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 CO₂ 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 m² 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 CO₂; 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 CO₂) 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 CO₂ 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 CO₂.

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 | PPSEN | P1 | P5 | Phint | GRNO | MXFIL | STMMX | MXNUP |
|----------|------|-------|----|----|-------|------|-------|-------|-------|
| Veery-10 | 1.00 | 1.20  | 350| 500| 100   | 20   | 1.60  | 3.00  | 4.20  |

1 VSEN: Sensitivity to vernalization; 2 PPSEN: Sensitivity to photoperiod; 3 P1: Thermal time from seedling emergence to end of juvenile phase; 4 P5: Thermal time (base 0 °C) from beginning of grain filling to maturity; 5 PHINT: Interval between successive leaf appearances (degree days); 6 GRNO: Coefficient of kernel number per stem weight at the beginning of grain filling (kernels g⁻¹ stem); 7 MXFIL: Potential kernel growth rate (mg kernel⁻¹ per day); 8 STMMX: Potential final dry weight of a single tiller (excluding grain) (g stem⁻¹); 9 MXNUP: maximum nitrogen uptake per day (g/m²).

**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 CO₂ 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 µmol/m²/s) were varied in both models and the +/- 25th percentile was calculated as the uncertainty range of the simulations.

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

| Cultivar | TSUM | HI | I50A | I50B | RUE | CO2_RUE |
|----------|------|----|------|------|-----|---------|
| Veery-10 | 1600 | 0.38| 200  | 200  | 1.50| 0.008   |

1 TSUM: Thermal time (base 0 °C) requirement from sowing to maturity in daily mean temperature; 2 HI: Harvest index; 3 I50A: Thermal time requirement for sowing fraction of light interception to reach 50%; 4 I50B: Thermal time requirement from 50% light interception to maturity; 5 RUE: Radiation use efficiency (above ground biomass + below ground, if harvestable product is below ground); 6 CO2_RUE: Relative increase in RUE per 1 ppm elevated CO₂ above 350 ppm.

Bugbee and Salisbury (18) reported a 3.8 g/m² grain yield from an earlier 1 m² 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 m² (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 O₂ and CO₂ 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: 

$$f_{Solar} = 1 - e^{(-k \cdot LAI)}$$

where k is the light extinction coefficient for wheat (0.6 in SIMPLE).

![Graph showing LAI, biomass, and fSolar over days after sowing](image)

Fig. S1. Observed (circles) and simulated (solid line) (A) LAI, (B) biomass, and (C) fSolar for the indoor experiment with 20 h 1400 μmol/m²/s light (50 MJ/m²/d) and 330 ppm atmospheric CO₂ 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/m²/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/m²/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/m²/d |
| 24 h light + Increased light intensity + **Elevated CO₂ concentration** from 330 ppm to 1200 ppm³ | 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 (ML/ha/y) | Water cost ($/ha/y) | Nutrient uptake (kg/ha/y) | Nutrient cost ($/ha/y) |
|----------------------------------------|--------------------------------------|---------------------|---------------------|---------------------------|------------------------|
| World average yield¹                  | 3,217                                | 2                   | 239                 | 106                       | 21                     |
| Highest yielding country – Ireland²    | 9,222                                | 6                   | 572                 | 303                       | 61                     |
| World record yield – New Zealand²     | 16,791                               | 10                  | 993                 | 552                       | 110                    |
| Experiment³                            | 71,445                               | 38                  | 3,822               | 2,350                     | 470                    |
| Simulation⁴                           | 114,235                              | 43                  | 4,300               | 3,725                     | 745                    |
| Theoretical⁵                          | 194,130                              | 43                  | 4,300               | 3,725                     | 745                    |

