<table>
<thead>
<tr>
<th>What is the overall objective of all cropping systems?</th>
<th>What is the overall objective of all cropping systems?</th>
</tr>
</thead>
<tbody>
<tr>
<td>To maximize resource capture and optimize resource use to achieve sustainable economic yields.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>What resources are we mainly interested in?</th>
<th>What are the three most prominent chemical elements in plants</th>
</tr>
</thead>
<tbody>
<tr>
<td>light energy, carbon, oxygen, water and nutrients</td>
<td>• Fruit?</td>
</tr>
<tr>
<td></td>
<td>• Wood?</td>
</tr>
</tbody>
</table>
What are the three most prominent chemical elements in dry plant parts

- Fruit?
- Wood?

\[
\begin{align*}
\text{Carbon} & : C \\
\text{Hydrogen} & : H \\
\text{Oxygen} & : O
\end{align*}
\]

Roughly in a ratio of 6:1:8

Where does all that CH$_2$O come from?

**PHOTOSYNTHESIS**

Photosynthesis is the process by which plants capture the energy in sunlight and convert it to a biologically usable form.

- The energy is stored in carbon bonds created during photosynthesis and liberated during respiration

\[
\begin{align*}
\text{Solar energy} & \xrightarrow{\text{absorbed by chlorophyll}} \text{Photosynthesis} \\
\text{Water} + \text{Carbon dioxide} \quad (\text{H}_2\text{O}) + (\text{CO}_2) & \xrightarrow{\text{Carbohydrates} + \text{Oxygen}} (\text{CH}_2\text{O})_n + (\text{O}_2) \\
\text{Chemical energy} & \xrightarrow{\text{To build and repair}} \text{Respiration}
\end{align*}
\]
• Plants, nature’s original solar energy collectors.

• What are nature’s natural solar energy cells?
  • Chloroplasts.

---

Chlorophyll

• Light energy is captured by the green pigment chlorophyll.
• Chlorophyll is found in all green tissues of plants.
• It is located in chloroplasts, specialized structures in the plant cells designed to be solar energy cells.

---

• The primary functions of leaves are to house and display the chloroplasts for solar energy collection.
• Problem: chloroplasts need an aqueous environment to function, air is dry and CO2 from air is required for photosynthesis.
• Solution: leaves with waxy cuticle to prevent dehydration and air control vents called stomates.
Carbon dioxide in the leaf tissue is readily consumed by photosynthesis. CO2 enters the leaf through pore that can be opened or closed.

When the pores are open to admit CO2, water escapes. Under conditions of water stress, the pores close, shutting down photosynthesis.

Carrying out photosynthesis is always a compromise between taking up CO2 and losing H2O.

Photosynthesis of individual leaves is light-saturated at 40-50% full sunlight. Below that, it falls off rapidly.
Photosynthesis Response to Temperature

Under non-stress conditions, daily single leaf or canopy photosynthesis is a direct function of the light intercepted by a leaf or canopy during a day.

(ie. Trees have this figured out very well.)
**Respiration**

Approximately 50 % of the C that is fixed in photosynthesis is used for respiration. This is necessary to liberate the energy stored in carbohydrates and fats.

Factors driving respiration rates:

- **Temperature** – respiration rate doubles for each 10 °C rise in temperature.
- **Oxygen** – respiration require oxygen and this can restrict respiration in roots under waterlogged conditions.

**H₂O and Nutrients** are also essential resources for plant growth and productivity but their capture and use will be discussed in more detail later in the class.
Carbon distribution is mainly controlled by the development and growth patterns of individual organs and their ability to compete for CH₂O’s

- A tree is a collection of semi-autonomous organs and each organ type has an organ-specific developmental pattern and growth potential.
- Organ growth is activated by endogenous and/or environmental signals.
- Once activated, environmental conditions and genetics determine conditional organ growth capacity.
- Realized organ growth for a given time interval is a consequence of organ growth capacity, resource availability and inter-organ competition for resources.
- Inter-organ competition for CHO’s is a function of location relative to sources and sinks of CHO’s, transport resistances, organ sink efficiency and organ microenvironment.

