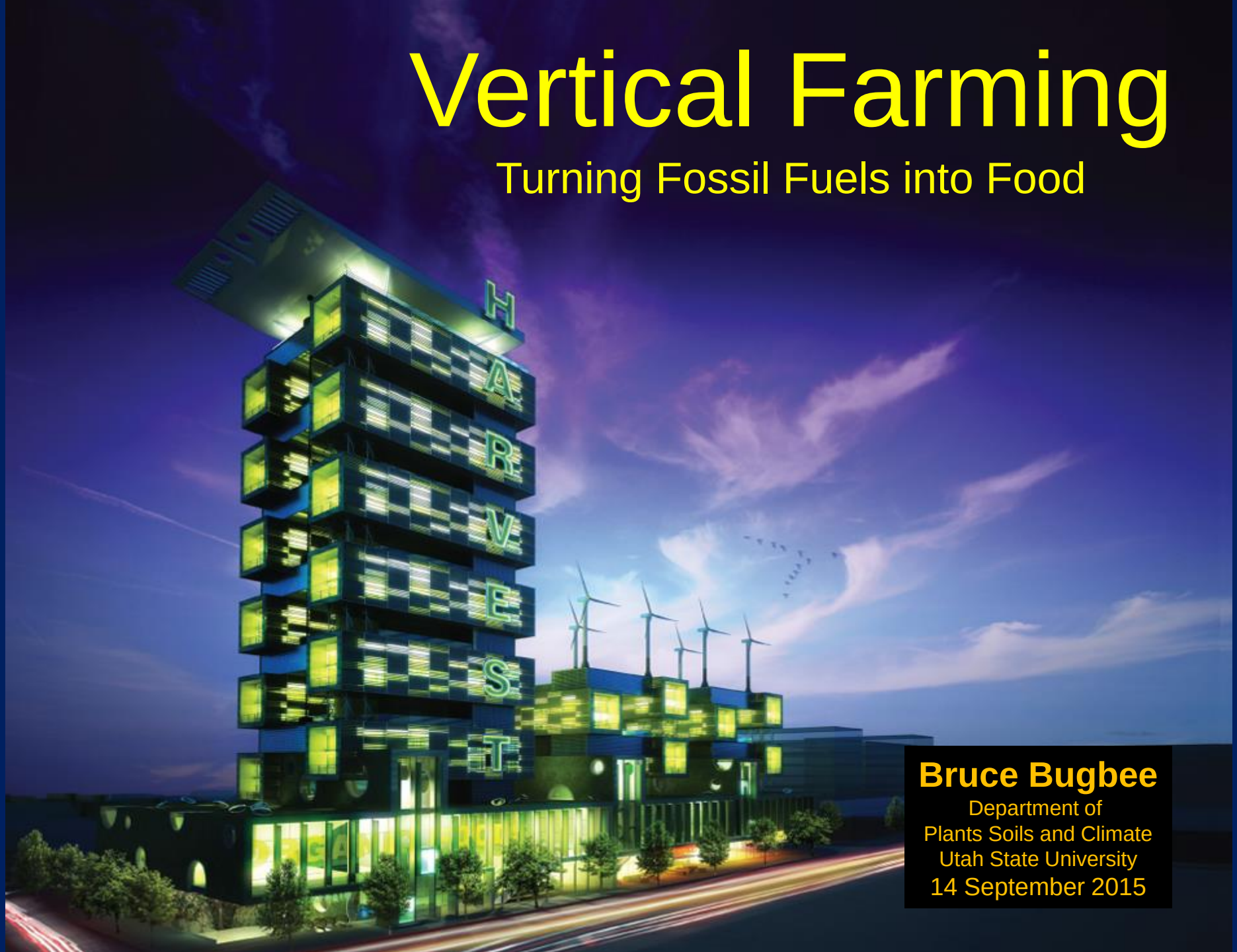
Vertical Farming

Turning Fossil Fuels into Food



Bruce Bugbee
Department of
Plants Soils and Climate
Utah State University
14 September 2015

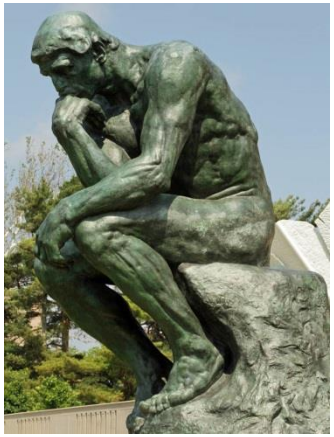
The New York Times

Sunday Review - 15 Feb 2014

Professors, We Need You!

Nicholas Kristof

"Some of the smartest thinkers on problems at home and around the world are university professors".



The New York Times

5 September 2015

Food Industry Enlisted Academics in G.M.O. Lobbying War, Emails Show

"Monsanto… has brought in a rarefied group of advocates: academics, brought in for the gloss of impartiality and weight of authority that come with a professor's pedigree".

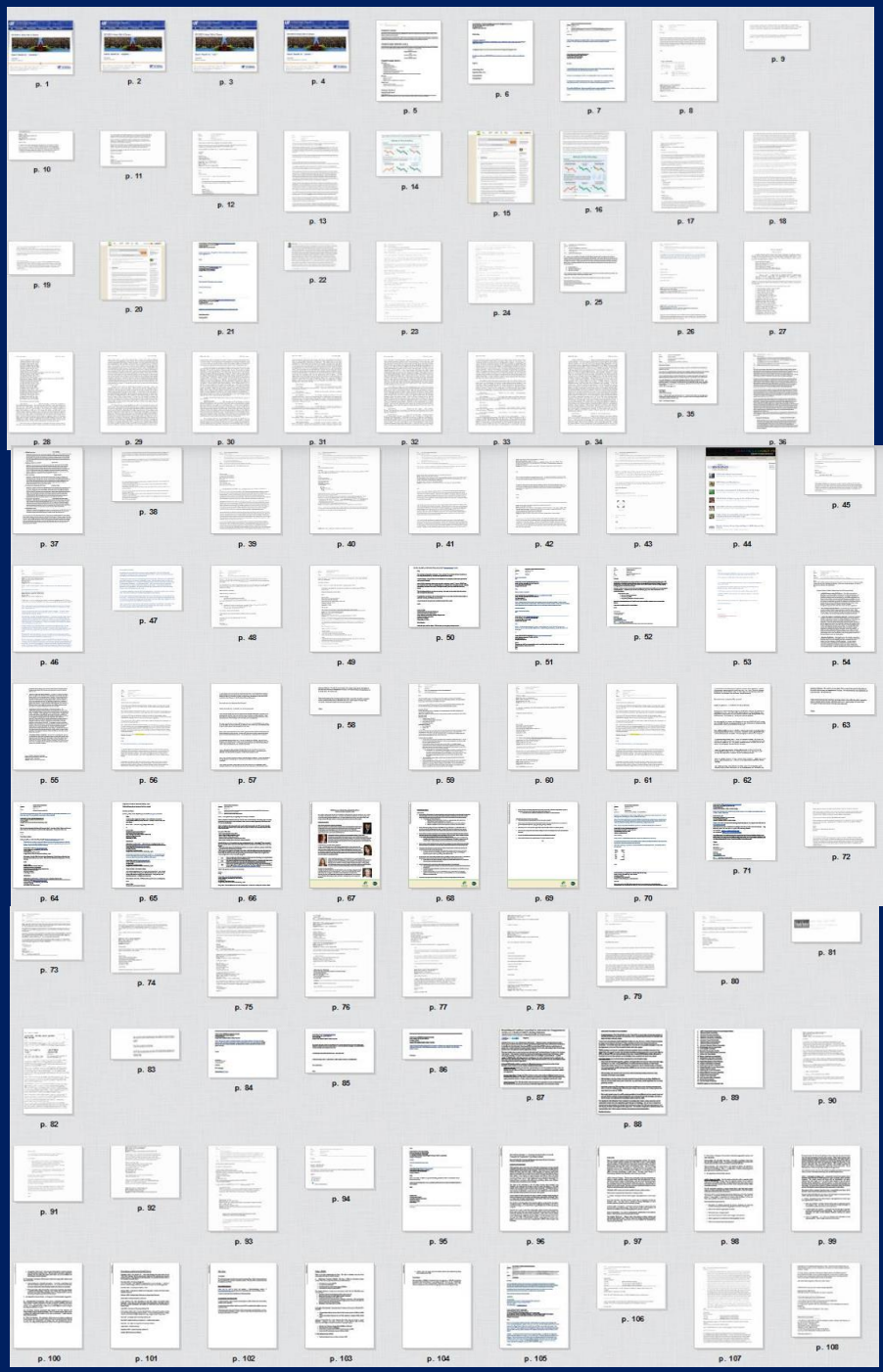
"Professors have a white hat in this debate".