¹10-year average yield, 2008-2017 (25).
²Guinness World Records, 2017 (26).
³Observed indoor experiment with 70-day season for 5 harvests/y, 20 h with 1400 μmol/m²/s light (50 MJ/m²/d), and 330 ppm atmospheric CO₂ concentration (16).
⁴Simulated 1 ha, 1-layer indoor experiment with 70-day season for 5 harvests/y, average of 24 h with 1800, 1900, and 2000 μmol/m²/s light (77, 81, and 86 MJ/m²/d) and +/- 10% RUE, and 1200 ppm atmospheric CO₂ concentration using the DSSAT-NWheat and SIMPLE models.
⁵Simulated 1 ha, 1-layer indoor experiment with 70-day season for 5 harvests/y, average of 24 h with 1800, 1900, and 2000 μmol/m²/s light (77, 81, and 86 MJ/m²/d) and +/- 10% RUE, and 1200 ppm atmospheric CO₂ 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.
⁶Water 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 CO₂ concentrations with indoor measurements from Monje and Bugbee (30). ML is million liters.
⁷Water cost based on higher range of agricultural water costs in United States ($100/ML) (32).
⁸N 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.
⁹P and K amounts estimated based on N amounts and average NPK relationship, where P = 0.2*N and K = 0.25*N (33).
¹⁰Nutrient 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 | 0.02 | 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/m²/s light (50 MJ/m²/d), and 330 ppm atmospheric CO₂ 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/m²/s light (77, 81, and 86 MJ/m²/d) and +/- 10% RUE, and 1200 ppm atmospheric CO₂ 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/m²/s light (77, 81, and 86 MJ/m²/d) and +/- 10% RUE, and 1200 ppm atmospheric CO₂ 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, CO₂, 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/m²/s light (86 MJ/m²/d) and 1200 ppm CO₂ 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 | 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    | %     |
| 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     |

Accounts for senescence and other darkness periods.
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/m²/year
Transpiration efficiency: 224 kg water transpired per kg wheat yield
Biomass ratio: 0.6 kg biomass (without grain) per kg wheat 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/m²/year

Simulated wheat yield from NWheat crop model.
Calculated from simulated yield and ET relationship.
Based on simulated biomass and yield.

2.0 Lighting Energy Calculations per Plot

Area of wheat plot: 1000 m²
Lighting electricity load: 1000 W/m²
PAR energy produced: 427 W/m²
Total lighting energy flow: 1000 kW
Radiated energy: 427 kW
Convected energy: 573 kW
Energy converted to biomass: 17 kW
Energy absorbed by transpiration: 325 kW
Net energy to air system: 85 kW

Radiated energy needs to be removed from the wheat plot.
Assumed to be captured and removed at source.

3.0 Vent System Calculations per Plot

Temp difference across plot: 3 K
Air flow required: 22.5 m³/s
Air flow per unit length: 0.225 m³/s/m
Area of air supply diffuser: 0.450 m²/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

https://farndocdaily.illinois.edu/2018/07/international-benchmarks-for-wheat-production.html
Vent system consumption 11.2 kW

4.0 Summary of Growing Zone Energy Results/Plot

| Consumption Type                      | Value       |
|---------------------------------------|-------------|
| 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

| Dimension                        | Value       |
|----------------------------------|-------------|
| 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 |
| 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   |

Ancillary spaces

6.0 Building Dimensions

| Dimension                        | Value       |
|----------------------------------|-------------|
| 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 m²
Number of ancillary stories | 2
Plan area of ancillary space | 1266 m²
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 m²

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:

Wheat Trust Capital Costs

1.0 Production Systems

| Planting Boxes | $/m² | 40 |
| Conveyor Systems | | 100 |
| Lighting | | 600 |
| Irrigation, pH Control and Nutrient Delivery | | 50 |
| CO2 Delivery System | | 30 |
| Ethylene Removal System | | 30 |
| Ventilation and Temperature Control | | 50 |

900 x 100000 m² = $ 90,000,000

2.0 Materials Handling and Logistics

| Seedling Handling | $/zone | 14000 |
| Reaping & Threshing Machinery | | 50000 |

+ Price from Paul Gauthier.
+ $500 for washer plus dryer moves 2m² of surface and has water, vent and movement controls built in.
+ $150 for 265W LED grow lamp. So, $0.6 per Watt.
+ A Northern FTF-603PTS crop Seeder costs $2000 and is 1.5m wide.
+ John Deere Combine at $500,000 can harvest 600,000m² per day.
Bailing and Packaging Machinery

5000
69000 x 10 zones = $690,000

~

“John Deere 459 baler at $50,000 can produce 20 bales an hour at 40 m$^{2}$ per bale.

3.0 Base Building

| Item                | $/m$^{2} | Plan Area | Cost per m$^{2}$ |
|---------------------|----------|-----------|------------------|
| Foundation          | $911,250 | 18225     | $50             |
| Structure           | $6,378,750 | 18225 | $350 |
| M&E Systems         | $8,201,250 | 18225 | $450 |
| Cladding            | $5,508,000 | 6885 | $800 |
| Roof                | $911,250 | 18225 | $50 |
| Fit-out Costs for Ancillary Areas | $3,290,625 | 2531 | $1300 |

RS Means suggest that the base cost for a warehouse was $104.84/sf in 2018. So, allowing for inflation, this would give about $1200/m$^{2}$ excluding fit-out.

https://www.rsmeans.com/model-pages/warehouse.aspx

JLL cost benchmarks for office fit-out suggest $120.18/sf to $216.07/sf, depending on quality and complexity, in 2018.

