Plant Canopies and Water: Why they use what they do

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Part 1 - Plant Leaves

Part 2 – Plant Canopies

Part 1 Outline

- Introduction
- leaf anatomy and stomata
- Diffusion of carbon dioxide and water
- Gas diffusion laws
- Transpirational water-loss summary
- Why hasn't Evolution created lower water use in plants?

Water use by plant leaves

- Among the most important determinates of crop yield
- "Crop losses to water shortage may exceed those from all other causes combined (Kramer, 1980)
- Water for metabolism (photosynthesis) is 1%, often less, than total water use
  - Carbon dioxide + water → Carbohydrate + Oxygen

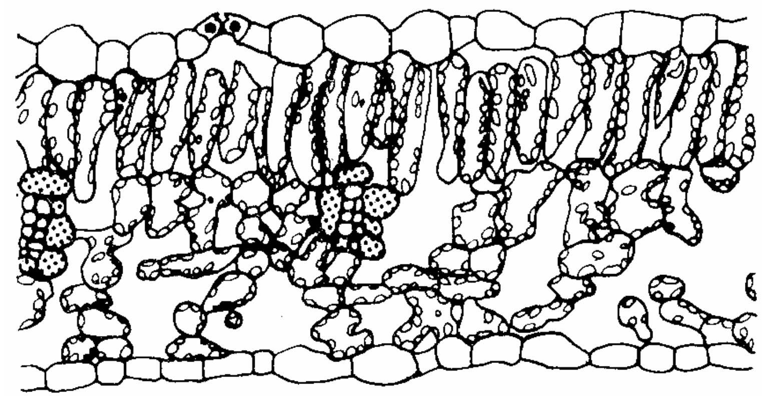
(metabolic use)

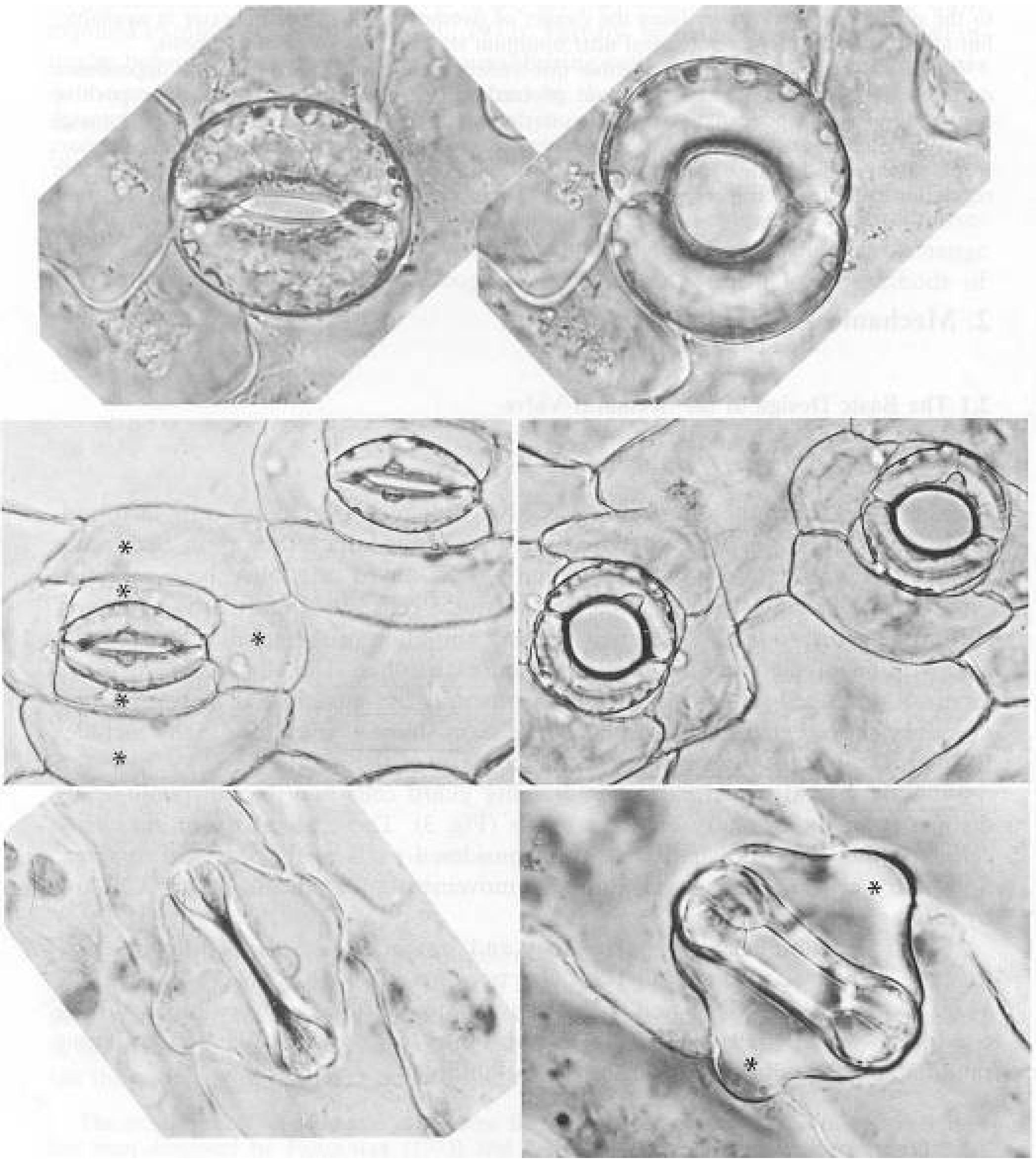
Water use by plant leaves

- Runoff, evaporation from surfaces etc. can be managed but -
- 50-75% of water use is for transpiration
  - Transpiration means water vapor loss through pores
  - Evaporation means conversion of liquid to gas
  - Water vapor loss during carbon dioxide uptake
    - Described by physics (they have laws about that)
    - “Conservative Characteristic”, we cannot repeal the laws of physics

Leaf anatomy

- Leaves are very thin
- Leaves have air spaces
- Carbon dioxide uptake occurs deep within leaves
- Water evaporates inside leaves, transpires through the stomata

