Urban Plant Factories:
High in the Sky
or...
Pie in the Sky?
Skyscrapers

Are greenhouses really wearing new clothes????

Vertical Greenhouses and Plant Factories
2014 NGMA Annual Meeting, Miami, Florida
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Various proposals related to hi-tech agriculture have been frequently based on growing food crops with no natural light, or at least very little natural light.

Plant factories and vertical greenhouses are today’s buzz.
Two of the More Imaginative Designs for Vertical Farms
Our road map for the next hour …

1. some background on the Vertical Farm (VF) concept
2. a reality check on crops that might be grown in a VF
3. a cost comparison related to photosynthetic lighting in a VF
4. how large is the carbon footprint with using all electric lighting to grow a crop? – the untold story …
5. what is the promise of more efficient lighting
6. photovoltaic panels as alternate sources of light for closed-system plant production – what do the numbers say
7. other possible ways to add light: flat mirrors, concentrating mirrors, light pipes, fiber optics

Ending with …

8. is there any possible future for closed-system greenhouses, and a suggestion to accomplish the goals of local food production while avoiding the closed-system problems
Our road map for the next hour …

And, if all goes well, time at the end for questions and discussion
The current handbook of vertical farms and closed food production systems

“... we know how to proceed – we can apply hydroponic and aeroponic farming methodologies in a multistory building and create the world’s first vertical farms.”

Dr. Dickson Despommier
vertical farms should be cheap to build, modular, durable, easily maintained, and safe to operate. They should also be independent of economic subsidies and outside support once they are up and running.”
However, the author acknowledges that…..

“No ecosystem can exceed the limits of biomass production, which is strictly limited by the total amount of incoming energy, period.”
For many people, rivers of doubt overflow their banks when considering the practicality of growing food economically in a closed system.

The current handbook of vertical farms and closed food production systems

One reason...
Tackling Doubts, One at a Time...
The easiest doubt to tackle is to examine the list of suggested potential crops, which includes:

- Greens and herbs
- Vine crops, small fruits, tree crops
- Wheat, corn, rice, other commodities…
Let’s first examine the claim that crops such as wheat are possible and farmland can be returned to its primordial state.

Economic viability of CEA wheat production is one metric that comes to mind.

The current handbook of vertical farms and closed food production systems
A world record for outdoor wheat production was set in 2010 in New Zealand with 1.567 kg m\(^{-2}\) (233 bu/acre)
At the other extreme, as part of a NASA study

PHOTOSYNTHETIC EFFICIENCY OF WHEAT IN HIGH IRRADIANCE ENVIRONMENTS
Bruce G. Bugbee and Frank B. Salisbury
Plant Science Department, Utah State University, Logan, Utah 84322-4820

NOTE:
Ithaca max = 64

4.5 kg m$^{-2}$ @ c. 150 mol m$^{-2}$ d$^{-1}$
2.0 kg m$^{-2}$ @ c. 55 mol m$^{-2}$-d$^{-1}$ (79 days seed to harvest)
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Relating 55 mol m\(^{-2}\) day\(^{-1}\) to reality......

4.5 kg m\(^{-2}\) @ c. 150 mol m\(^{-2}\) day\(^{-1}\)
2.0 kg m\(^{-2}\) @ c. 55 mol m\(^{-2}\) day\(^{-1}\) (79 days seed to harvest)
So we have two candidates for yields that might be possible in a plant factory:

- **Record field production**: 1.567 kg m\(^{-2}\), one harvest yearly
- **High intensity growth chamber production**: 2.0 kg m\(^{-2}\) per harvest

**Four harvests, growth chamber yields**

\[ 4 \times 2 = 8.0 \text{ kg m}^{-2} \text{ yearly} \]

At 55 mol m\(^{-2}\) d\(^{-1}\)
(775 \(\mu\)mol m\(^{-2}\) s\(^{-1}\)
For 20 hours day\(^{-1}\))

\[ = 1.64 \text{ lb ft}^{-2} \]

What is it worth?
## Example wheat prices:

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<th>Month</th>
<th>$/metric ton</th>
<th>$ kg(^{-1})</th>
<th>$ lb(^{-1})</th>
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<tr>
<td>Dec 2011</td>
<td>$269</td>
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<td>Jan 2012</td>
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<td>Feb 2012</td>
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<tr>
<td>Apr 2012</td>
<td>$266</td>
<td>$0.266</td>
<td>$0.121</td>
</tr>
</tbody>
</table>

Source: World Bank

Take average as $0.125 \text{ lb}^{-1}$
GROSS YEARLY INCOME:

\[ ($0.125 \text{ lb}^{-1}) (1.64 \text{ lb ft}^{-2} \text{ yr}^{-1}) = $0.20 \text{ ft}^{-2} \text{ yr}^{-1} \]

and this is gross income!

