Subsidies (# of facilities)	20,487	42,346
Wheat Production (No Hay) per Subsidies[3] (M t/subsidies)	40	82
Wheat and Hay Production per Subsidies[3] (M t/subsidies)	62	129
Cost per Wheat Yield (No Hay) ($/kg)	13.27	6.42
Cost per Wheat and Hay Yield ($/kg)	8.49	4.11
People Fed[4] (M people)	569	1,175

[1](*37*).

[2]Total running cost per facility per year with building costs spread over 20 years (average cost of 1800-2000 μmol/m^2/s scenarios from Table S7).

[3]Wheat yield = 1942.50 t/facility; Hay production = 1092.70 t/facility (average yield of 1800-2000 μmol/m^2/s scenarios from Table S4).

[4]Mean consumption = 70 kg/capita (mean across all countries (*25*). For 2050, this is >1B people fed when using all agricultural subsidies for indoor wheat facilities.

Comparison of outdoor and indoor annual solar radiation

Glasshouse option: The light from the sun for one crop layer is substantially lower in a glasshouse than from high intensity indoor artificial light. The annual amount of sun light is about 25% of the highest indoor light scenario at the equator (12% in central Europe and 9% at the poles; based on NASA POWER for 2019 compared with 365 days of 24 hours with 2000 umol/m2/s, Table S10). In addition, the sun can supply only one single layer of a crop in a glasshouse, but artificial light supplies light to 10 layers (or even 100 layers in the scaled-up version). Hence, the light-limited production is a magnitude less in a glasshouse compared to indoor and despite lower building and running costs also economically not feasible for producing wheat. To generate the needed energy from solar panels for indoor production would require about the same area which would be saved through the indoor production (e.g., 4.16 km^2 for the 24 h with 2000 $\mu mol/m^2/s$ light with 1200 ppm atmospheric CO_2 theoretical scenario, see “Power Production” sheet in cost analysis above).

Table S10. Annual solar radiation comparison between three outdoor locations in different latitudes (equatorial, mid-latitude, and north pole) and two indoor scenarios.

Location	Annual solar radiation ($MJ/m^2/y$)
Nairobi, KE[1]	7,860.4
Wageningen, NL[1]	3,848.4
North Pole[1]	2,897.9
Indoor – most energy efficient scenario[2]	15,658.5
Indoor – maximum light scenario[3]	31,280.5

[1]Source: NASA POWER database for 2019.
[2]SRAD at 24 h with 1000 $\mu mol/m^2/s$ light (42.9 $MJ/m^2/d$) and 1200 ppm atmospheric CO_2.
[3]SRAD at 24 h with 2000 $\mu mol/m^2/s$ light (85.7 $MJ/m^2/d$) and 1200 ppm atmospheric CO_2.