https://www.constructiondive.com/news/jll-releases-cost-benchmark-guide-for-office-buildouts/519920/

5.0 Total Facility Cost

Production Systems $90,000,000
Materials Handling and Logistics $690,000
Base Building $25,201,125

$115,891,125

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 m$^{2}$
Cost per m$^{2}$ of Planted Area $1,159/m$^{2}$

Building Floor Area (Main Floor plus Mezzanine) 19491 m$^{2}$
Cost per m$^{2}$ of Building $5,946/m$^{2}$

6.0 Site Acquisition and Development

Land Area $= 3 \times$ Plan Area $= 54675$ m$^{2}$

Land plus Site Preparation Costs $= 40 /m^{2}$

Total Site Costs $= 2,187,000

On average, agricultural land is valued at $3140/acre, or $0.776/m$^{2}$.

https://downloads.usda.library.cornell.edu/usda-esmis/files/pn89d6567/qb98mj07s/rv042w81z/AgriLandVa-08-02-2018.pdf

Site preparation can cost up to $40/m$^{2}$.

https://blog.parkenterpriseconstruction.com/commercial-site-work-costs-guide

“Operations & Management” sheet:
# Wheat Trust Operating and Maintenance Costs

## 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|
| Transportation and Logistics       | 5      | 75000         | $375,000  |
| **Total Employment Cost: salary x 1.4** | 65     |               | **$3,990,000** per year |

Three shifts of 15

This is the total salary bill.

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 |
| Nutrient Content of Biomass          | 2.00%          |
| Nutrient Consumption                 | 69666 kg/year  |
| Price of Nutrients                   | $1.00 per kg   |
| **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       |
| Price of CO2                         | $3.00 per tonne|
| **Total Cost of CO2**                | $204,259 per year |
| pH Control                           | $6,967 per year |
| Ethylene Removal                     | $20,426 per year |

Fertilizer costs vary from $350 to $850 per short ton depending on the nutrients required: [https://www.ers.usda.gov/data-products/fertilizer-use-and-price.aspx](https://www.ers.usda.gov/data-products/fertilizer-use-and-price.aspx)

CO2 costs are examined here and are expected to drop over time: [https://hub.globalcsinstitute.com/publications/accelerating-uptake-ccs-industrial-use-captured-carbon-dioxide/2-co2-market](https://hub.globalcsinstitute.com/publications/accelerating-uptake-ccs-industrial-use-captured-carbon-dioxide/2-co2-market)

10% of the Nutrient cost is assumed for pH control chemicals.

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 m³ per year |
| Price of Water       | $0.10 per m³       |
| **Total Cost of Water** | $45,360 per year |

The cost of water for agricultural use varies from $5 to over $100 per 1000m³. The higher value is assumed here: [https://www.oecd.org/unitedstates/45016437.pdf](https://www.oecd.org/unitedstates/45016437.pdf)
4.0 Maintenance

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

5.0 Annual O&M Cost

| Description                                    | Amount       |
|------------------------------------------------|--------------|
| Employees                                      | $3,990,000   |
| Nutrients, CO2, pH, Ethylene                   | $301,318     |
| Water                                          | $45,360      |
| Maintenance                                    | $505,997     |
| **Total**                                       | **$4,842,675** per year |

“Executive Summary” sheet:

| Wheat Trust Executive Summary                  | 24  | 2000 | Theoretical |
|------------------------------------------------|-----|------|-------------|
| 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 |
| Revenue from Hay                               | 182,398 | $/year | 1.82 $/yr | 90 |
| Total Revenue                                  | 587,728 | $/year | 5.88 $/yr | 290 |
| 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 |

| Future scenario                                | 2019 | 2050 |
|------------------------------------------------|------|------|
| Cost/return                                    | 45/1 | 6/1  |
| Return                                         | 587,728 | 2,350,910 |

| 4x |
|---|
### 2.0 Energy

| Description                      | Value       |
|----------------------------------|-------------|
| Energy Consumption               | 799364 MWh/year | 7.99 MWh/yr |
| Energy Cost                      | 15,987,286 $/year | 159.87 $/yr |

### 3.0 Capital Costs

| Description                              | Value       |
|------------------------------------------|-------------|
| Production Systems                       | $90,000,000  |
| Materials Handling and Logistics         | $690,000    |
| Base Building                            | $25,201,125 |
| Site Acquisition and Development         | $2,187,000  |
| **Cost per year financed at 5%**         | $5,903,906  |