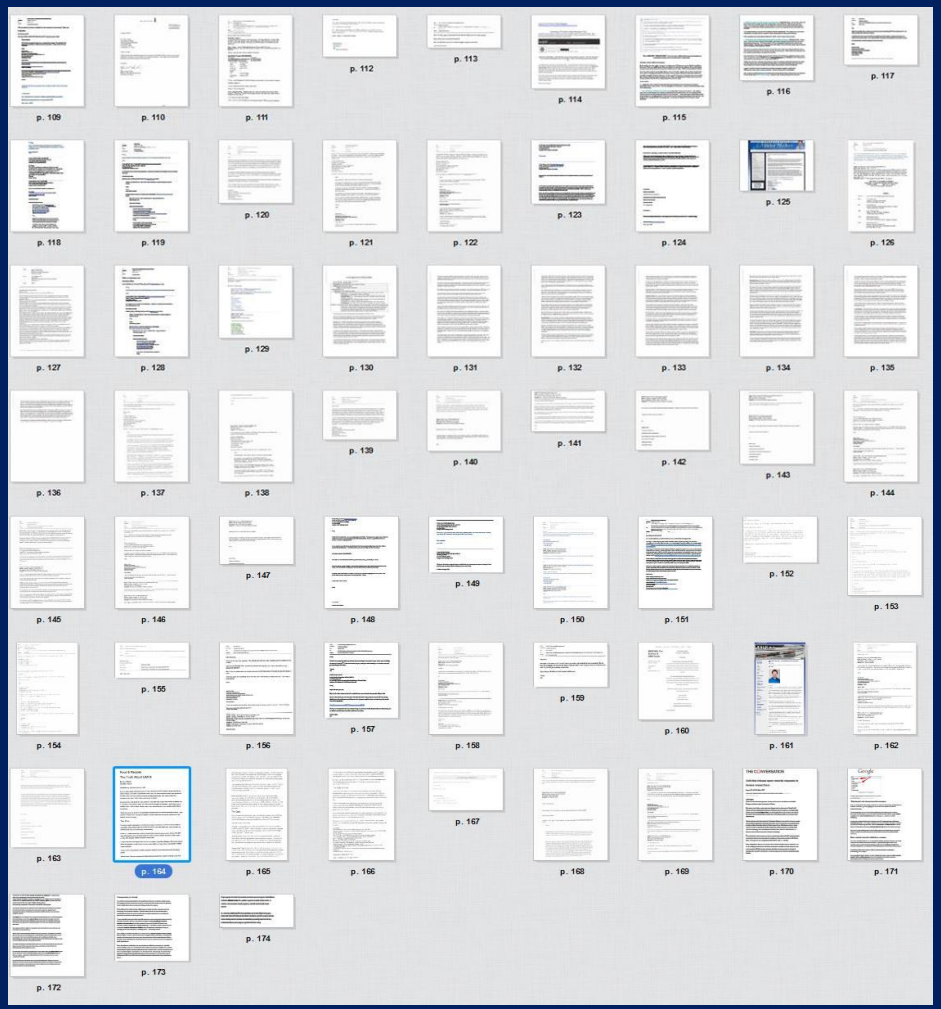
Charles Benbrook

Agricultural Economist
Former Research Professor
Center for Sustaining Agriculture
Washington State University

Kevin Folta

Molecular Biologist
Chair of the Horticultural Sciences Department
University of Florida





174 pages of
Kevin Folta's
e-mail


HARVEST

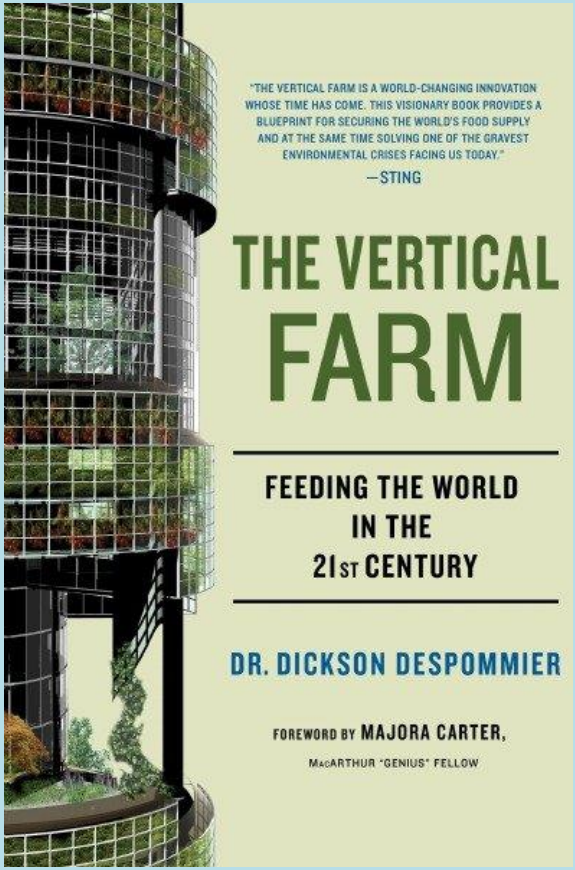
Common claims of proponents

"Green Sense Farms uses 0.1 % of the water, land, and fertilizer of field farming".

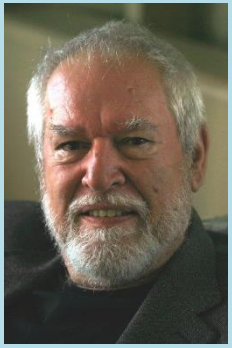
"Lower energy consumption than glasshouse growing".

"70 % less water used".

"Vertical farming greatly reduces our carbon footprint and minimizes the use of fresh water".