Drawings of an indoor vertical wheat facility

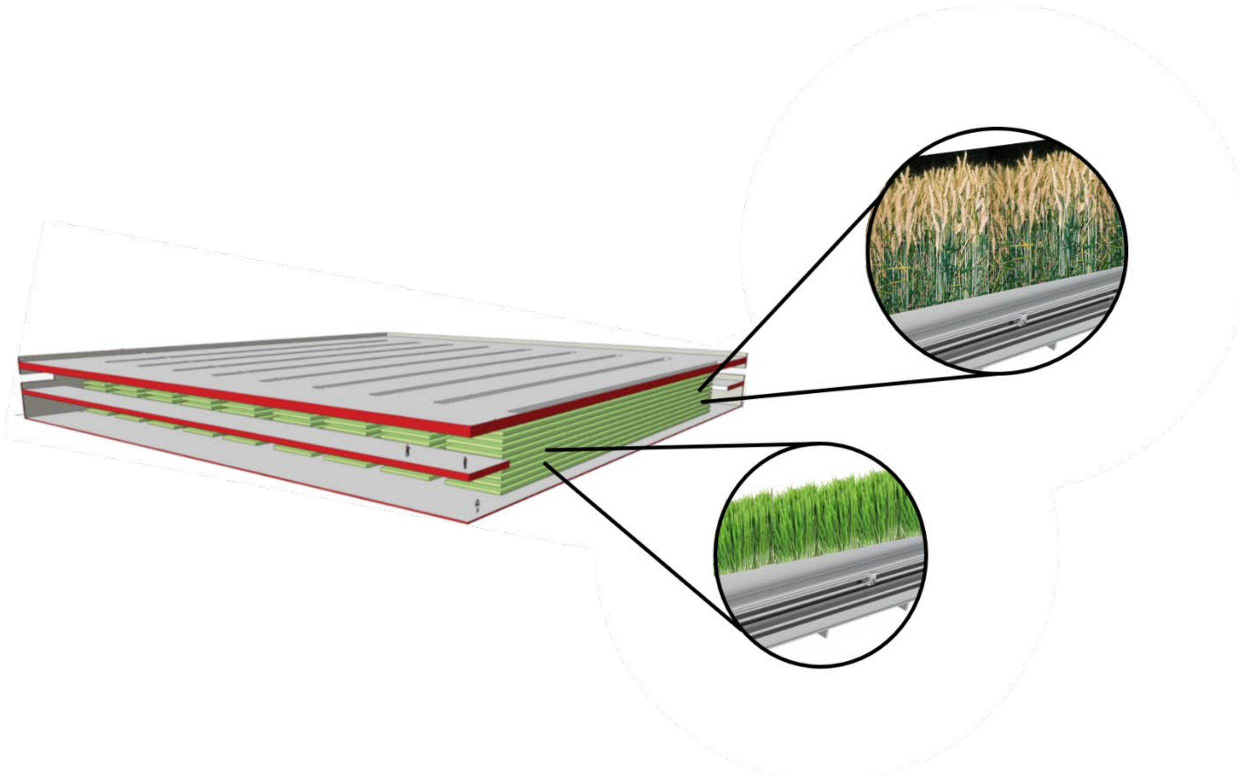

Fig. S3. Drawing of a 1 ha (100 x 100 m), 10-layer (each layer 1 m high) indoor vertical wheat growing facility. Wheat is planted at front and moves on conveyor to the back in 70 days, where it is harvested. Magnified areas show wheat on conveyor belt at early (front) and late (back) stage of wheat development.

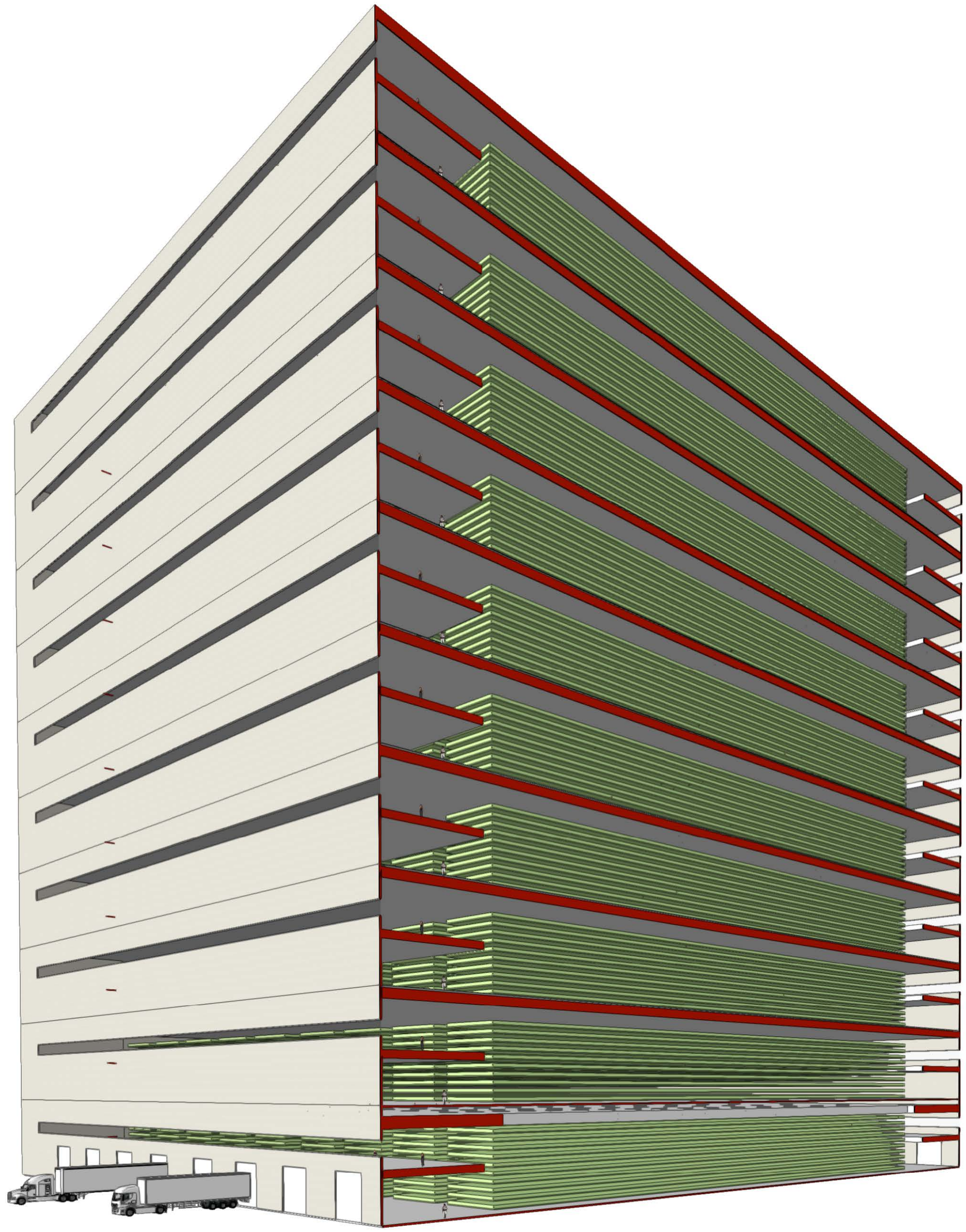

Fig. S4. Drawing of multiple, 1 ha (100 x 100 m), 10-layer (each layer 1 m high) indoor vertical wheat growing facility units (four 10-layer units are shown). Wheat is planted at front and moves on conveyor to the back in 70 days, where it is harvested. Magnified areas show wheat on conveyor belt at early (front) and late (back) stage of wheat development.

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