One of the most practical examples of this concept is this type of tree.

Main points

- **Organ development and growth** dictate tree growth and production (not *vice versa*).
- **Organ development** is *not* same as **organ growth**.
- **Organ development** dictates **organ growth potential** but full growth potential does not have to be fulfilled for development to continue.
- **Organ growth** depends on **development** but **organ development** does *not* depend on **organ growth** beyond a minimum threshold.
What does this carbon distribution look like through time as the plant grows?

Results from a new, 3-dimensional computer graphics based simulation model called L-PEACH.
L-system: a language based approach

- \( I[+A][-A]IA \)
- \( I \rightarrow I I \)

Axiom:

- \( A \)
- \( I[+A][-A]IA \)
- \( I[+A][-A]IA \)
- \( I[+A][-A]IA \)
- \( I[+A][-A]IA \)

Variables:

- \( A \rightarrow I(1)[+A][-A]I(1)A \)
- \( I(x) \rightarrow I(x+1)I(x+1) \)

(Lindenmayer and Prusinkiewicz, 1990)

Basic concepts for understanding tree architecture

- The basic structure of shoots is consistent (HSMCs)
- Three types of shoots
  - Proleptic
  - Syleptic
  - Epicormic
- Two kinds of shoot growth
  - Preformed
  - Neoformed
- Apical dominance
  - “Reiteration”

Hidden Semi-Markov Chain models of shoots

(Fournier et al. 1998)
The different size categories of Nonpareil shoots

- **Long**
  - Total node number: 95
  - Mean total node number: 95
  - Mean length: 127.3 cm

- **Medium-long**
  - Total node number: 73

- **Medium**
  - Total node number: 29

- **Medium-short**
  - Total node number: 16

- **Short**
  - Total node number: 8

### Almond Cultivars

I. Comparison of 1-year-old proleptic and epicormic shoot structure of three almond cultivars with different tree architectures

- **'Nonpareil'**
  - Mean total node number: 95
  - Mean length: 127.3 cm

- **'Aldrich'**
  - Mean total node number: 80
  - Mean length: 124.9 cm

- **'Winters'**
  - Mean total node number: 100
  - Mean length: 107.5 cm

#### Long Proleptic Shoots

- **'Nonpareil'**
  - Mean total node number: 95
  - Mean length: 127.3 cm

- **'Aldrich'**
  - Mean total node number: 80
  - Mean length: 124.9 cm

- **'Winters'**
  - Mean total node number: 100
  - Mean length: 107.5 cm

#### Summer Fire on Nemaguard

Long shoot: 5 states + Terminal bud

- Initial Probabilities
  - 0.92
  - 0.08

- Occupancy distribution mean
  - 3.50
  - 12.30
  - 5.74
  - 3.89
  - 2.05

- Transition Probabilities
  - B>V
  - 0.41
  - 0.99
  - 0.99
  - 0.33
  - 0.11

- Observation Distribution
  - Probability axillary meristem fate
  - 0 > 1
  - 2 > 1 > 0
  - 0 > 1 > 2

- Probability number of flowers per node
  - 0.92
  - 0.92
  - 0.92
  - 0.92
  - 0.92

- Probability distribution
  - B > V
  - 0.41
  - 0.99
  - 0.99
  - 0.33
  - 0.11

- Probability number of flowers per node
  - 0.92
  - 0.92
  - 0.92
  - 0.92
  - 0.92

- Initial number of flowers
  - 28.5 nodes
Three types of shoots

- **Syleptic**: shoots that grow out from lateral meristems in the axils of leaves without an intervening period of dormancy.
- **Proleptic**: shoots that grow out from terminal or lateral meristems after a dormant bud has been formed.
- **Epicormic**: shoots that grow from dormant epicormic meristems on older branches after a pruning cut, limb break or extreme limb bend.
Two types of shoot growth

- Preformed shoot growth: shoot growth that grows as an extension of internodes between nodes that are preformed in dormant buds (usually limited to 6-12 nodes).