The book that ignited the current passion for closed food production systems

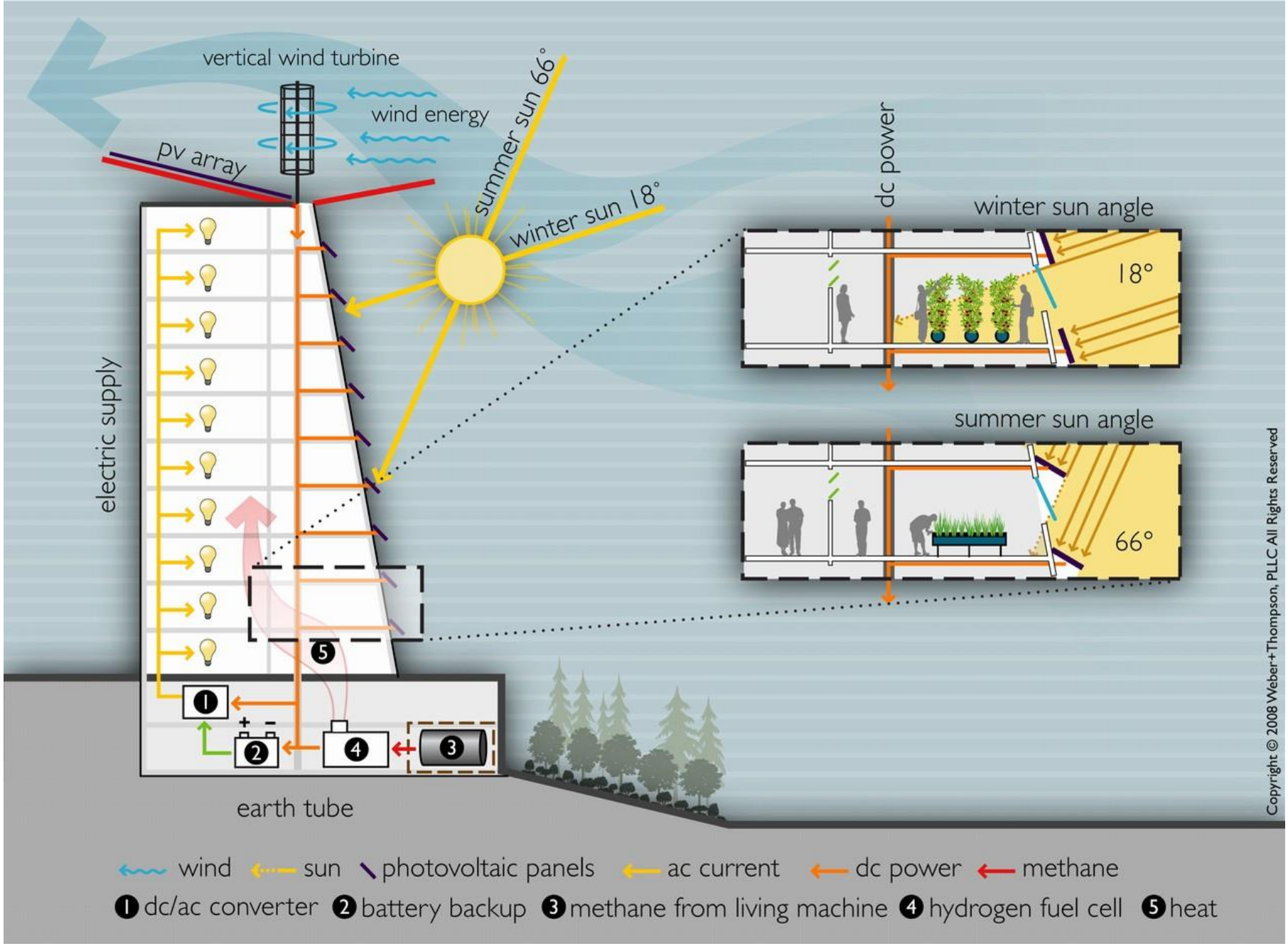


"We can apply hydroponic methodologies in a multistory building and create vertical farms."

Dickson Despommier
Professor of Public Health

Werner Heisenberg

"An expert is someone who can avoid the worst errors in their own discipline."




PEPPERS
CHIVES
LETTUCE
CHERRIES
APPLES
CABBAGE
STRAWBERRIES
THYME
TOMATOES
PEAS
MINT
SPINACH
PEACHES
BRUSSEL SPROUTS
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CABBAGE
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CHERRIES

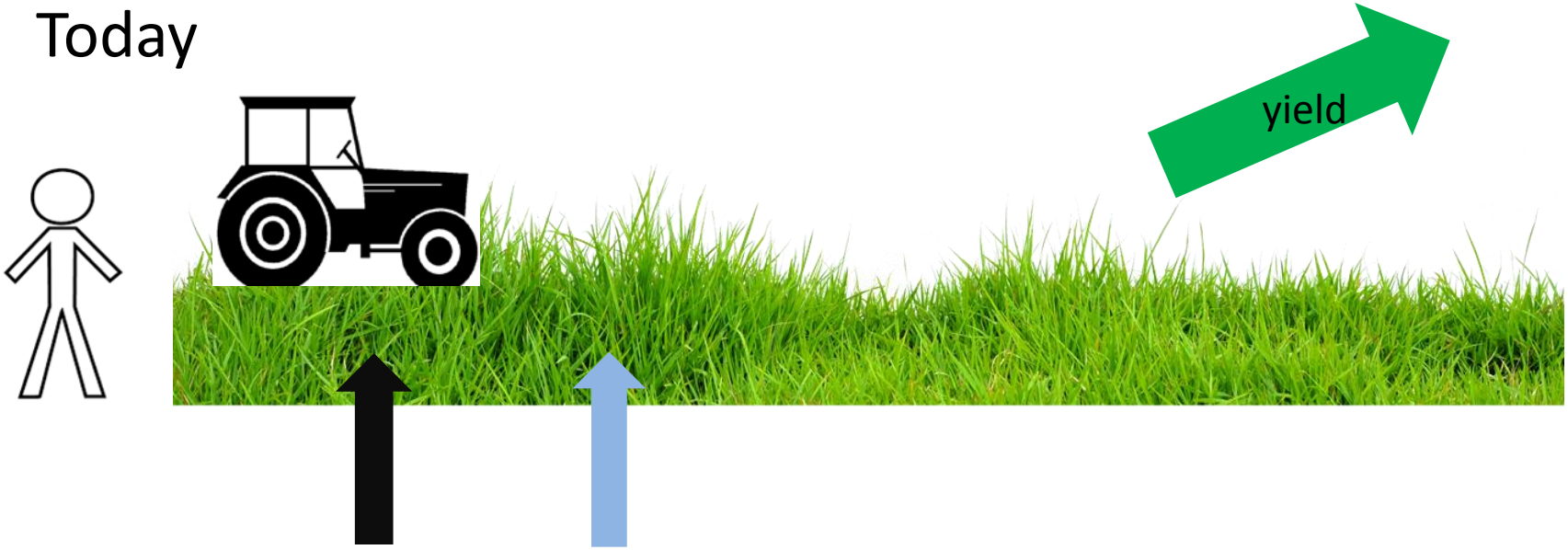
One of the first vertical farms is going up in Jackson WY

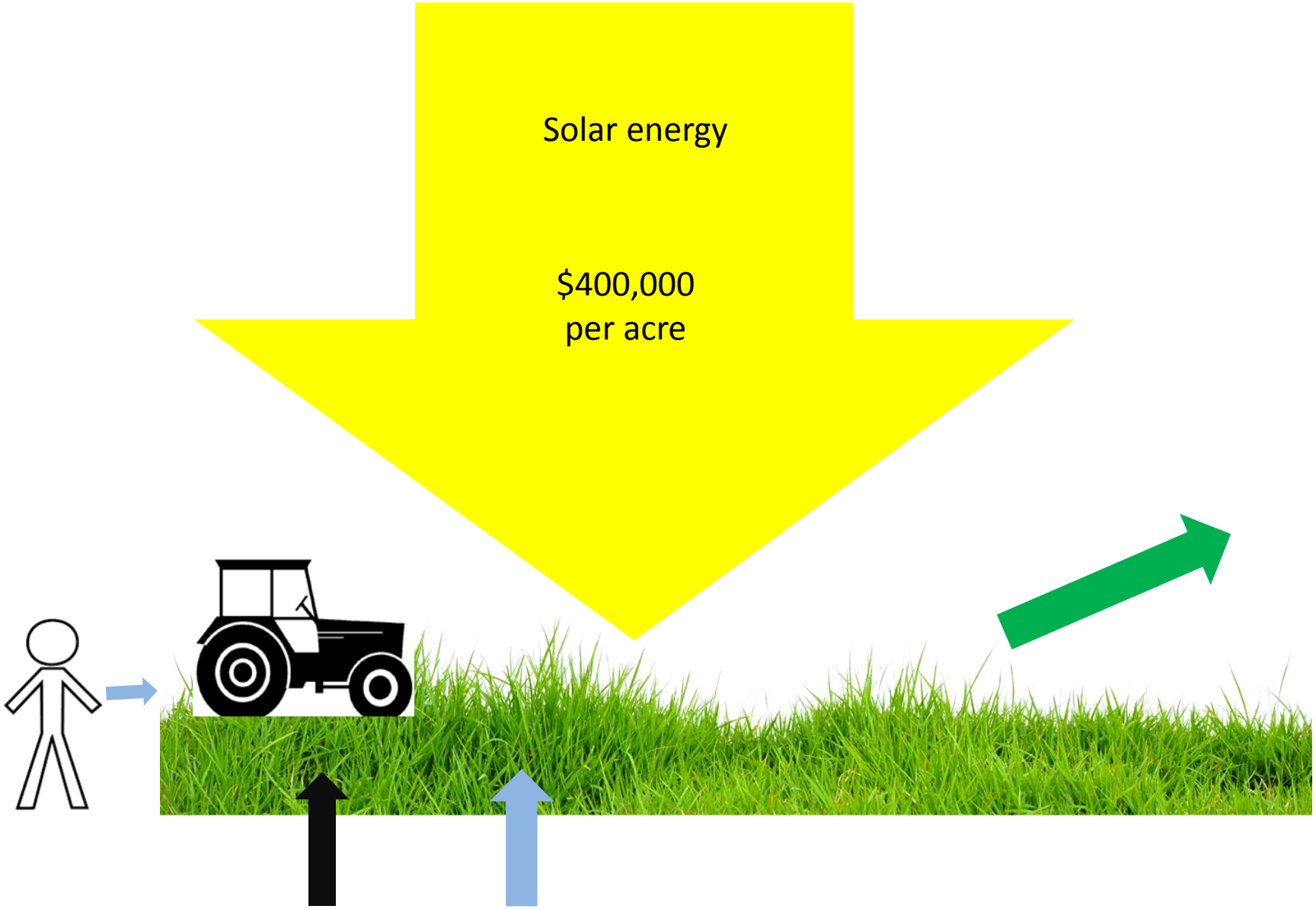
A vacant lot will soon become a three-story greenhouse producing 100,000 pounds of produce per year for the Jackson community.