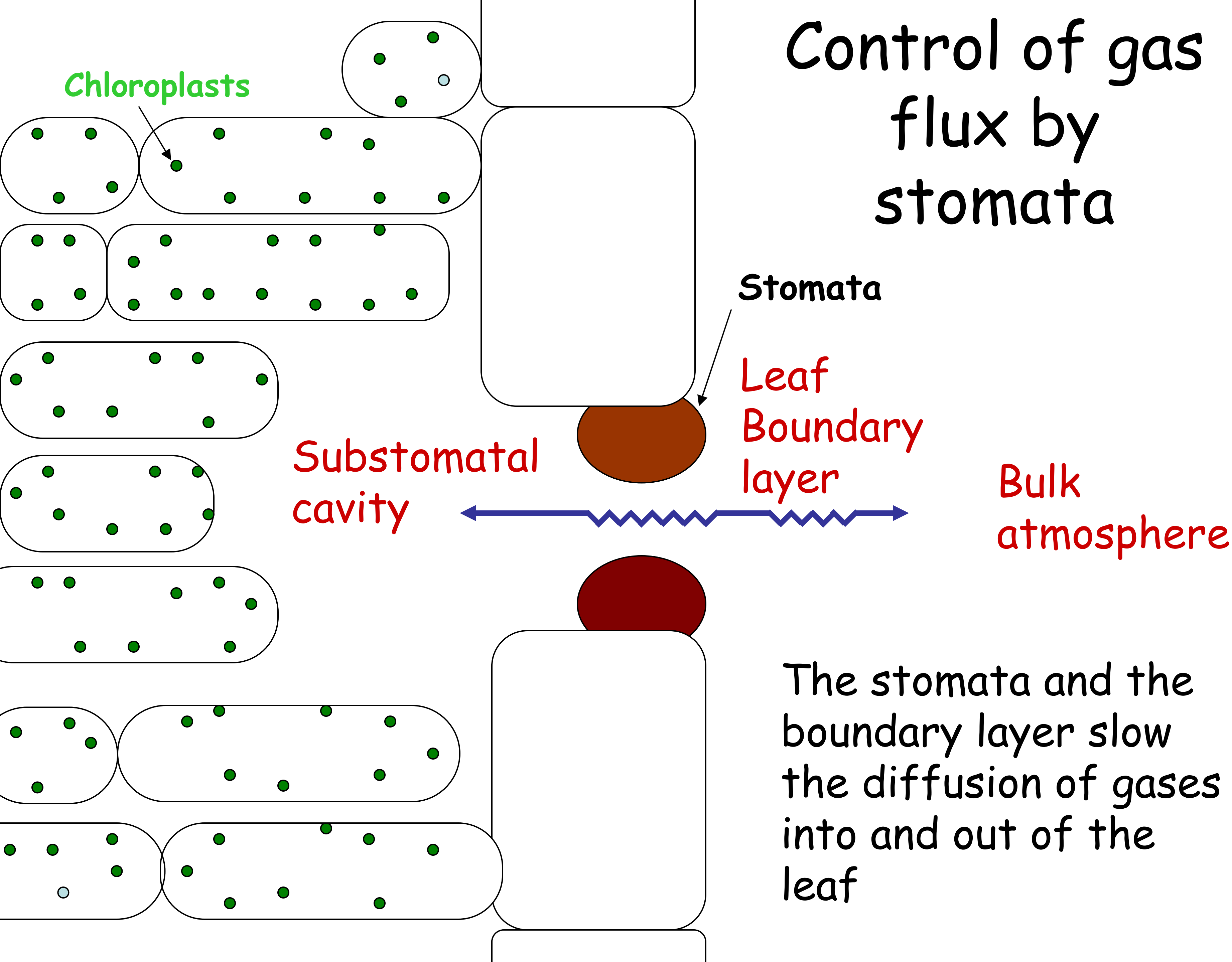




Stomata are adjustable pores in the leaf surface

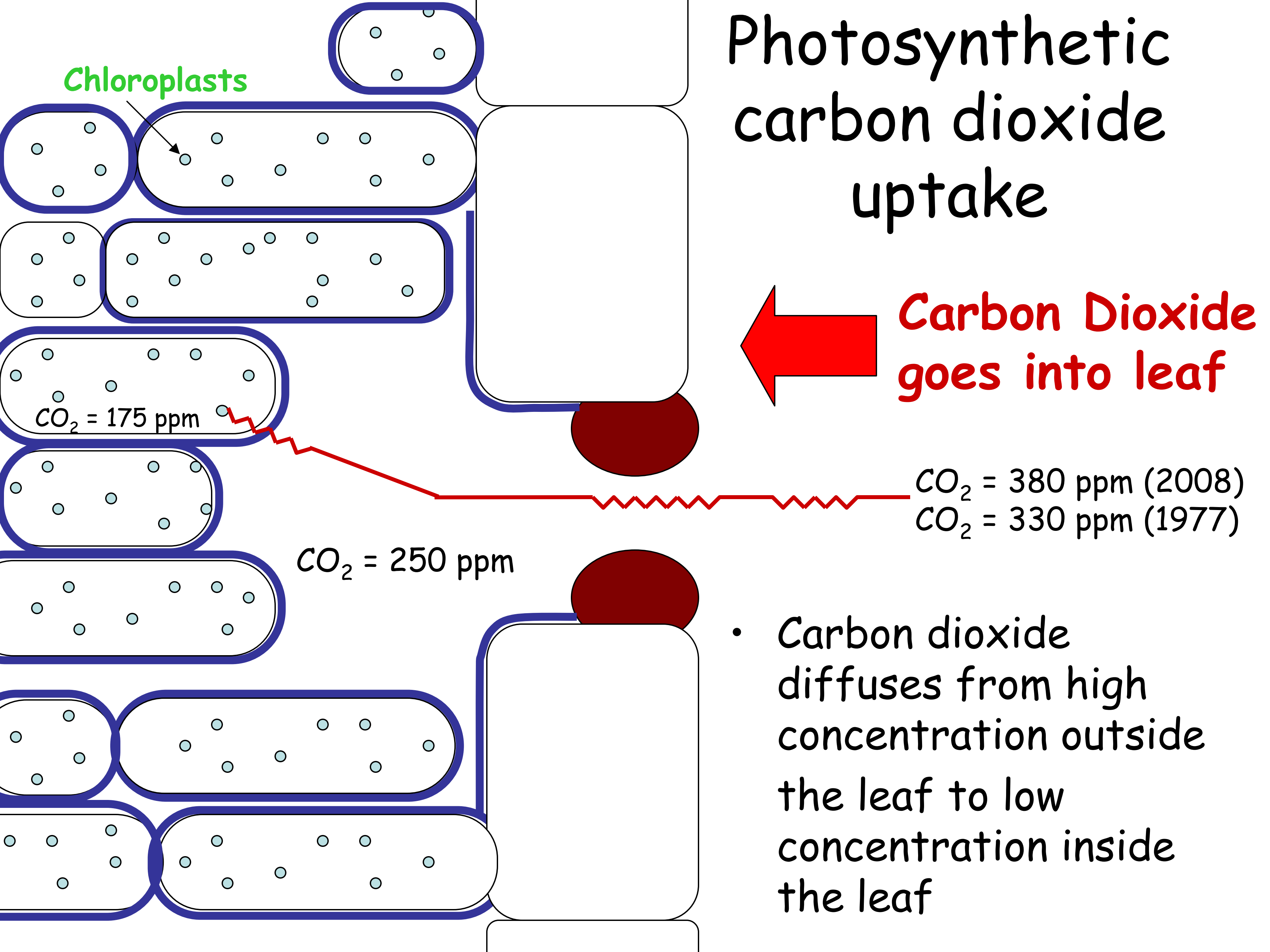
Control of water movement through plants is primarily at the stomata

Control of gas flux by stomata



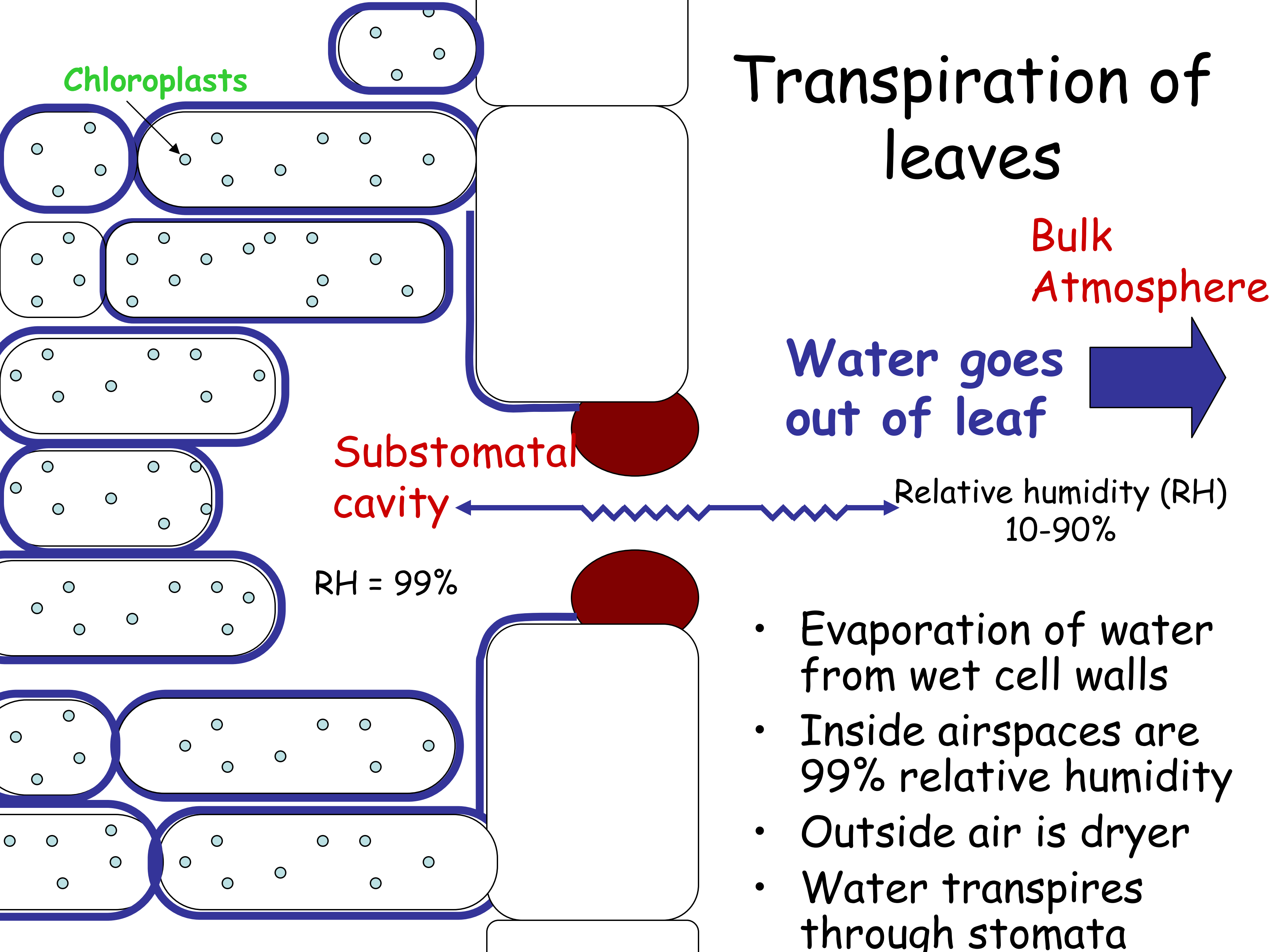
The stomata and the boundary layer slow the diffusion of gases into and out of the leaf