Conclude? Any crop considered must be much more valuable than any commodity. Corn, wheat, etc., can not possibly be crops. Can NOT replace outdoor agriculture!
Income is one perspective. Cost is another. What is the cost of just the electricity to run the lights to grow the wheat?

Assume efficient lighting: HPS or good LEDs

Yearly income is $0.20 \text{ ft}^{-2}; what is the electricity bill?

Specific question:
What will the electricity cost for a loaf of bread if the wheat is grown using only electrically-generated light?
Start with 1 kilogram of wheat

Yields 1.3 liters of kernels

Makes 2.6 liters of flour

Makes 3.7 loaves of bread
DLI = 55 mol m\(^{-2}\) d\(^{-1}\) (every day)

55 \times 365 = 20,000 mol m\(^{-2}\) yr\(^{-1}\)

3 mol kWh\(^{-1}\)

6,667 kWh m\(^{-2}\) yr\(^{-1}\)

electricity cost:
$667 \text{ m}^{-2} \text{ yr}^{-1}$

assume electricity at $0.10 kW h^{-1}$

$23$/loaf to pay the electric bill

Cornell data for 400W HPS

wheat productivity 8.0 kg m\(^{-2}\) yr\(^{-1}\) @ DLI = 55

1 kg produces c. 3.7 loaves

29.6 loaves of bread in a year

1 kg produces c. 3.7 loaves
Well, commodities won’t pay, so….

Consider a non-commodity crop such as butterhead lettuce.

Model for discussion can be the CEA lettuce greenhouse near Ithaca now operated by Challenge Industries as “Finger Lakes Fresh”.
FLF demonstrated productivity

Production capacity is 1245 heads/day,
Equal to 760 heads/m²-year
What is the extra cost of total closure???

Meaning 100% Artificial Light
Productivity as from the Finger Lakes Fresh greenhouse

Total closure means that supplemental lighting of lettuce uses 3x the kWh/head as for a greenhouse in Ithaca at a DLI=17 mol per square meter.
Conclude?

Hydroponic vegetable production is already marginal in many situations.

Tripling the kWh per head of lettuce, for example, seems economically questionable today, and in the foreseeable future.

But…depends on the market price.
But...depends on the market price.

This is where the enthusiasts base their argument on cost, for example.

They have a “special” deal.

Their local market will support a higher price for locally-grown food.

The greater quality will make a higher price acceptable.
OK, probably true -- but, let’s explore some other factors outside lighting energy input and cost…

But first, some asides …
Data to this point refers to supplemental lighting only.

A plant factory production scenario will, in all likelihood, require air conditioning with even more electricity needed for temperature control.

A greenhouse should not.
Additional points to consider:

• Climates better than Ithaca’s reduce the need for supplemental light by half.

• Production cost in a greenhouse can be lowered by adding CO₂ – reducing yearly lighting for lettuce by one-half in Ithaca!

• In a closed system one can add CO₂ to reduce light by approximately one-third no matter where it is located.

• These changes bring CEA salad crop carbon footprints down close to those of imports from California to New York – not the case for a plant factory.

NOTE: Assuming a DLI of 17 mol m⁻²
So … on to carbon footprints

What is the carbon footprint associated with creating sufficient light to grow a food crop with 100% supplemental light???

A generally overlooked point!
Mean of all U.S. sources, with coal and gas at 32% each, is 460 g/kWh


Accessed 8 January 2014
What does this mean in a practical sense????
Average passenger car emits 5100 kg CO₂ per year*.

5100 kg from one car is equivalent to CO₂ emitted to grow 5100/8.05 = 636 kg of lettuce if all light is electrical!

or c. 4000 heads (@160 g/head)

As another comparison...