February 24, 2015

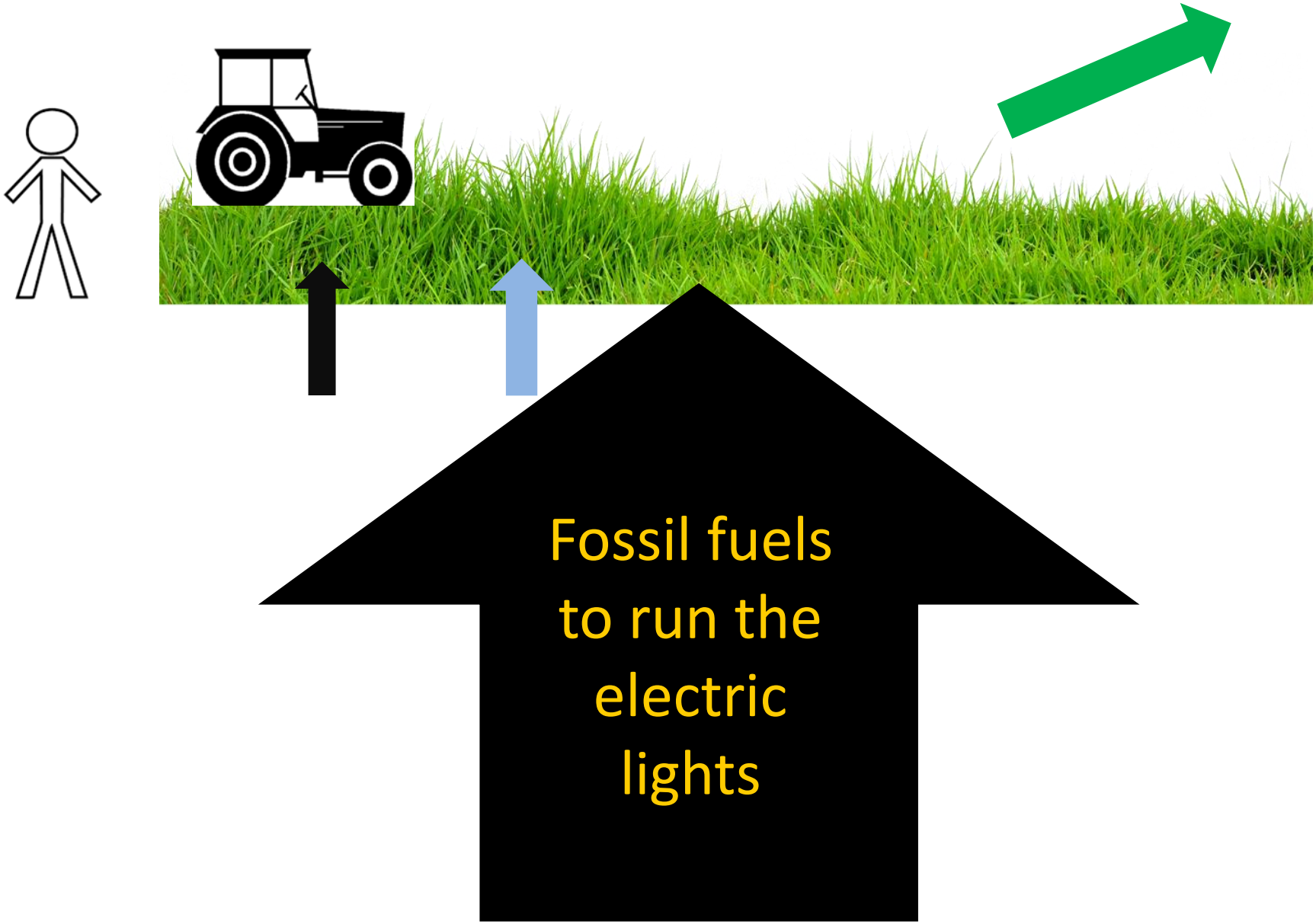
100 years ago

Today




Solar energy
$400,000
per acre

Without sunlight



At solar noon

2000 µmol m^{-2} s^{-1}

1000 W m^{-2}

photovoltaic panels: 15% efficient

150 W m^{-2}

The best LEDs can produce 1.74 umol/J

70% transmission

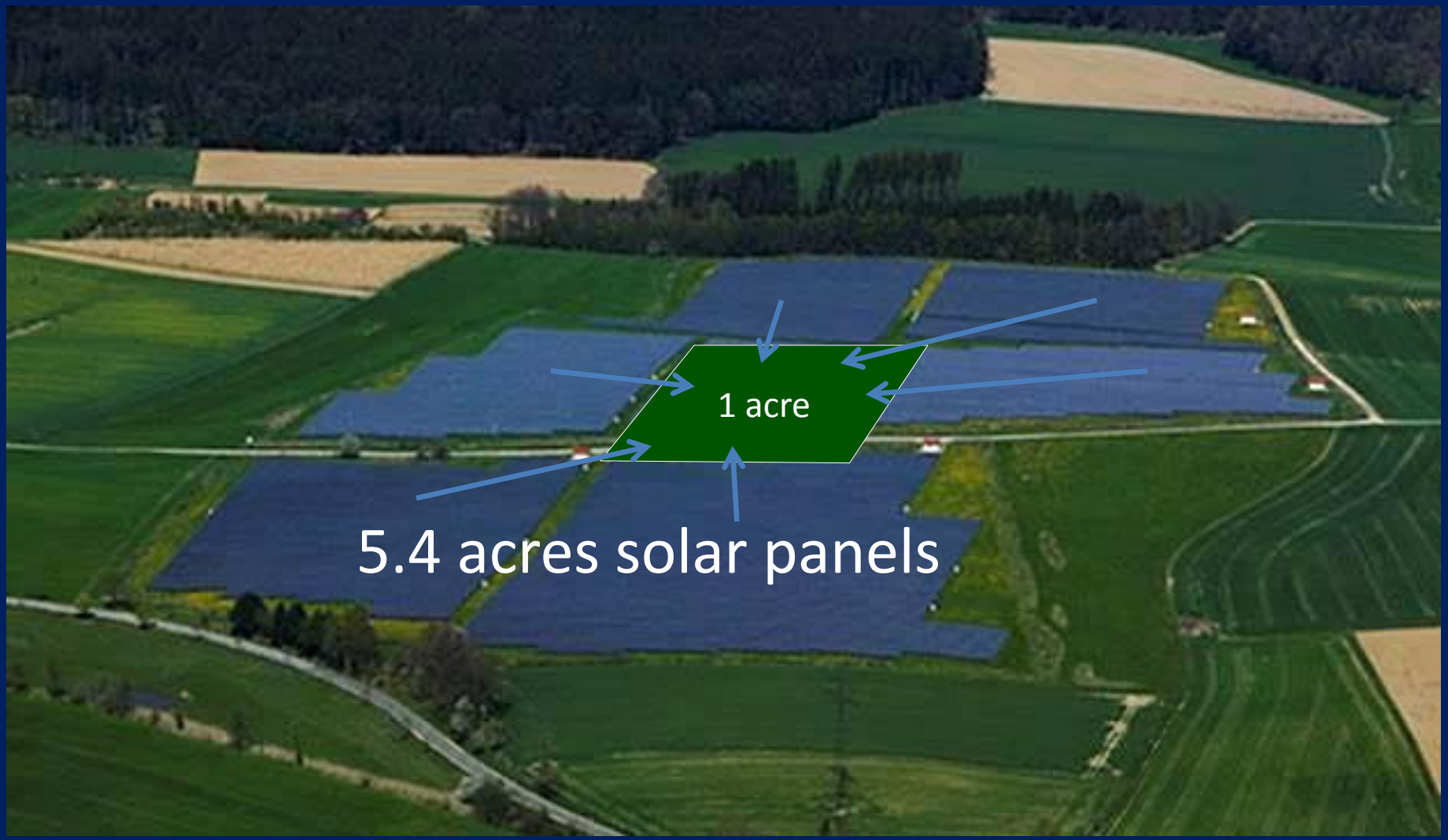
1400 µmol m^{-2} s^{-1}

transmitted to the plant canopy

260 µmol m^{-2} s^{-1}

delivered to the plant canopy

Crop area with equivalent photon flux using electricity from the best solar panels and the best electric lights



Corn ethanol
Energy balance studies

Net energy
(btu per gallon)

[1 gal = 114,000 btu]

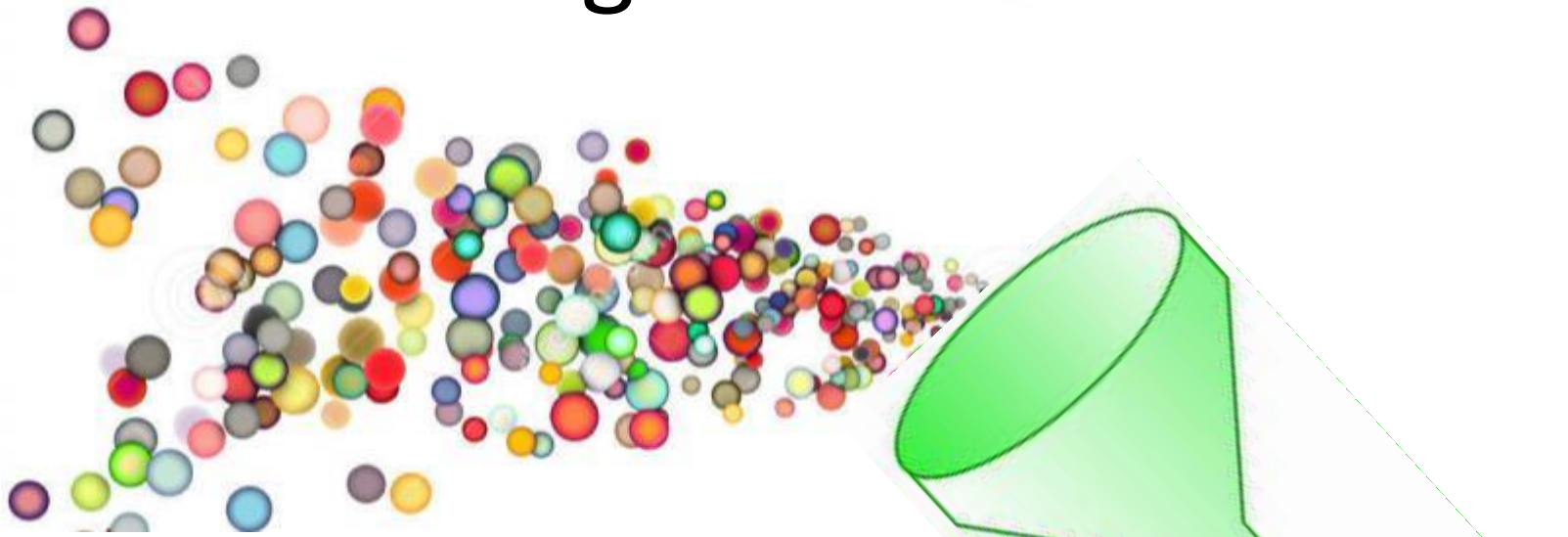
Net energy
value ratio

1.2
1.1
- 0 -
0.9
0.8

Dr. David Pimental

Emeritus Professor of Evolutionary Biology
Cornell University

Turning Photons into Food



6.02×10^{23} photons

1 mole of photons

1 gram
of dry biomass

0.5 gram
of yield

B. Bugbee and F. Salisbury. 1988.
Exploring the Limits of Crop productivity: Plant Physiology 88:869-878.

Turning photons into food
potentially achievable yield for lettuce

Input: one mole of photons

1. Absorption of photosynthetic photons by leaves: 0.90
2. Quantum yield: moles of carbon fixed per mole of photons absorbed: 0.07
3. Conversion efficiency in respiration: 0.65
4. Harvest Index: 0.85

mol C/mol photons = 0.035

Lettuce biomass (minimal protein) can be a low carbon fraction (42%)
12 grams per mole carbon/0.42 = 28.6 grams biomass per mole of carbon

28.6 x 0.035 = 1 gram per mole of photons

Frantz, Bugbee, et al. 2004.
Exploring the Limits of Crop productivity: Lettuce. JASHS. 129:331.

Marc van Iersel. 2003. Carbon use efficiency depends on growth respiration, maintenance respiration, and relative growth rate. A case study with lettuce. Plant Cell and Environment. 26: 1441–1449.