Photosynthetic carbon dioxide uptake



- Carbon dioxide diffuses from high concentration outside the leaf to low concentration inside the leaf

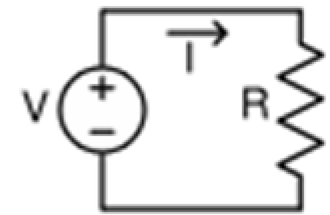
Transpiration of leaves



- Evaporation of water from wet cell walls
- Inside airspaces are 99% relative humidity
- Outside air is dryer
- Water transpires through stomata

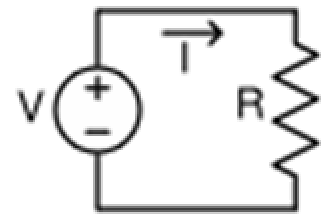
Understanding Gas Movement Into and Out of Leaves

- Ohm's Law (Fick's 1st Law)
  - V = I R
  - Potential difference (voltage)
    - Can be measured different ways
    - Partial pressures, the amount of the total pressure accounted for
    - Units of Pascals (Pa)
    - Atmosphere is ~ 100 kPa
    - Water inside a leaf 2.8 kPa at 23°C
    - Water outside a leaf 0.28-2.5 kPa
    - Typical 2.8 kPa – 1.4 kPa = 1.4 kPa "voltage"



Understanding Gas Movement Into and Out of Leaves

- Ohm's Law (Fick's 1st Law)
  - V = I R
  - Water
    - Water inside a leaf 2.8 kPa at 23°C
    - Water o
    - Typical 2
  - CO_2 (1 Pa ~
    - 38 Pa ou
    - 25 Pa in
    - Typical 3
- A/T ∝ 13 P
- CO_2 m.w. =



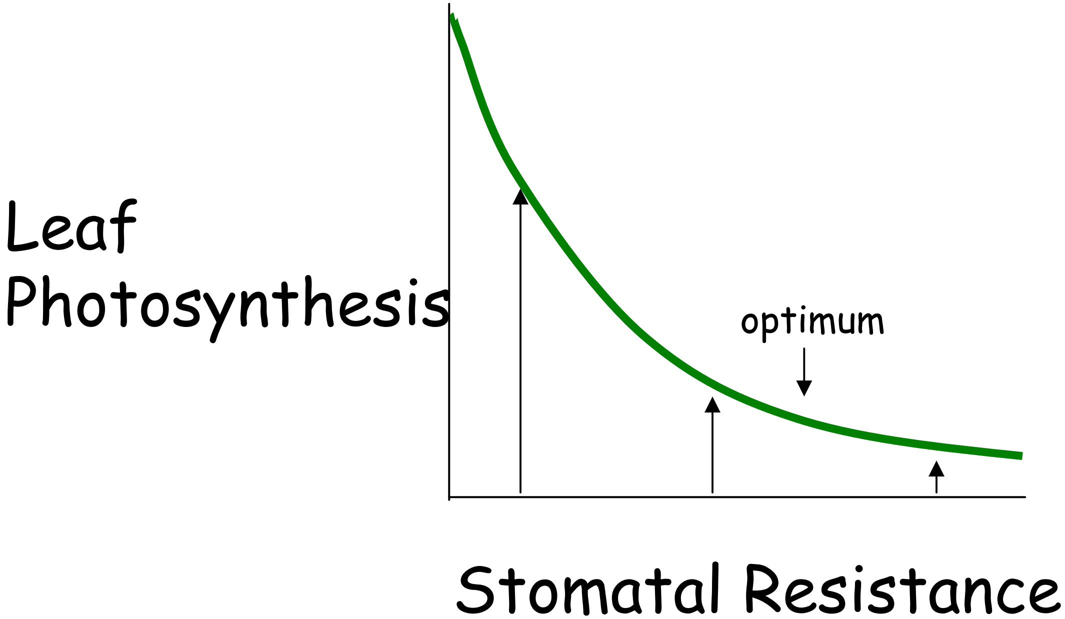
At least 100 water molecules are required for every carbon dioxide molecule taken up by crops

- A/T = 13 Pa / (1400 Pa X 1.6) = 0.0058

Leaf stomatal resistance controls leaf assimilation

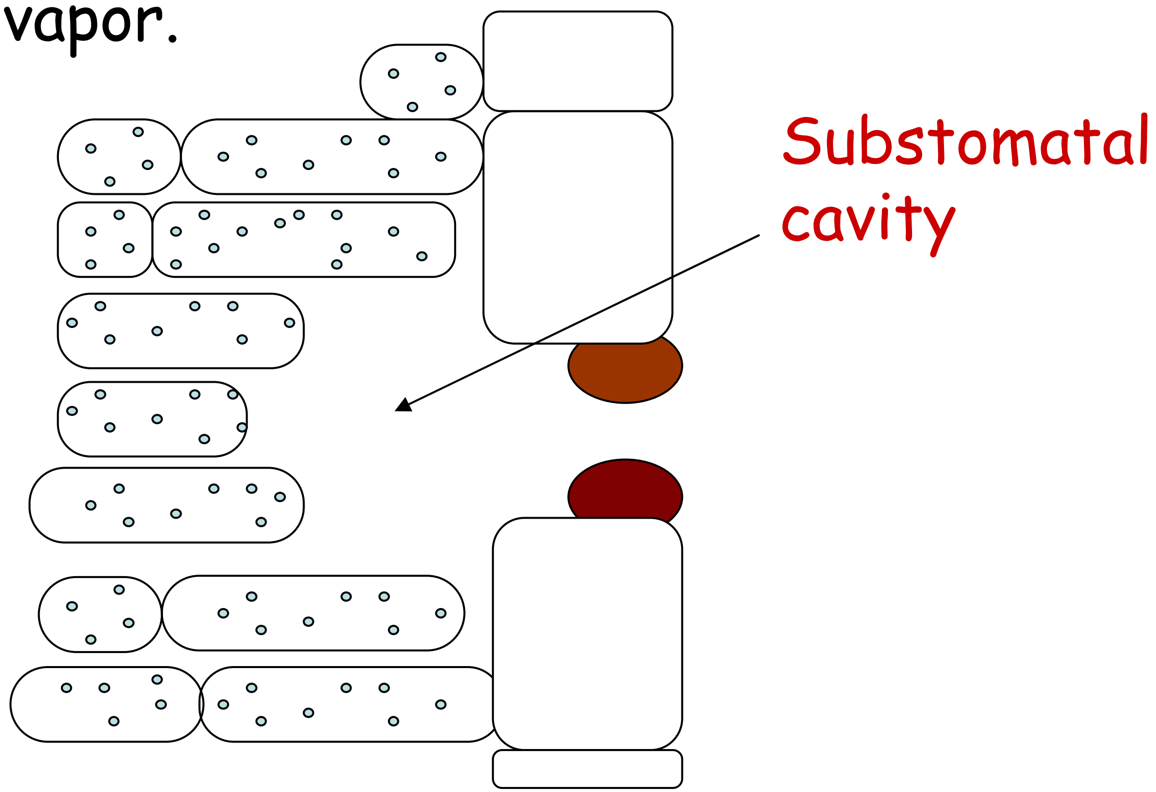
Most leaves operate near their optimum for maximizing leaf photosynthesis and minimizing transpiration

Leaf seems to be “trying” to conserve water



Leaf resistance control of leaf assimilation

Furthermore, leaves have a substomatal cavity that is of a size that maximizes the diffusion of carbon dioxide and minimizes the diffusion of water vapor.