- Neoformed shoot growth: shoot growth that grows as a result of the production of new nodes that are produced during the current growing season.

Three manifestations of apical dominance

- Correlative inhibition: suppression of lateral shoot growth by a vigorously growing apical meristem during the current season’s growth.
- Apical control: tendency for terminal and distal lateral shoots to depress the growth of more basal (subordinate) shoots.
- Shoot epinasty: tendency for actively growing upper, distal shoots to influence the branch angle of basal shoots (usually making them wider).
Carbohydrate/resource balance

- If allowed to grow naturally, when a tree goes into dormancy its natural shoot growth potential for the following spring is a function of a balance between the carbohydrate and nutrients stored prior to dormancy and the number of buds.
- Any pruning during dormancy will change this balance in favor of stimulating more growth, perhaps even latent, epicormic meristems.

“Reiteration”

- Reiteration is the tendency for a tree to “replace” any vegetative part of the tree that is lost or removed through limb breakage or pruning. In the case of loss of major pieces of individual units like shoots, the new shoot will have characteristics similar to the shoot that is being replaced.
- The “strength” of reiteration will depend on the type of pruning cut, the amount growth that was lost, and the timing of the pruning.

If we think of the tree as a collection of semi-autonomous parts, what are the main parts of a tree that we need to worry about from a CHO sink point of view?

- Shoot growth - both annual and daily
- Trunk growth
- Root growth
- Carbohydrate storage
- Fruit growth
In peach, length growth of most shoots except water sprouts (epicormic shoots) is finished by June.

This is different in almonds.

Contrary to popular opinion, shoots grow most rapidly in the afternoon when temperatures are high and stem water potential is recovering form a daily minimum.

Seasonal patterns of proleptic almond shoot growth at three rates of irrigation. Note that shoot growth slowed down by June but then there was a second flush but addition of nodes was more continuous.

Trunk diameter growth continues through most of the growing season.
Root growth tends to be episodic in many species. There is usually a burst of activity in spring, a lull in mid-summer and a second burst in fall.

Peach example. (mini-rhizotron data)

Fig. 6. The seasonal patterns of mean (± SE) root growth rates (g DW/day) measured in ingrowth root bags during four periods (Table 1) in 'O'Henry' peach trees subjected to three different thinning treatments; defruited (T1), commercially thinned (T2), and unthinned (T3).

CHO storage in perennial tissues.

The bark has the highest concentrations of CHO but because the mass of woody tissue is greater there is more total CHO content in the wood (xylem tissue).

Five-yr-old wood is still active in storing and mobilizing CHO.
How much non-structural CHO is stored in a tree and where?

### Accumulation of Carbohydrates

**TABLE 7.1 Distribution of Starch and Sugars in Grimes Apple Tree in Mid-October**

<table>
<thead>
<tr>
<th>Component</th>
<th>Dry weight (lb)</th>
<th>Starch and sugar</th>
<th>Percent of dry weight</th>
<th>Starch (lb)</th>
<th>Percent of dry weight</th>
<th>Sugar (lb)</th>
<th>Percent of dry weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leaves</td>
<td>32.82</td>
<td>3.09</td>
<td>9.41</td>
<td>0.92</td>
<td>2.80</td>
<td>2.17</td>
<td>6.61</td>
</tr>
<tr>
<td>Spikes</td>
<td>6.33</td>
<td>0.69</td>
<td>10.90</td>
<td>0.37</td>
<td>0.85</td>
<td>0.32</td>
<td>5.05</td>
</tr>
<tr>
<td>Wood aged:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 year</td>
<td>5.94</td>
<td>0.65</td>
<td>10.94</td>
<td>0.35</td>
<td>0.80</td>
<td>0.30</td>
<td>5.05</td>
</tr>
<tr>
<td>2 years</td>
<td>7.12</td>
<td>0.72</td>
<td>10.25</td>
<td>0.45</td>
<td>0.82</td>
<td>0.38</td>
<td>3.90</td>
</tr>
<tr>
<td>3 years</td>
<td>8.74</td>
<td>0.65</td>
<td>9.73</td>
<td>0.51</td>
<td>0.84</td>
<td>0.34</td>
<td>3.69</td>
</tr>
<tr>
<td>4-6 years</td>
<td>24.07</td>
<td>2.48</td>
<td>9.56</td>
<td>1.22</td>
<td>3.00</td>
<td>1.06</td>
<td>3.31</td>
</tr>
<tr>
<td>7-10 years</td>
<td>124.00</td>
<td>7.20</td>
<td>5.81</td>
<td>4.48</td>
<td>3.60</td>
<td>2.74</td>
<td>3.21</td>
</tr>
<tr>
<td>11+ years</td>
<td>101.20</td>
<td>5.95</td>
<td>5.88</td>
<td>4.01</td>
<td>3.96</td>
<td>1.94</td>
<td>1.92</td>
</tr>
<tr>
<td>Stem</td>
<td>68.10</td>
<td>7.57</td>
<td>11.10</td>
<td>6.14</td>
<td>9.00</td>
<td>1.43</td>
<td>2.10</td>
</tr>
<tr>
<td>Total</td>
<td>400.01</td>
<td>22.91</td>
<td>7.29</td>
<td>18.53</td>
<td>4.63</td>
<td>10.68</td>
<td>2.67</td>
</tr>
</tbody>
</table>