Turning photons into food
potentially achievable yield for tomatoes

Input: one mole of photons

1. Absorption of photosynthetic photons by leaves:	0.90	.80
2. Quantum yield: moles of carbon fixed per mole of photons absorbed:	0.07	.06
3. Conversion efficiency in respiration:	0.65	.60
4. Harvest Index:	0.85	.60
mol C/mol photons	= 0.035	0.017

Lettuce biomass (minimal protein) can be a low carbon fraction (42%)
12/0.42 = 28.6 grams biomass per mole of carbon

28.6 x 0.035 = 1 $gram_{dry}$ / mole 0.5 g_{dry}/mol

Theoretical economics

Cost of electricity

$$\frac{\$\ 0.10}{1\ \text{kWh}} * \frac{1\ \text{kwh}*}{6.12\ \text{mol}} = \frac{\$\ 0.016}{1\ \text{mole}} * \frac{1\ \text{mole}}{0.5\ g_{dry}} = \frac{\$\ 32}{kg_{dry}}$$

Value of products

Wheat  $\frac{\$\ 9}{1\ \text{bushel}} = \frac{\$\ 0.32}{kg_{dry}}$

Tomatoes  $\frac{\$\ 4.54}{1\ \text{lb.}} = \frac{\$\ 10}{\text{kg fresh (90\% water)}} = \frac{\$\ 100}{kg_{dry}}$

Lettuce  $\frac{\$\ 4.54}{1\ \text{lb.}} = \frac{\$\ 10}{\text{kg fresh (95\% water)}} = \frac{\$\ 200}{kg_{dry}}$

* Nelson JA, Bugbee B (2014) Economic Analysis of Greenhouse Lighting: Light Emitting Diodes vs. High Intensity Discharge Fixtures. PLoS ONE 9(6): e99010.

Cost of electricity for Basil under electric lights:

$$4.2 \frac{g\ basil}{mol\ photons}$$

$$1.87 \frac{\mu mol}{J}$$

$$\frac{\$0.10}{kWhr}$$

$$= \frac{\$0.004}{g\ basil}\left(\frac{\$0.10}{oz}\right)$$

Basil from the store:

$$\left(\frac{\$1}{oz}\right)$$

Analysis of the Environmental impacts of indoor farming

Common claims of proponents

"Green Sense Farms uses 0.1 % of the water, land, and fertilizer of field farming".

"Lower energy consumption than glasshouse growing".

"70 % less water used".

"Vertical farming greatly reduces our carbon footprint and minimizes the use of fresh water".

