

# Teaching Ag Tech: Managing Soil Moisture with Sensors

---

DYLAN CASEY AND IAN  
AKSLAND

SOIL AND CROP  
SCIENCES

COLORADO STATE  
UNIVERSITY



# Outline

---

- Introductions
- Agriculture in the 21<sup>st</sup> century: How did we get here and where are we going?
- The role of the Internet of Things (IoT) and open-source electronics in Agriculture
- Measuring soil water status directly and indirectly (using sensors!)
- Soil-Plant-Water relationships
- Developing a sensor-based irrigation system
- Introduction to Arduino

# Who we are: Dr. Jay Ham's Micrometeorology and Environmental Physics Lab

---



Ian Aksland



Dylan Casey



Maria  
Christina  
Capurro

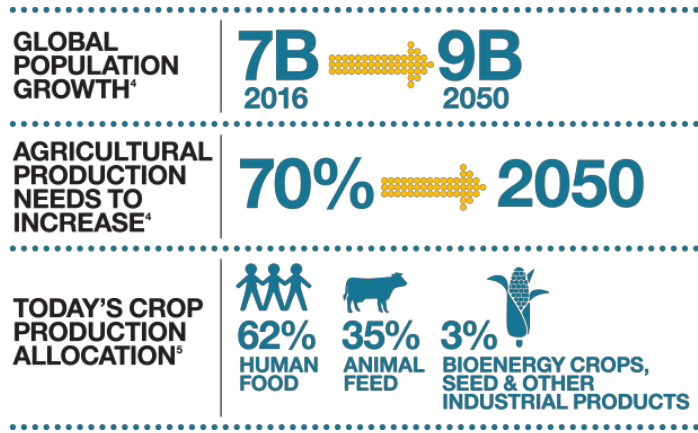


Hairik Honarchian

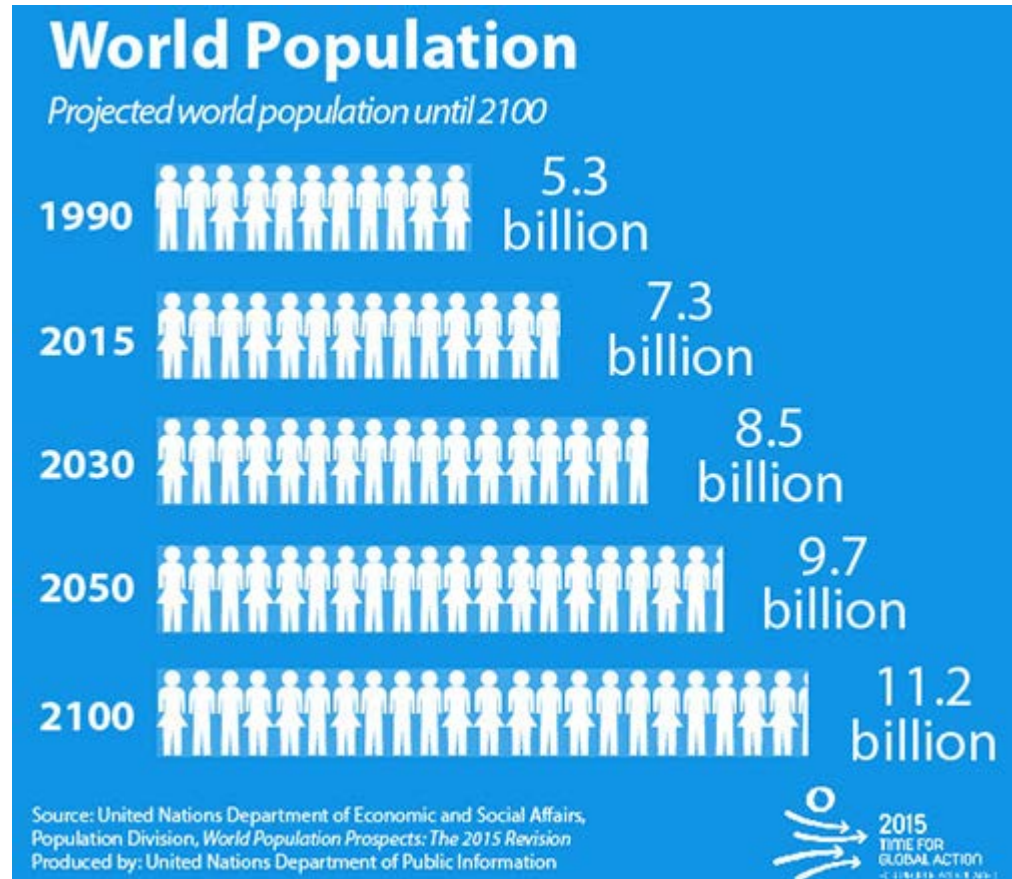


Dr. Jay Ham

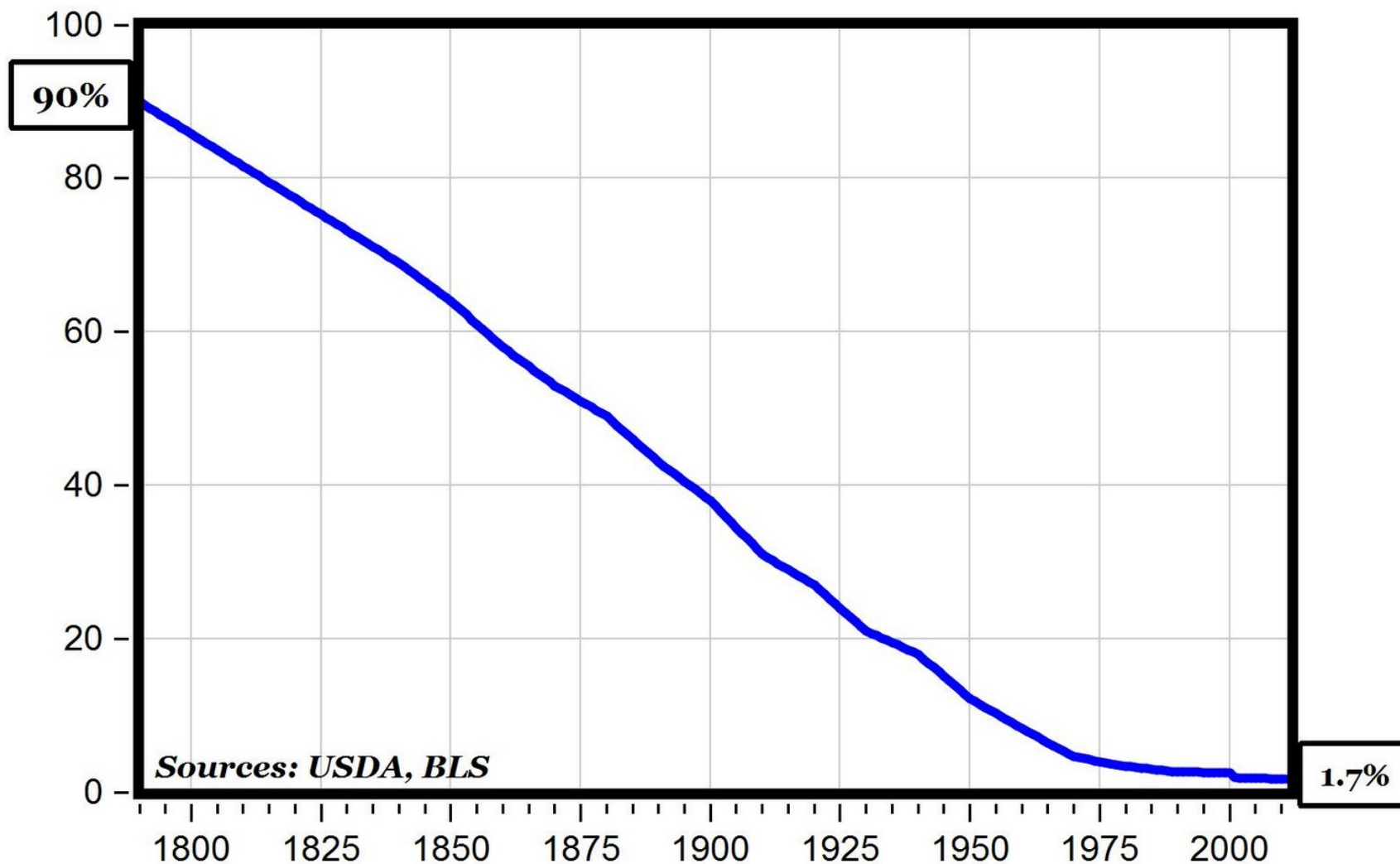
# Meeting the needs of a growing population