Summary
Transpirational Water Loss -

1. always occurs if plants are growing and 100-1000 g water are lost per g of plant biomass.
2. occurs as water vapor loss through stomata.
3. Is less in humid areas like Midwest than arid areas like the West.
4. can be modeled using an Ficks' law
5. is normally 100 fold greater than carbon dioxide uptake.
6. causes high rates of crop growth to result in high water cost per carbon dioxide.
7. typically accounts for most water use by crops.

Why Hasn't Evolution Created Lower Water Loss in Plants?

Some researchers believe that evolution over millions of years would have overcome relatively large water loss if large water use was not required for "other reasons".

"Other reasons" might be

- controlling plant temperature by transpirational cooling
- transporting nutrients from soil to root bymass flow
- transporting nutrients from root to leaf in the transpiration stream

Why Hasn't Evolution Created Lower Water Loss in Plants?

When water is absolutely limiting survival of terrestrial plants in an environment, like a desert, environments that have existed for millions of years, plants adapt with modifications like

- sinking stomata below leaf surface
- having thick waxey cuticles on the leaf
- reducing number of stomata per unit area
- opening stomata at night when humidity is high and storing carbon biochemically for day time photosynthesis

But, they have **not** created a mechanism that passes carbon dioxide more quickly than water

Why Hasn't Evolution Created Lower Water Loss in Plants?

Not just any mechanism can be developed by evolution.

Although some researchers believe that a membrane could be created to allow more carbon dioxide to pass through than water, it is highly unlikely that the membrane could sustain a high enough flow of carbon dioxide to sustain a high plant growth rate.

Why Hasn't Evolution Created Lower Water Loss in Plants?

Unfortunately, even if the plant could develop a mechanism for getting carbon dioxide uptake with very little water use, a good case can be made for requiring HIGH transpiration rates for either of the following reasons:

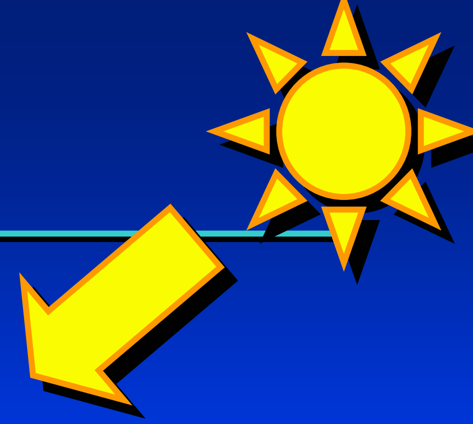
- adequate movement of nutrients from the bulk soil to the root to sustain high growth rates
- adequate transport of nutrients from roots to leaves and reproductive organs

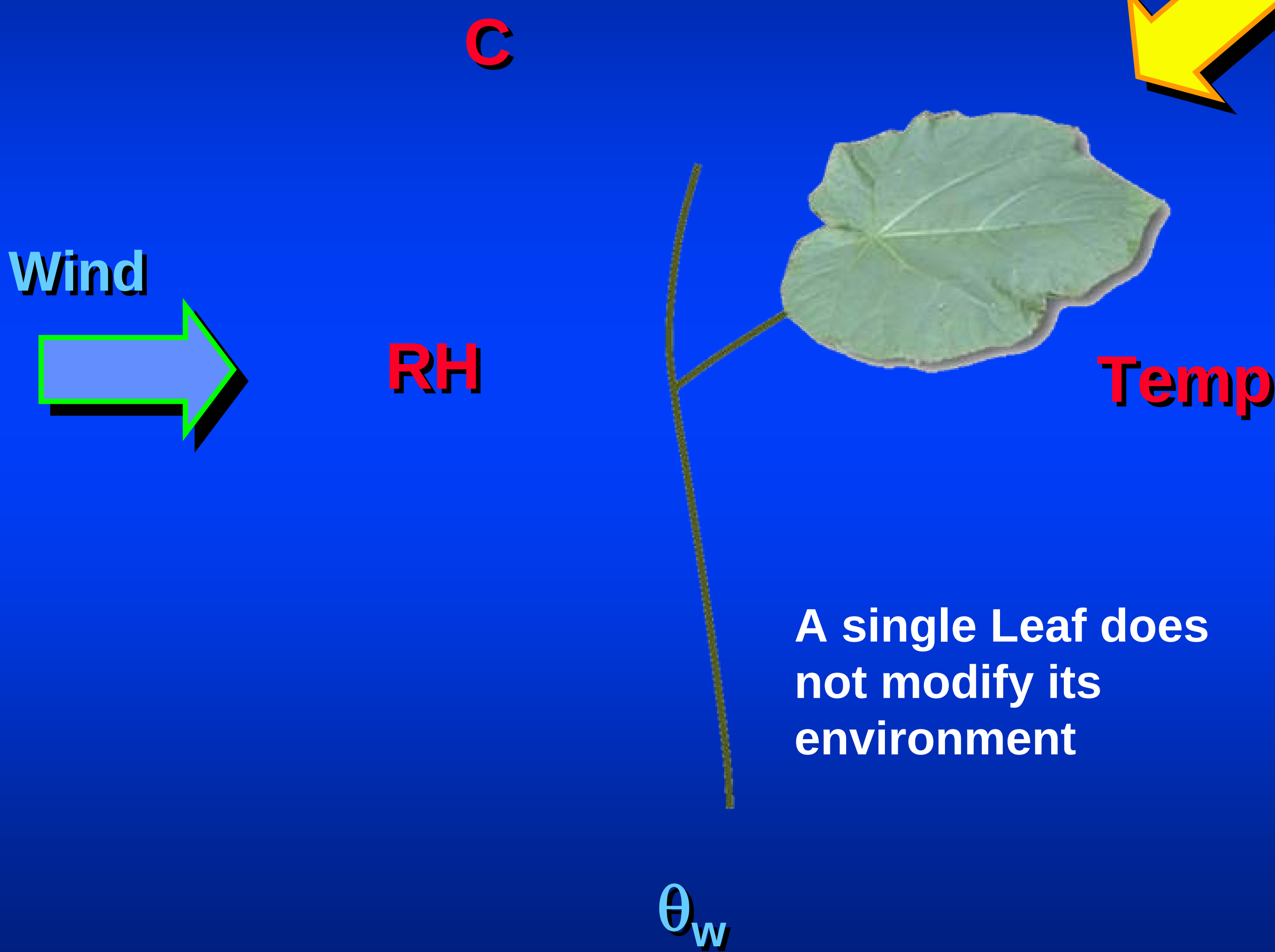
Part 2 - Canopy Transpiration

Part 2 Outline

- Introduction
- Transpiration Efficiency (canopy)
  - Transpiration proportional to productivity
- Water-Use Efficiency (canopy)
  - Evaporation losses do not contribute to productivity
- Magnitudes of evaporation losses
- Reducing evaporation losses
- Conclusion