Seminal paper: over 570 citations

Food-Miles and the Relative Climate Impacts of Food Choices in the United States

Christopher Weber and H. Scott Matthews, *Environ. Sci. Technol.* **2008,** *42*, 3508-3513

Average US Household

	Tons of CO_2 equivalents per yr
All Food	8.1
Food Transport	0.4
Car (12,000 miles)	4.4

Conclusions:

1. Transportation is a small component of our food system cost.
2. "*What we eat has a bigger effect on the environment than the cars we drive*".

B. Bugbee. TEDx talk. November 2013. "Turning Water into Food".

Food-Miles and the Relative Climate Impacts of Food Choices in the United States

Christopher Weber and H. Scott Matthews, *Environ. Sci. Technol.* **2008,** *42*, 3508-3513

% of Greenhouse Gas Emissions for Transport

Average of all food types

1000 km 4 %

Fresh fruits and vegetables

1000 km 11 %

4500 km 50 %

Transporting fresh produce in a refrigerated truck can be up to 50% of the food cost

Relationship between CO_2 and CO_2equivalent (CO_2e)

Global Warming Potential (GWP)
of the three major gasses in agriculture

Carbon dioxide	(CO_2)	1
Methane	(CH_4)	30
Nitrous oxide	(N_2O)	300

Relative to CO2, the multiplier for methane is 30
the multiplier for nitrous oxide is 300

kg CO_2 equivalents per kg tomatoes

New York State

Lou Albright
Cornell

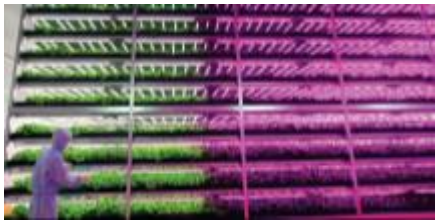
Production 0.3 0.3 0.5 2 - 4

Transport 0.3 **Heating** 2 **Electricity** 9

Grown and shipped from CA

Hoop House

Heated Greenhouse



Maximum Potential for
Indoor Farming

Heated greenhouse and imported data derived from: de Villiers, D., Wien, H., Reid, J., and Albright, L. 2011. Energy use and yields in tomato production: field, high tunnel and greenhouse compared for the northern tier of the USA. Acta Hort. 893:373-380.

kg CO_2 equivalents per kg lettuce

Michigan

Mike Hamm
Michigan State University

Production 0.2

Transport 0.8

Grown and shipped from CA

0.2

Hoop House

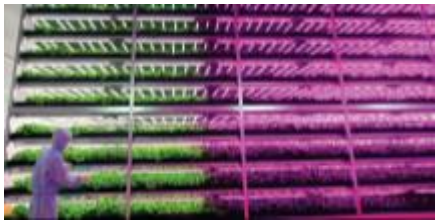
0.4

Heating 1.5

Heated Greenhouse

1 - 2

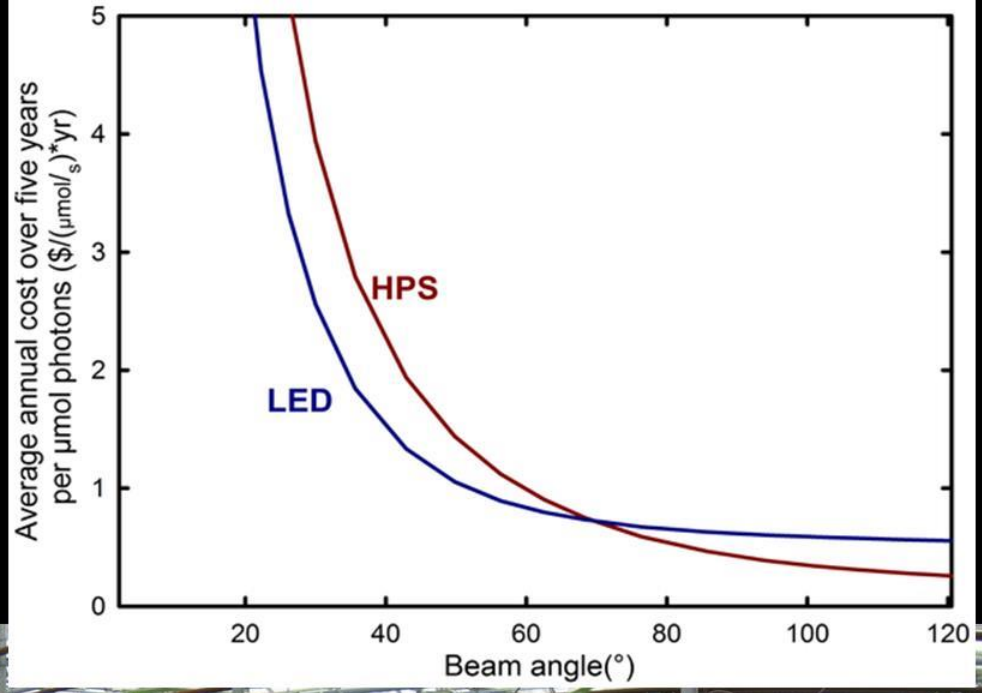
Electricity 3.6



Maximum Potential for Indoor Farming

Imported and hoophouse data derived from: R. Plawecki, R. Pirog, A. Montri, and **Michael Hamm** 2013. Comparative carbon footprint assessment of winter lettuce production in two climatic zones for Midwestern market. *Renewable Ag. and Food Systems: 29 (4) 310-318*

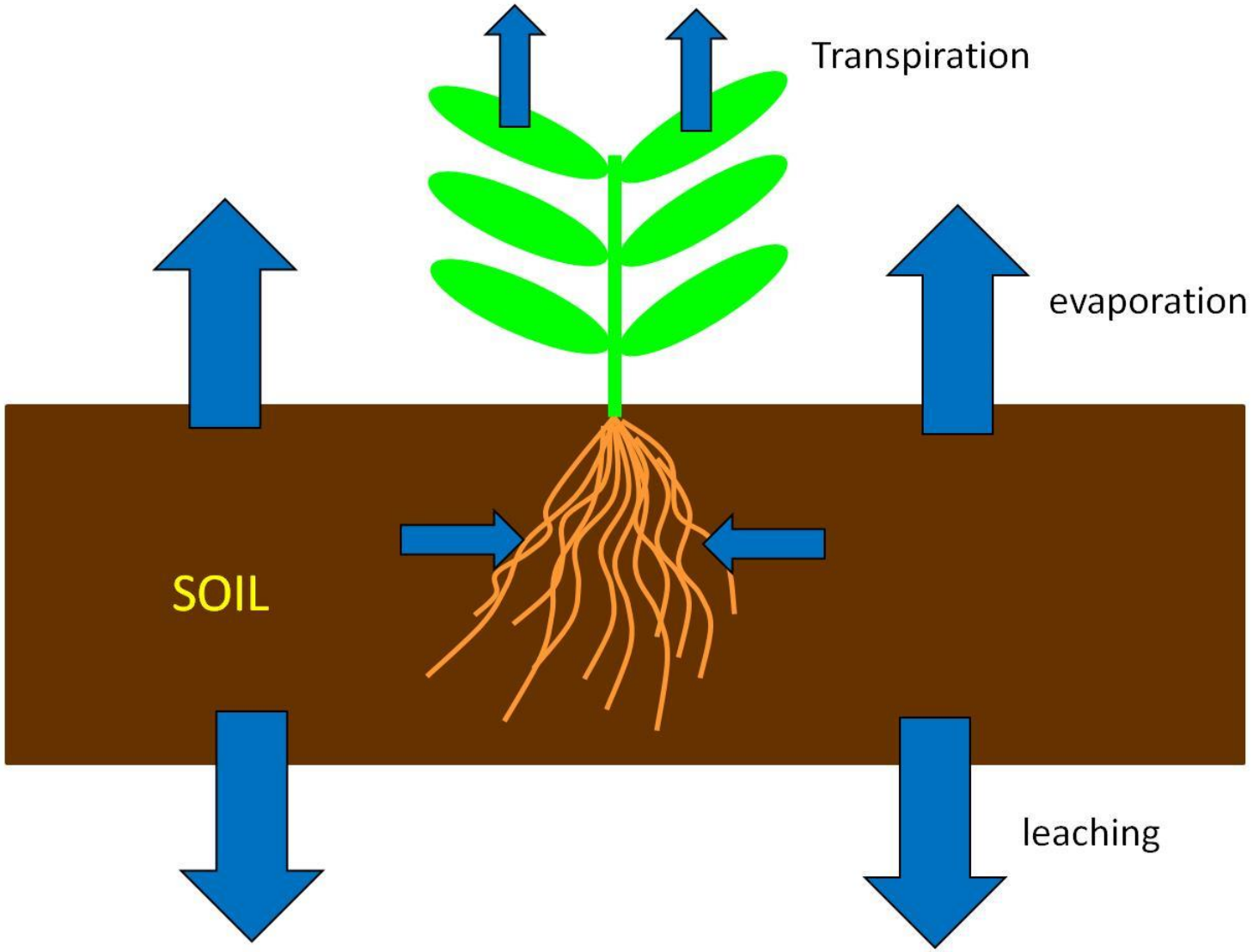
Indoor farming using LEDs in multiple layers will need to compete with much lower cost supplemental lighting from HPS technology in greenhouses