If only electric light is available, each head of lettuce triggers a volume of CO$_2$ to the atmosphere that would nearly fill three 55 gallon drums.

(7.48 gal/ft$^3$)
How about in an Ithaca greenhouse?

Productivity: 760 heads m\(^{-2}\) yr\(^{-1}\)

Head weight: 150 to 160 g

Yearly lettuce mass: 118 kg m\(^{-2}\) yr\(^{-1}\)

DLI: 17 mol m\(^{-2}\) d\(^{-1}\)
6205 mol m\(^{-2}\) yr\(^{-1}\)

Efficacy: 3 mol kWh\(^{-1}\)

620 kWh m\(^{-2}\) yr\(^{-1}\)

5.3 kWh kg\(^{-1}\)

At power station: 0.46 kg kWh\(^{-1}\)

2.42 kg CO\(_2\) per kg lettuce

70% from the sun
30% from the utility

Compared to 8.05
Conclude for lettuce?

•Growing with all supplemental light adds c. 8 lb CO$_2$ to the atmosphere at the power plant, per lb lettuce.

•If grown in a greenhouse in cloudy Ithaca, the added CO$_2$ is 2.4 lb per lb of harvested lettuce.

•This is still not wonderful, but the closed growing system, with all supplemental lighting, adds 8.05/2.4 = three and a third times more CO$_2$ to the atmosphere. Sustainable agriculture?

•This disregards the additional carbon footprint from the embedded energy in a large, multi-story building rather than a greenhouse.

•Also the probable need for air conditioning in a closed facility.
How about tomato if all light is electric??

example productivity
5.2 kg m\(^{-2}\) mo\(^{-1}\)
1.06 lbs ft\(^{-2}\) mo\(^{-1}\)

assume 12 mo production cycle

yearly tomato yield
62 kg m\(^{-2}\) yr\(^{-1}\)
12.7 lb ft\(^{-2}\) yr\(^{-1}\)

DLI at 20 mol m\(^{-2}\) d\(^{-1}\)
7300 mol m\(^{-2}\) yr\(^{-1}\)

efficacy
3 mol kWh\(^{-1}\)

with all elec. light
2433 kWh m\(^{-2}\) yr\(^{-1}\)
226 kWh ft\(^{-2}\) yr\(^{-1}\)

39 kWh kg\(^{-1}\)
18 kWh lb\(^{-1}\)

0.46 kg CO\(_2\) kWh\(^{-1}\)

9 m\(^3\) CO\(_2\) kg\(^{-1}\)
145 ft\(^3\) CO\(_2\) lb\(^{-1}\)

18 kg CO\(_2\) kg\(^{-1}\)
18 lb CO\(_2\) lb\(^{-1}\)
Conclude for tomato?

- Growing with all supplemental light adds c.18 lb CO$_2$ to the atmosphere at the average power plant for each lb of tomato harvested. This is 2.25 times the carbon footprint for lettuce!

Why is tomato worse than lettuce?

- One reason could be photosynthesis to produce leaves and the stem, neither of which adds to the harvest but each requires light to grow. Moreover, tomato has a higher dry matter content than lettuce.
But, why worry about this???

Compare carbon footprints for transported lettuce...


<table>
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<tr>
<th>Source</th>
<th>Calculated kg CO₂ / kg Lettuce</th>
<th>From</th>
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<td>All imports to NY</td>
<td>0.70</td>
<td>Transport</td>
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<td>(Average food miles: 2963)</td>
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<tr>
<td>Plant factory</td>
<td>8.05</td>
<td>Lighting</td>
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<tr>
<td>Plant factory, added CO₂</td>
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<td>Lighting</td>
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<td>CEA in Ithaca, LASSI</td>
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<td>Lighting</td>
</tr>
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</table>

* Table 4.7, lighting to DLI = 17 mol m⁻²
Is there a solution to the light problem?

- Advanced light sources for plant factories have been suggested, such as LEDs, concentrating (or other) mirrors, photovoltaic panels, and high-cost items such as fiber optic or light pipe networks.

- Can this work? Is it sustainable? Must we violate the laws of physics to make it work?