Leaf vs. Canopy Behavior





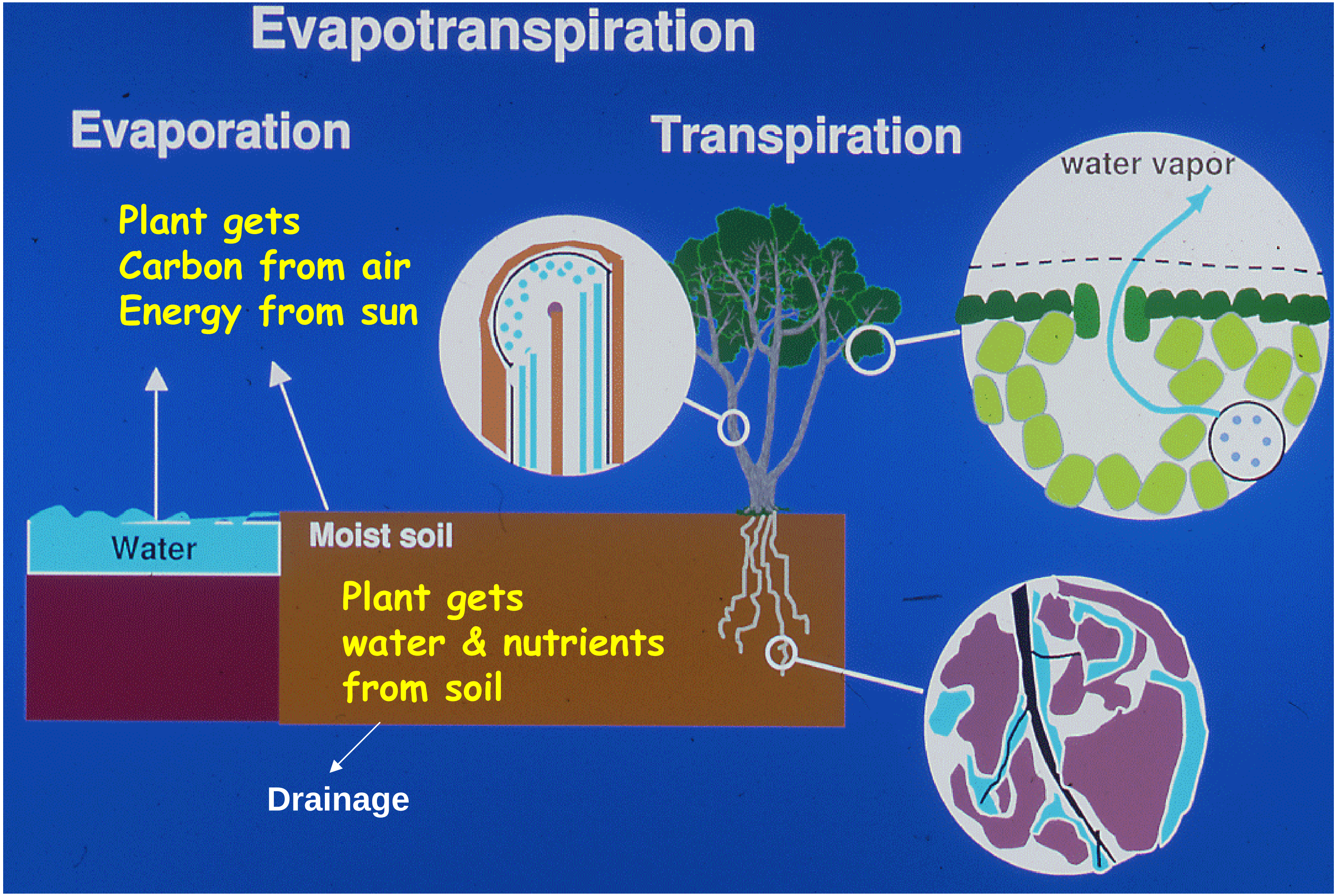
A single Leaf does not modify its environment

Leaf vs. Canopy Behavior

Introduction

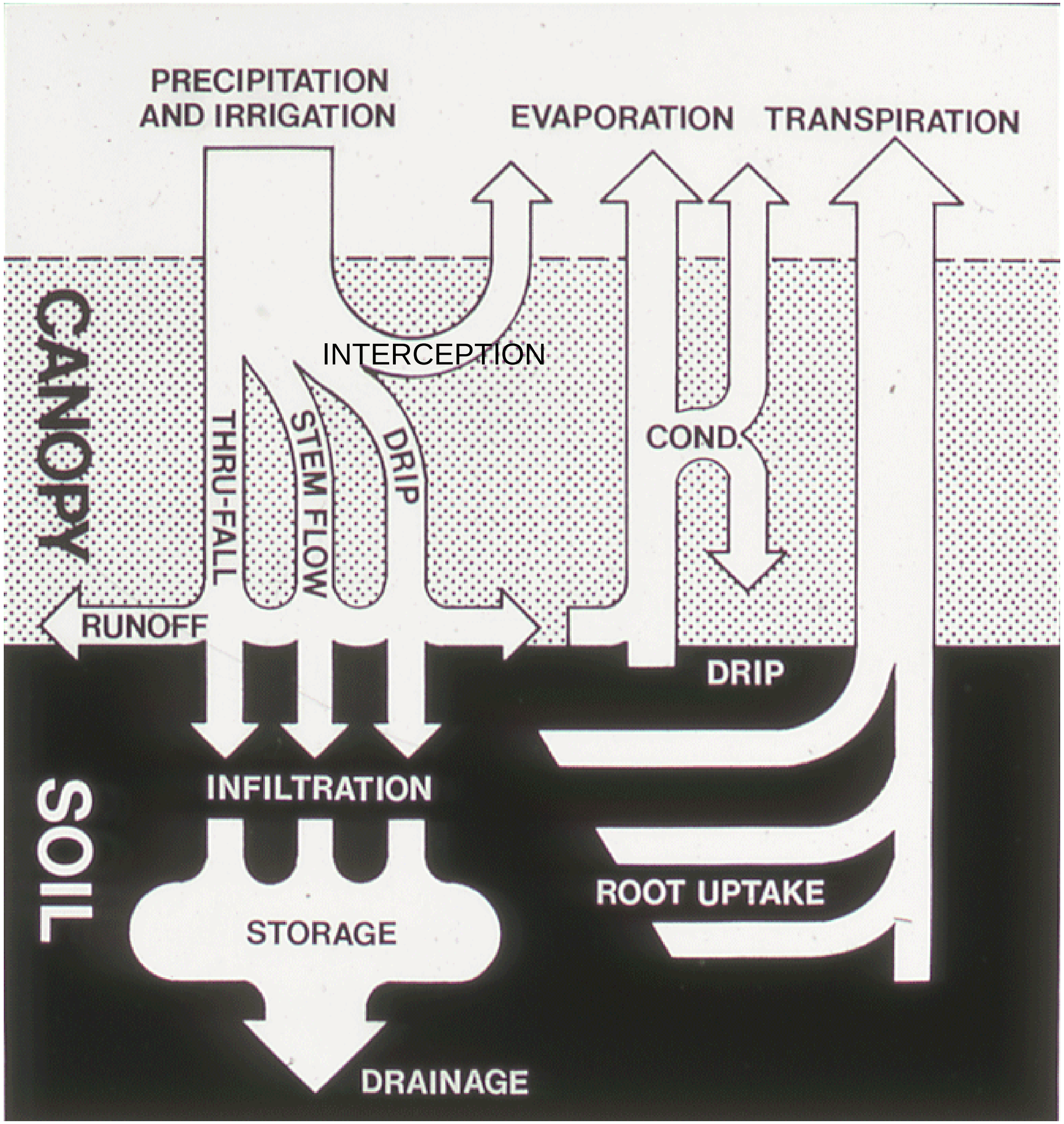
- Canopies are complex arrangements of plant parts including leaves, stems, branches, flowers etc.
- Canopy water cycles have many components and magnitudes of these components are different for different vegetation types, soils and weather.

Evaporation versus Transpiration



Introduction

Components of canopy water cycle



Introduction

- Water that goes through the plant (TRANSPIRATION) is proportional to productivity
- Transpiration efficiency is extremely difficult to improve for the reasons discussed in Part 1.