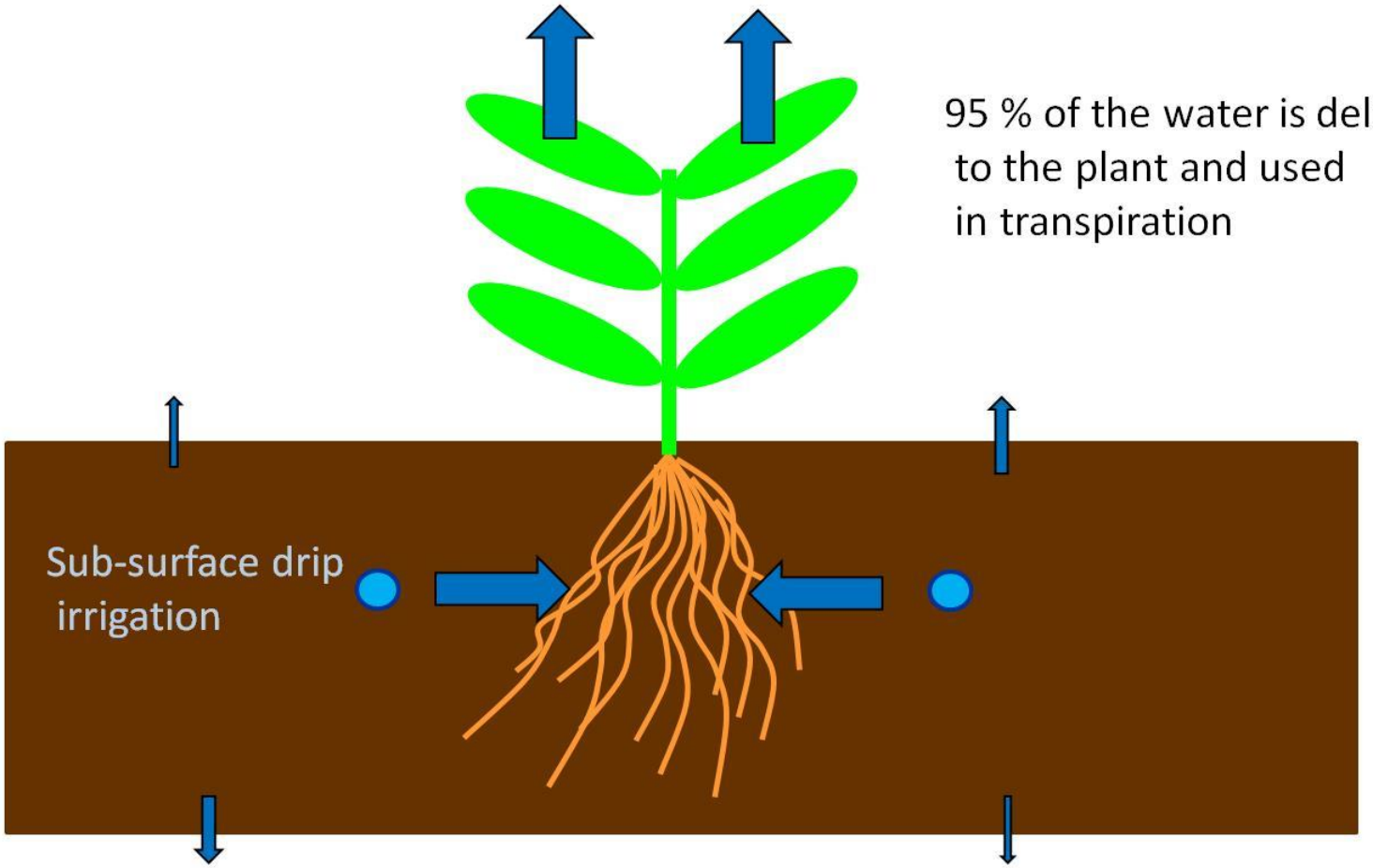
Nelson JA, Bugbee B (2014) Economic Analysis of Greenhouse Lighting: Light Emitting Diodes vs. High Intensity Discharge Fixtures. PLoS ONE 9(6): e99010. doi:10.1371/journal.pone.0099010
http://127.0.0.1:8081/plosone/article?id=info:doi/10.1371/journal.pone.0099010

Water

Water use in crop production is 70% of US water use
The public perception is massive water waste