### 4.0 Operations and Maintenance

| Description                              | Value       |
|------------------------------------------|-------------|
| Employees                                | $3,990,000  |
| Nutrients, CO2, pH, Ethylene             | $301,318    |
| Water                                    | $45,360     |
| Maintenance                              | $505,997    |
| **Total**                                | $4,842,675  |

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### “Power Production” sheet:

#### Wheat Trust Power Production

| Description                              | Value       |
|------------------------------------------|-------------|
| **Energy Demand**                        | 799364 MWh |

#### Energy Supply - Solar

| Description                              | Value       |
|------------------------------------------|-------------|
| Peak Solar Radiation Intensity           | 950 W/m²    |
| Equivalent hours at full output          | 1840 hours/year |
| Generation Efficiency                     | 22%         |
| Area of PV required                      | 2078647 m²  |
| Land Use Efficiency                      | 50%         |
| Land Area Required for PV Array          | 4157293 m²  |
| Dimensions of PV Facility                | 2.04 km x 2.04 km or 2.30 km Diameter |

#### 3.0 Cost of PV Generation Facility
| Description                          | Value       | Unit | Source                           |
|-------------------------------------|-------------|------|----------------------------------|
| Generation Capacity                 | 434         | MW   | [https://www.nrel.gov/docs/fy19osti/72133.pdf](https://www.nrel.gov/docs/fy19osti/72133.pdf) |
| Cost $/W                            | 1.13        |      |                                  |
| Cost of PV Generator                | $491        | million | [https://www.nrel.gov/docs/fy19osti/71714.pdf](https://www.nrel.gov/docs/fy19osti/71714.pdf) |
| Cost of energy storage $/W          | 0.91        |      |                                  |
| Cost of Energy Store                | $395        | million | [https://www.nrel.gov/docs/fy19osti/71714.pdf](https://www.nrel.gov/docs/fy19osti/71714.pdf) |
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 CO2 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 $/year) |  | Simulation Scenario – 24 h Light Intensity (μmol/m²/s) |
|-----------------------------|----------|-----------------------------------------------|
|                            | 400      | 600 | 800 | 1000 | 1200 | 1400 | 1600 | 1800 | 1900 | 2000 |
| Energy Cost¹ ($M)           | 3.22     | 4.81| 6.41| 8.00 | 9.60 | 11.20| 12.79| 14.40| 15.19| 15.99|
| Capital Cost² ($M)          | 3.50     | 3.80| 4.10| 4.40 | 4.70 | 5.00 | 5.30 | 5.60 | 5.75 | 5.90 |
| O & M³ Cost ($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 (SM)                 | 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/Return¹ (-)     | 36.9     | 29.2 | 26.8| 26.1 | 26.5 | 27.1 | 27.7 | 28.3 | 28.6 | 28.8 |

| 2050 Costs (Million $/year) |  | Simulation Scenario – 24 h Light Intensity (μmol/m²/s) |
|-----------------------------|----------|-----------------------------------------------|
|                            | 400      | 600 | 800 | 1000 | 1200 | 1400 | 1600 | 1800 | 1900 | 2000 |
| Energy Cost² ($M)           | 1.61     | 2.41 | 3.20| 4.00 | 4.80 | 5.60 | 6.40 | 7.20 | 7.60 | 7.99 |
| Capital Cost³ ($M)          | 2.45     | 2.60 | 2.75| 2.90 | 3.05 | 3.20 | 3.35 | 3.50 | 3.58 | 3.65 |
| O & M Cost⁴ ($M)            | 1.07     | 1.10 | 1.13| 1.16 | 1.19 | 1.22 | 1.25 | 1.28 | 1.29 | 1.31 |
| Total Cost ($M)             | 5.13     | 6.11 | 7.08| 8.06 | 9.04 | 10.02| 11.00| 11.98| 12.47| 12.95|
| Return⁵ ($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/Return¹ (-)     | 4.6      | 3.6  | 3.4 | 3.3  | 3.3  | 3.4  | 3.5  | 3.5  | 3.6  | 3.6  |

¹At $0.02/kWh.
²Financed at 5%/y.
³Operations and maintenance.
⁴Wheat price at $200/t.
⁵Using cost of energy only.
⁶Half of 2019 energy costs.
⁷Half of 2019 production systems costs and financed at 5%/y.
⁸Employment costs reduced from $3,990,000/y to $500,000/y.
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 CO₂, 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/m²/s (17, 26, 34, 43, 51, 60, 69, 77, 81, and 86 MJ/m²/d, respectively).