Transpiration Efficiency (canopy)

- Transpiration efficiency equation

TE = kg plant biomass per kg water transpired

$$TE = \frac{\text{Productivity}}{\text{Transpiration}} = \frac{P}{T} = \frac{0.005}{0.7(1.8)^{\overline{Tair}/10}\,(1 - RH)}$$ (For C3 plants)

$\overline{T}_{air}$ = Daytime averaged air temperature

$\overline{RH}$ = Daytime averaged relative humidity

$$\frac{P}{T} = \frac{0.005}{0.7\,(1.8)^{\overline{Tair}/10}(1 - \overline{RH})}$$ For C3 plants (like soy bean)

$$\frac{P}{T} = \frac{0.010}{0.7\,(1.8)^{\overline{Tair}/10}(1 - \overline{RH})}$$ For C4 plants (like corn)

Transpiration Efficiency (canopy)

- Transpiration efficiency equation

C3 Plants

$$\frac{P}{T} = \frac{0.005}{0.7\,(1.8)^{\overline{Tair}/10}\,(1 - \overline{RH})}$$

C4 Plants

$$\frac{P}{T} = \frac{0.010}{0.7\,(1.8)^{\overline{Tair}/10}\,(1 - \overline{RH})}$$

Wisconsin

$$\frac{P}{T} = \frac{0.005}{0.8} = 0.006 = 0.6\%$$

$$\frac{P}{T} = \frac{0.010}{0.8} = 0.012 = 1.2\%$$

Missouri

$$\frac{P}{T} = \frac{0.005}{1.5} = 0.003 = 0.3\%$$

$$\frac{P}{T} = \frac{0.010}{1.5} = 0.007 = 0.7\%$$

Arizona

$$\frac{P}{T} = \frac{0.005}{2.5} = 0.002 = 0.2\%$$

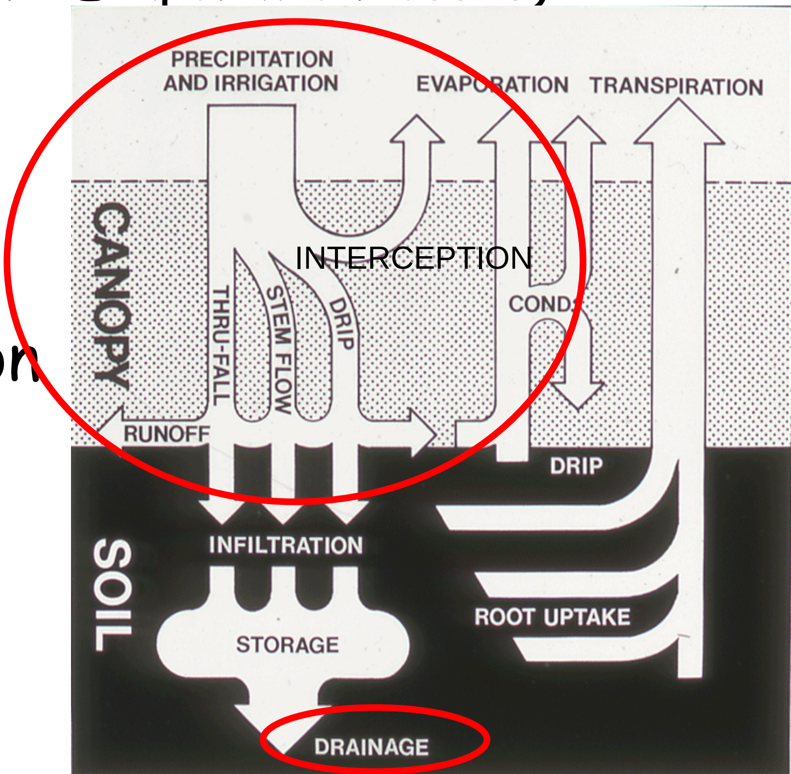
$$\frac{P}{T} = \frac{0.010}{2.5} = 0.004 = 0.4\%$$

Water-Use Efficiency

- Water that goes through the plant (TRANSPIRATION) is proportional to productivity
- Water that does NOT go through the plant (EVAPORATION LOSSES) does not contribute to productivity.
- Evapotranspiration (Et) = Transp. + Evaporation
- Transpiration efficiency is extremely difficult to improve, but evaporation losses can be manipulated to improve water use.

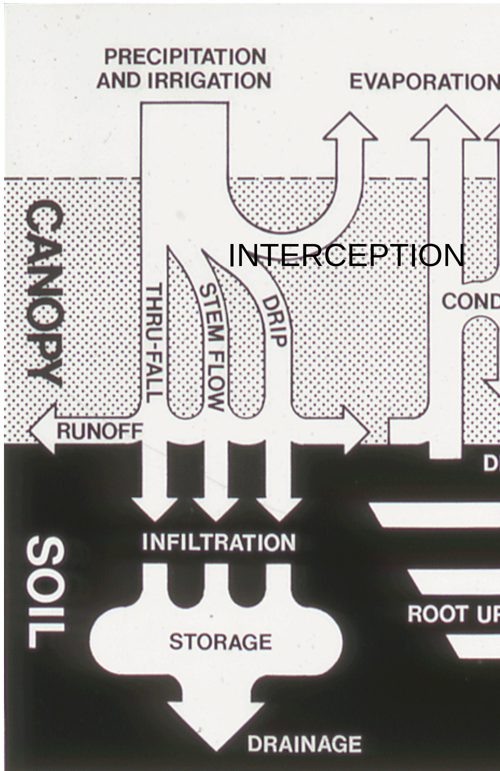
Water-Use Efficiency

- Water-use efficiency is lower than transpiration efficiency
  - WUE = Productivity/(Precipitation + Irrigation)
  - WUE = Productivity/(Transpiration + Evaporation losses)
- Pathways for water loss
  - Soil evaporation
  - Interception by foliage
  - Irrigation droplet evaporation
  - Runoff
  - Drainage



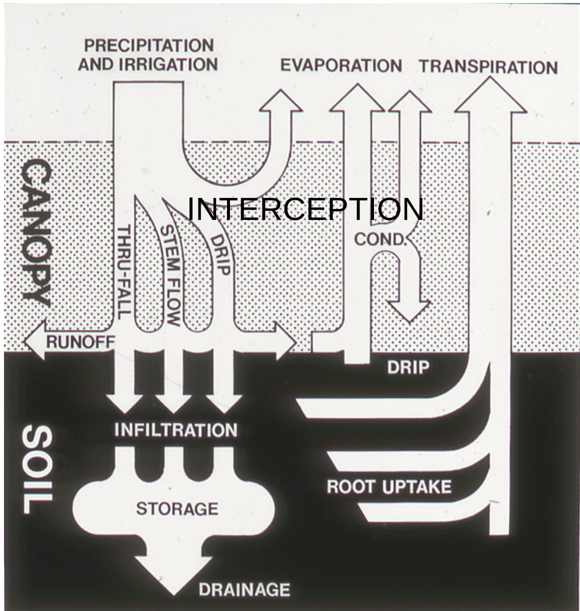
Magnitudes of water loss terms

- Pathways for water loss
  - Soil evaporation – 10% to 50% of Et
  - Interception by foliage - 10% to 50% of Et
  - Irrigation droplet evaporation
    - -1% to 10% (extreme of 30%) of Et
  - Runoff – 0% to 30%
  - Drainage – 0% to 50%



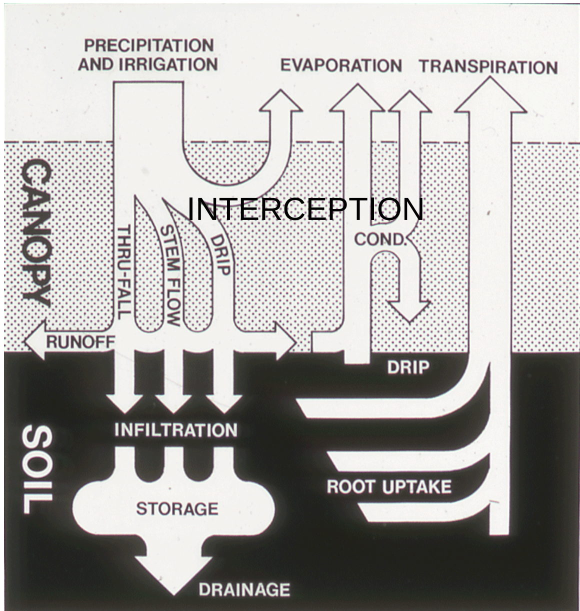
Magnitudes of water loss terms

- Example > 8-day irrigated corn crop (LAI=3)
  - Precip + Irrigation 79 mm
  - Transp 27 (55% of total Et)
  - Soil Evaporation 18
  - Interception 4 mm
    - Total Et 49 mm
  - Drainage 1 mm
  - Runoff 0
  - Increased soil storage 29 mm