Water use in high value crops is greatly reduced by efficient irrigation

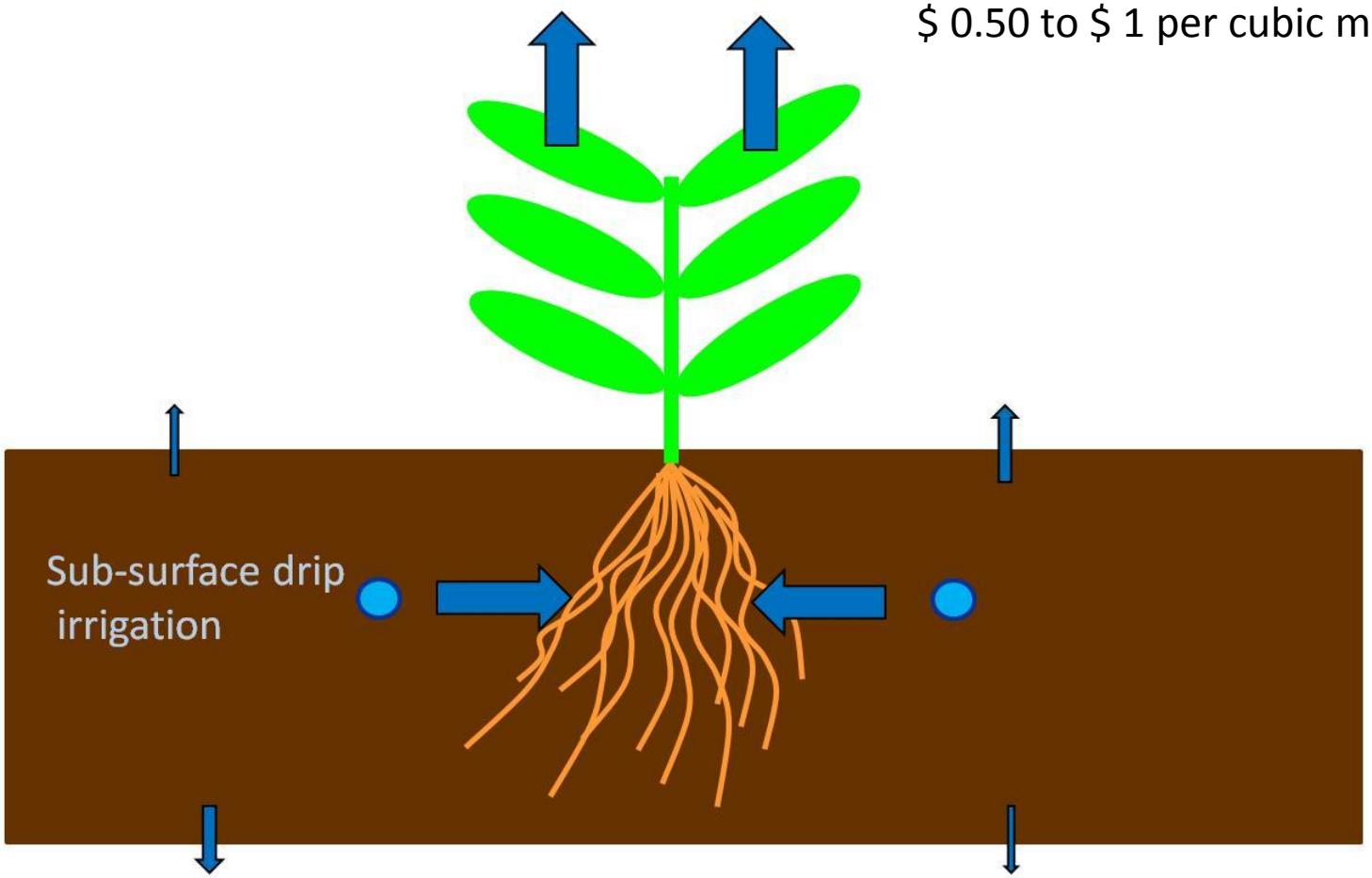


95 % of the water is delivered to the plant and used in transpiration

Cost to condense water vapor
out of the air
$ 14 per cubic meter

Cost of water from the grid
$ 0.25 per cubic meter

Cost to desalinize sea water
$ 0.50 to $ 1 per cubic meter

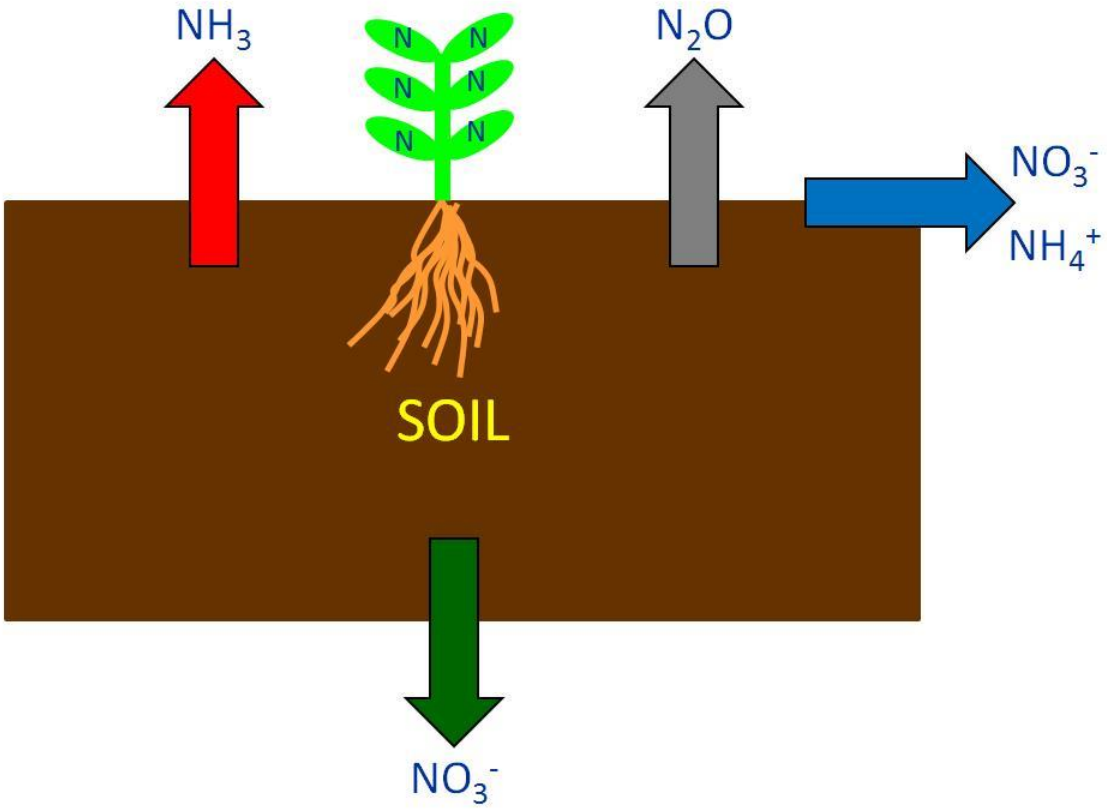


Desalinization

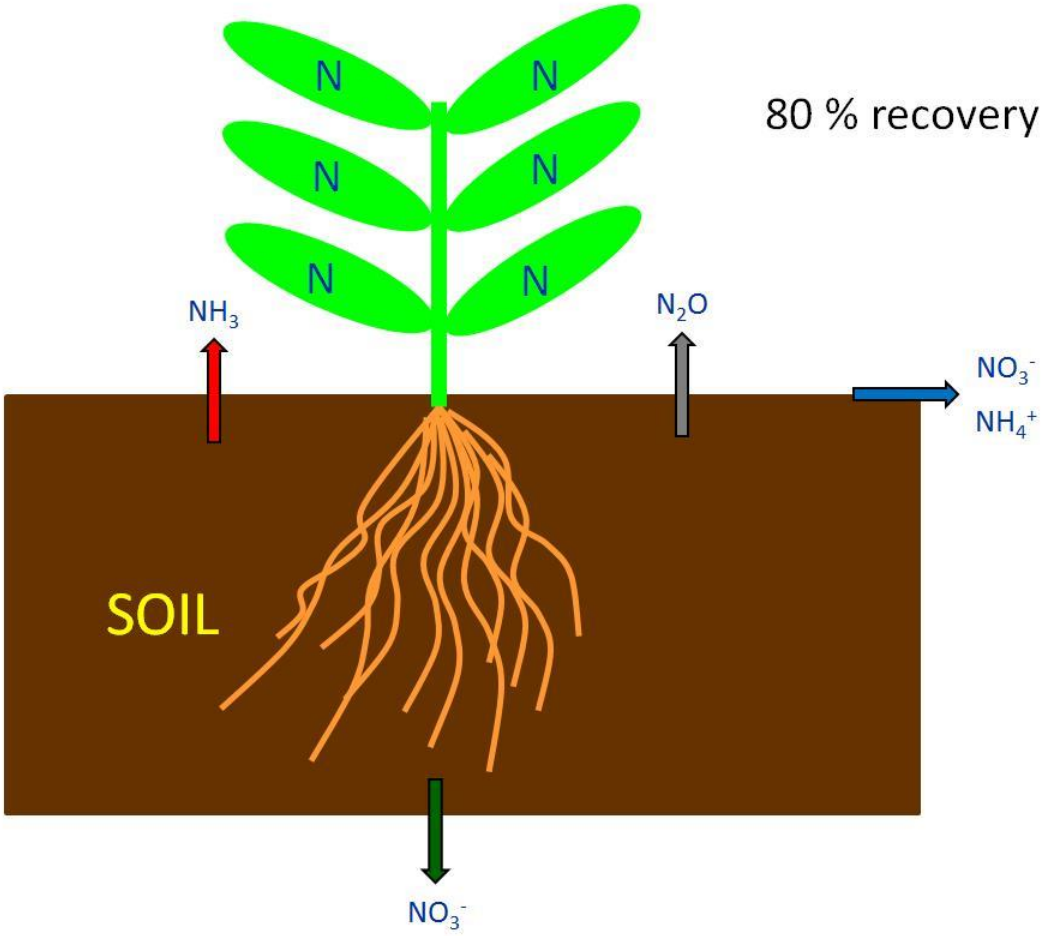
Sydney Australia

Fertilizer use

Environmental losses of Nitrogen
The public perception: Massive losses



Environmental losses of Nitrogen are greatly reduced in high value crops



Carbon footprint of some food products

kg CO2e per kg food

Source: LIVESTOCK'S LONG SHADOW: Environmental issues and options
UN food and agriculture organization. 2006.
http://www.fao.org/docrep/010/a0701e/a0701e00.HTM

Summary

1. Urban agriculture should maximize the direct use of sunlight

2. Indoor farming systems do not necessarily improve water and fertilizer use efficiency