| 2019 Costs (Million $/year) | Theoretical Scenario – 24 h Light Intensity (μmol/m²/s) |
|-----------------------------|---------------------------------------------------------|
| Energy Cost¹ ($M)           | 400 | 600 | 800 | 1000 | 1200 | 1400 | 1600 | 1800 | 1900 | 2000 |
| 3.22                        | 4.81 | 6.41 | 8.00 | 9.60 | 11.20 | 12.79 | 14.40 | 15.19 | 15.99 |
| Capital Cost² ($M)          | 3.50 | 3.80 | 4.10 | 4.40 | 4.70 | 5.00 | 5.30 | 5.60 | 5.75 | 5.90 |
| O & M Cost³ ($M)            | 4.56 | 4.60 | 4.64 | 4.67 | 4.71 | 4.74 | 4.78 | 4.81 | 4.83 | 4.84 |
| Total Cost ($M)             | 11.28 | 13.22 | 15.15 | 17.08 | 19.01 | 20.94 | 22.87 | 24.81 | 25.77 | 26.73 |
| Return⁴ ($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/Return⁵ (-)     | 34.9 | 27.6 | 25.3 | 24.6 | 25.0 | 25.6 | 26.2 | 26.7 | 27.0 | 27.2 |

| 2050 Costs (Million $/year) | Theoretical Scenario – 24 h Light Intensity (μmol/m²/s) |
|-----------------------------|---------------------------------------------------------|
| Energy Cost⁶ ($M)           | 400 | 600 | 800 | 1000 | 1200 | 1400 | 1600 | 1800 | 1900 | 2000 |
| 1.61                        | 2.41 | 3.20 | 4.00 | 4.80 | 5.60 | 6.40 | 7.20 | 7.60 | 7.99 |
| Capital Cost⁷ ($M)          | 2.45 | 2.60 | 2.75 | 2.90 | 3.05 | 3.20 | 3.35 | 3.50 | 3.58 | 3.65 |
| Operations and Maintenance Cost⁸ ($M) | 1.07 | 1.10 | 1.13 | 1.16 | 1.19 | 1.22 | 1.25 | 1.28 | 1.29 | 1.31 |
| Total Cost ($M)             | 5.13 | 6.11 | 7.08 | 8.06 | 9.04 | 10.02 | 11.00 | 11.98 | 12.47 | 12.95 |
| Return⁹ ($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 |

¹At $0.02/kWh.
²Financed at 5%/y.
³Operations and maintenance.
⁴Wheat price at $200/t.
⁵Using cost of energy only.
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) |
|------------------------------------------------|--------------------------------------|
|                                                 | Experiment¹  | Simulation & Theoretical², ³    |
| Base building, production systems, and materials handling and logistics⁴ | 4,895        | 5,645                           |
| Light⁵                                          | 9,096        | 14,813                          |
| Cooling/heating/ventilation⁴                    | 66           | 359                             |
| CO₂                                             | 0            | 195                             |
| Ethylene removal                                | 0            | 20                              |
| Water (cost will be lower if recycled)          | 38           | 43                              |
| Macro- and micro-nutrients                      | 42           | 67                              |

¹Indoor experiment with 70-day season for 5 harvests/y, 20 h with 1400 μmol/m²/s light (50 MJ/m²/d), and 330 ppm atmospheric CO₂ concentration.
²Simulated indoor experiment with 70-day season for 5 harvests/y, average of 24 h with 1800, 1900, and 2000 μmol/m²/s light (77, 81, and 86 MJ/m²/d), and 1200 ppm atmospheric CO₂ concentration using the DSSAT-NWheat and SIMPLE models with a theoretical harvest index of 0.64 (27, 28).
³Simulation 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.
⁴Financed at 5%/y. Production systems include costs of planting boxes, conveyor system, lighting system, irrigation, pH control, nutrient, and CO₂ 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.
⁵Cost 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 \(\mu\)mol/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 \(\mu\)mol/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 km² for the 24 h with 2000 µmol/m²/s light with 1200 ppm atmospheric CO₂ 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/m²/y) |
|-------------------|----------------------------------|
| Nairobi, KE¹      | 7,860.4                          |
| Wageningen, NL¹   | 3,848.4                          |
| North Pole¹       | 2,897.9                          |
| Indoor – most energy efficient scenario² | 15,658.5 |
| Indoor – maximum light scenario³   | 31,280.5                         |

¹Source: NASA POWER database for 2019.
²SRAD at 24 h with 1000 µmol/m²/s light (42.9 MJ/m²/d) and 1200 ppm atmospheric CO₂.
³SRAD at 24 h with 2000 µmol/m²/s light (85.7 MJ/m²/d) and 1200 ppm atmospheric CO₂.
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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