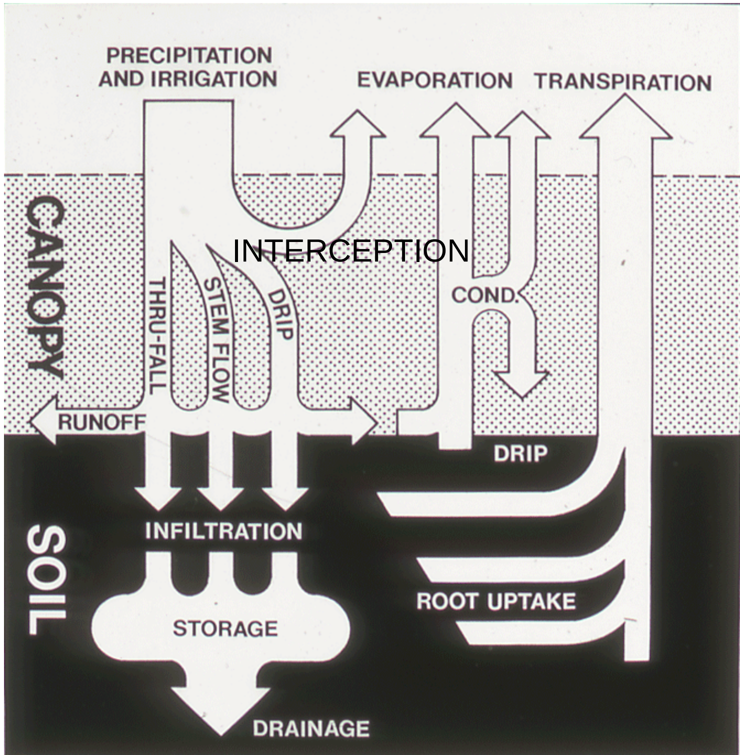
Magnitudes of water loss terms

- Example > 8-day irrigated ~~corn~~ wheat crop
  - Precip + Irrigation 79 mm
  - Transp 27 (55% of total Et)
  - Soil Evaporation ~~18~~ 12
  - Interception ~~4~~ 10
    - Total Et 49 mm
  - Drainage 1 mm
  - Runoff 0
  - Increased soil storage 29 mm



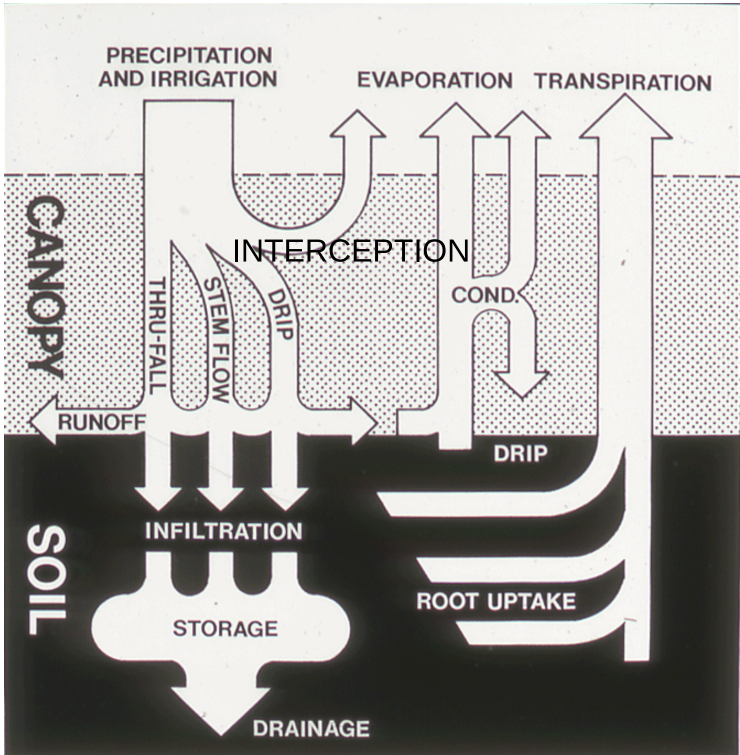
Magnitudes of water loss terms

- Evaporation losses are always a significant part of precipitation or total evapotranspiration, but the components that dominate differ



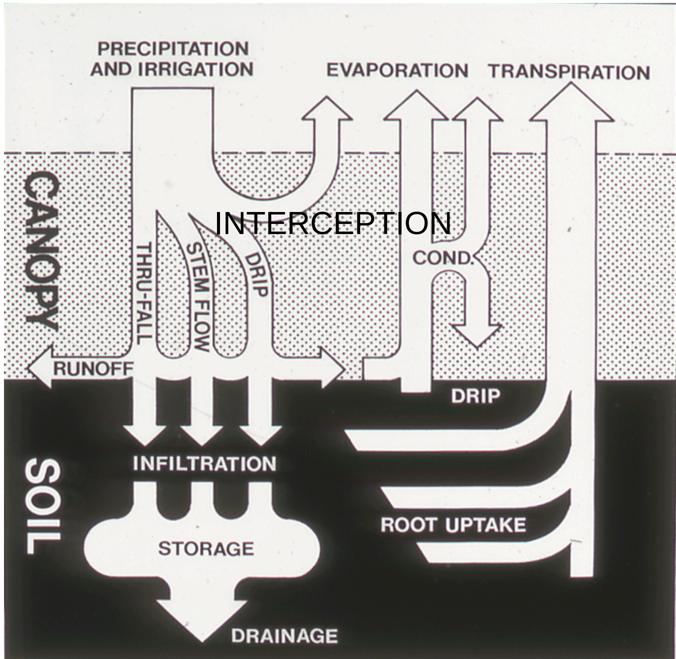
Magnitudes of water loss terms

- Interception can dominate when
  - Leaves are small (grasses)
  - Precip or irrigation come in small amounts frequently
  - Residue is present
    - Chopped Ag residue ~10%
    - Prairie residue ~50%
    - Residue reduces soil evap.



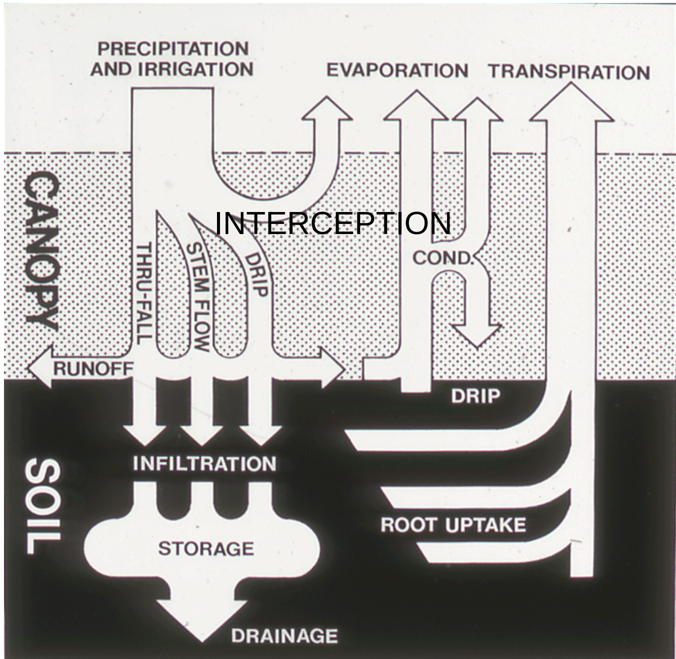
Magnitudes of water loss terms

- Soil evaporation can dominate when
  - Canopies are more open
  - Finer textured soils (silt loams, clays etc.)
  - Frequent precip or irrigation in small amounts
  - 10 – 25% of total Et even for canopies of full cover