- Start by considering electrically-generated light in general.
Planck's Law

Planck's constant

speed of light

Avogadro's number

wavelength of the light

theoretical maximum efficacy

Or real-world efficacy, near 3 mol/kWh

µmol s⁻¹ W⁻¹ = wavelength/119.6

mol/kWh = nm wavelength/33.2

wavelength in nm, 10⁻⁶ m

real world efficiency

thermal losses

electrical losses

optical losses

instantaneous integrated over time

Result is a wall plug efficiency of perhaps 20% for HPS and 25% for LEDs

Philips LumiLED:
Blue 26 to 47%
Green: 11 to 15%
Red: 18 to 36%

Still...
Conclude about LEDs?

• LED technologies are improving and their costs are shrinking … but don’t believe the Internet!!

• Claims that today’s commercial LEDs are much more efficient are not justified by data. Current LED arrays are typically compared to incandescent lamps, which are notoriously inefficient.

• HID luminaires and T5 fluorescent fixtures are also much more efficient than incandescent bulbs, with efficiencies approaching the best LEDs.
What about Photovoltaics???

But first, what about greenhouses!!!

One can view a modern greenhouse as 70% efficient as a solar light collector/transmitter to grow plants indoors.
Back to … What about Photovoltaics???

How efficient is a PV system in converting sunshine to indoor light for plant growth?
Back to … What about Photovoltaics???

• First point: Today’s panels are typically 15 to 18% efficient.

• Second point: De-rating factors typically reduce SYSTEM output by c. 28%*.

• Third point: The highest efficiency for today’s PV panels can be c. 40%, but the de-rating factors still apply.

So, Now what about Photovoltaics???

- Good standard PV panel is 18% efficient
- Use PV chart analysis method
- Apply standard de-rating parameter values
- Ithaca: 223 kWh m\(^{-2}\) yr\(^{-1}\)
- 28% loss of theoretical output
- Efficacy = 3 mol kWh\(^{-1}\)
- Panels provide 669 mol m\(^{-2}\) yr\(^{-1}\) (based on panel area)
- DLI = 17 => 6205 mol m\(^{2}\) yr\(^{-1}\)
- 1 m\(^{2}\) of panel provides 10.8% of need in 1 m\(^{2}\) growing area (669/6205)
- Panel area = 9.3 times the lighted area!
So, Now what about Photovoltaics???

- One can conclude the PV panel area must be many times the growing area, even with very efficient PV panels.
- Solar availability is asynchronous with need.
- (Nuance: Wasting the renewable PV power deprives someone else who does not have access to a renewable substitute.)
Other suggestions…….

Flat mirrors to direct sunlight into a vertical farm/plant factory have been suggested.

Concentrating mirrors to direct sunlight into a vertical farm/plant factory have been suggested.
Can we use flat Mirrors?

Reflection of diffuse sunlight is equally diffuse
Another flat mirror suggestion:
Direct solar light from the side???

Single plant canopy in a VF greenhouse or plant factory

But...would need three-degree-of-freedom tracking!!
Focusing mirrors???
Focusing mirror arrays configured to direct sunlight to a distant receiver???
Yet another real issue...

Solar angles in summer are very different from solar angles in winter, making any tracking difficult and expensive.

This leads to light reflection considerations.
IMPORTANT:
Reflectivity goes up sharply for incident angle greater than c. 55 degrees away from normal.
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But, ending on a somewhat more positive note...
Possible Alternative: Peri-urban greenhouses

Peri-urban: Immediately adjoining an urban area; between suburbs and the countryside

Considerations:

- Less expensive land and lower construction costs (greenhouses compared to skyscrapers).
- Access to infrastructure for energy, water, and ready transport to markets.
- Can be located away from the air pollution plume created downwind of large cities.
Are there scenarios where complete closure of plant production systems might make sense………

• When water recapture is far more valuable than electricity. (Middle East?)
• The world runs almost solely on renewable energy for electricity production.
• The world runs almost solely on fission nuclear energy for electricity production.
• Fusion energy becomes a cost-effective reality.
But, except for possible water recapture benefits, these scenarios are unlikely in our lifetimes.
Are there small-scale applications where complete closure of plant production systems might make sense……..

Germination chambers?  
Tissue culture rooms?  
GMO research?  
Fairbanks, Alaska?  
South Pole Research Station?
Conclude?

Is the emperor wearing any new clothes?

Do numbers lie?

Can we violate the laws of physics?

You can decide.
Thank You!