*Adapted from Munson (1942)

### Describing fruit growth potentials

The potential growth rate of all of these fruit types can be predicted with a relative growth rate (decreasing compound interest rate) function.

(We will discuss this further later)

---

**L-Peach**

- **Input data**
  - L-PeachParameters
- **Model components**
  - Architectural model
  - CH₂O and H₂O transport algorithms
- **Output data**
  - 3D visualization (L-STUDIO)
- **Quantitative data**
  - L-PeachGraphing

**L-Peach Representation**

Diagram showing the integration of architectural model, CH₂O and H₂O transport algorithms, and quantitative data components.
Modeling = Simplifying

“Source-sink algorithm”

<table>
<thead>
<tr>
<th>Physiological / hydraulic entity</th>
<th>Electric entity</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>mass or volume</td>
<td>charge</td>
<td>q</td>
</tr>
<tr>
<td>mass or volume flow rate</td>
<td>current</td>
<td>i</td>
</tr>
<tr>
<td>hydrostatic potential, pressure</td>
<td>electric potential</td>
<td>v</td>
</tr>
<tr>
<td>pressure difference</td>
<td>potential difference, voltage</td>
<td>v, e</td>
</tr>
<tr>
<td>hydraulic resistance</td>
<td>resistance</td>
<td>r</td>
</tr>
<tr>
<td>hydraulic conductance</td>
<td>conductance</td>
<td>g</td>
</tr>
</tbody>
</table>

Mathematically this approach amounts to numerically solving a system of nonlinear equations using the Newton-Raphson method.

\[
V_2 = \frac{V_1 R_{p1} + E_{p2} R_{p2}}{R_{s2} + R_{p2}}
\]

Obviously, it is not important for you to know how we modeled the carbohydrate distribution in a simulated tree.

However, I believe that it is important for you to understand that it was possible to realistically simulate tree growth purely by having sub-models of the potential growth of all the tree parts and then model the distribution of CHO in the tree by having all of these parts compete for CHO over time and as their growth potentials demanded it.

The most important thing about this is it means that the **plant does not distribute** the CHO within the plant, but the **CHO gets distributed within the plant by the competition for CHO among the plant parts** and that is function of the developmental patterns of the plant parts and their ability to compete.
Carbon distribution is mainly controlled by the development and growth patterns of individual organs and their ability to compete for CH₂O’s.

- A tree is a collection of semi-autonomous organs and each organ type has an organ-specific developmental pattern and growth potential.
- Organ growth is activated by endogenous and/or environmental signals.
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- Inter-organ competition for CHO’s is a function of location relative to sources and sinks of CHO’s, transport resistances, organ sink efficiency and organ microenvironment.

Commercial Practices:
- Simulating responses to pruning
- Simulating responses to fruit thinning