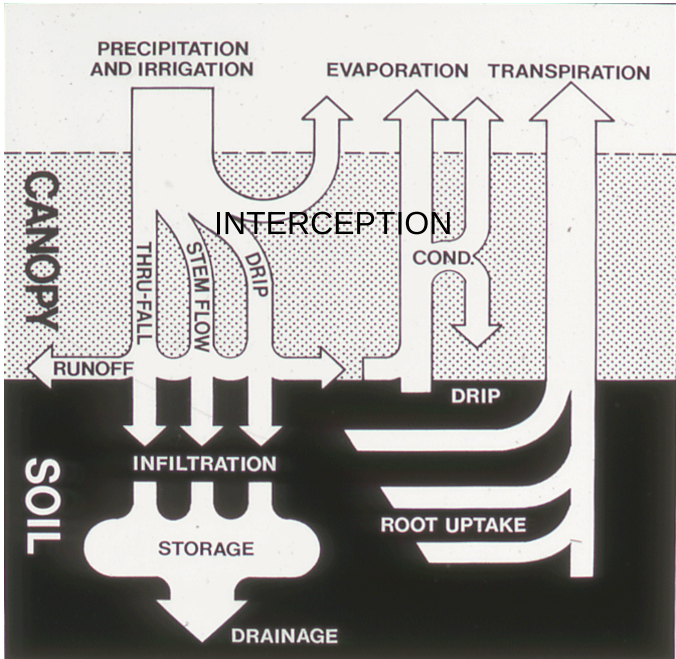
Magnitudes of water loss terms

- Irrigation droplet evaporation
  - Warm irrigation water (surface water) with high winds
    - 30% evaporative loss for fossil water at 70C in Saudi Arabia oil fields
    - Negative losses with ground water because it is cold



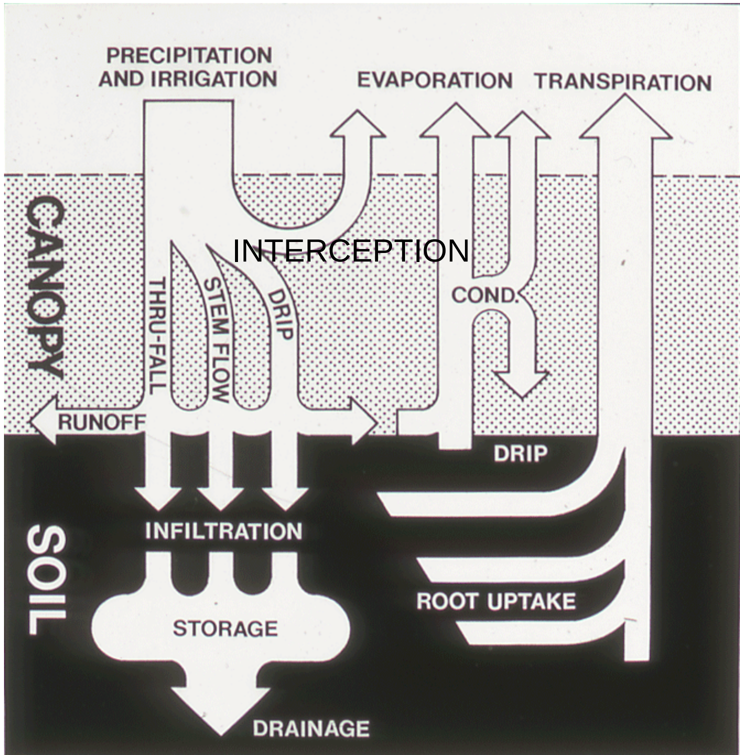
Magnitudes of water loss terms

- Drainage and Runoff
  - Large drainage losses with sand soils and heavy rains or irrigation applications
  - Fine texture soils (clay loams, sandy clays, etc.) have greater runoff losses but small drainage losses.
  - Soils with macro pores (no-till with residue) have low runoff and more drainage losses (25-40% in Wisc.)



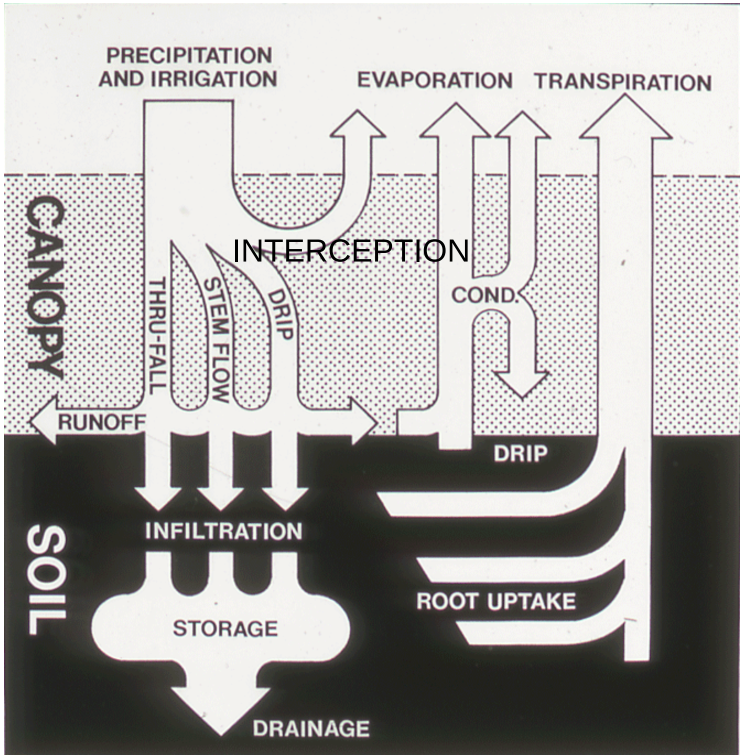
Magnitudes of water loss terms

- The bottom line is that transpiration usually is between 50 and 75% of total evapotranspiration, and a lesser percentage of precipitation.
- If one form of water loss does not get you, another will !



Minimizing Water Loss

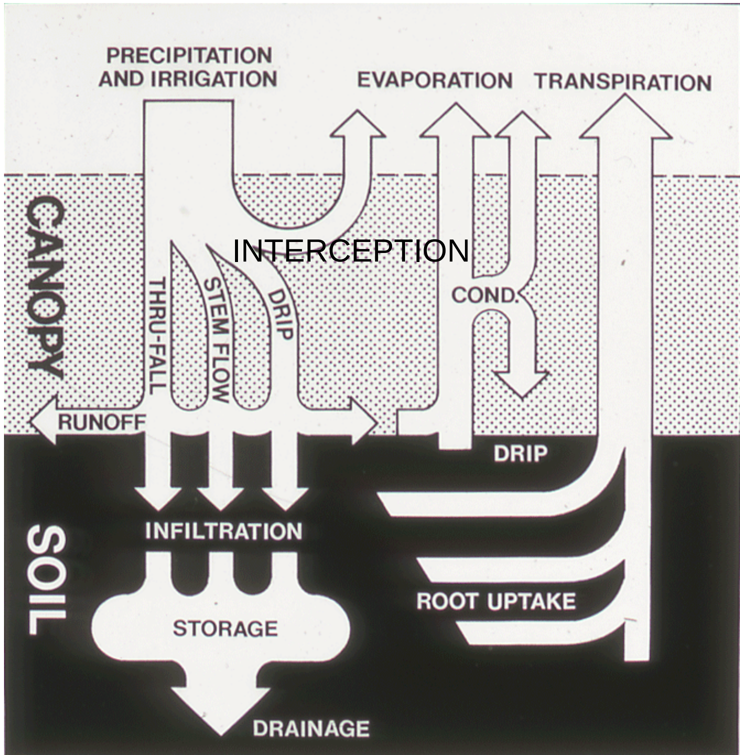
- Crop genetics and management can be modified to reduce water loss and improve yield for individual cases.
- Wheat in Australia
  - Breed increases in stem stem resistance to water movement so more water during reproductive phase providing higher yield under severe water stress



Minimizing Water Loss

- Crop genetics and management can be modified to reduce water loss and improve yield for individual cases.

- Improvements usually are minor, but can be the difference between no yield and a small yield.



Conclusion

- Although water loss by plants can be manipulated through plant breeding and management to exploit particular environments, reducing transpiration below current levels is likely to reduce productivity by comparable amounts.
- Although evaporation is more easily manipulated than transpiration, reducing one component, like soil evaporation, is likely to increase another component, like interception.