Land expansion will not fulfill crop production needs

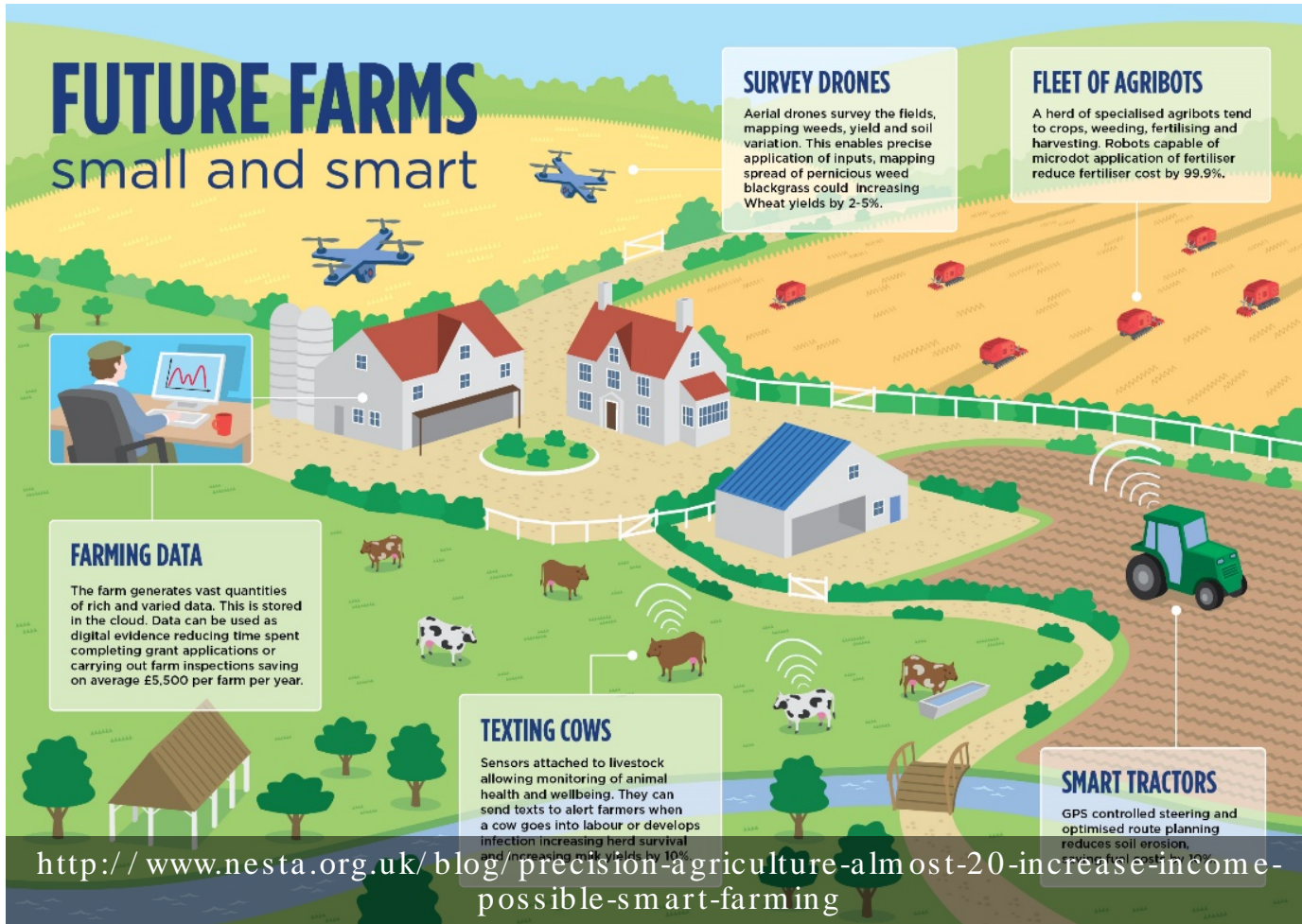


# Farm Jobs, % of Total U.S. Jobs 1790 to 2011



# Smart Farming

- Farms of the future will leverage sensor technology, the internet of things, and big data to improve decision making and increase efficiency.



A high-angle, blurred photograph of several people walking on a light-colored floor with a grid pattern. The people are out of focus, appearing as dark silhouettes against the bright floor. The overall scene suggests a busy, public space like a transit station or a large office building.

# An Internet of Things

"In the next century, planet earth will don an electronic skin.

It will use the Internet as a scaffold to support and transmit its sensations." - *Neil Gross 1999*

# What is the Internet of Things?

---



- A Network of Physical Devices: Sensors and Actuators
- With Embedded Electronics and Software
- Connected to the Internet
- Allowing exchange of information and interaction with the world

# The Maker Movement

**Make:**  
We are all Makers

PROJECTS ▾ STORIES ▾ EVENTS ▾ SHOP ▾ COMMUNITY

MAKE: PROJECTS

## Garduino: Geek Gardening with Arduino

Create an automated watering, light, and temp control system.

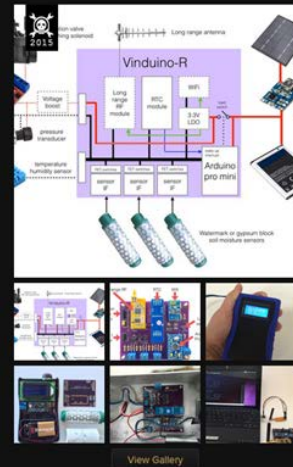
By Luke Iseman Time Required: A weekend Difficulty: Moderate



## Vinduino, a wine grower's water saving project

Monitoring soil moisture at different depths to determine when to irrigate, and - more importantly - how much water is needed. Save 25%!

 Benier van der Lee



### DESCRIPTION

If you want to save water, talk to a farmer. California farmers, including myself, target voluntarily to reduce agricultural water consumption by 25%. This reduction (25% of 42 million acre feet/year) is more than the annual urban water use (8 million acre feet/year), and is much more effective than any residential water reduction.

The Vinduino project started out of necessity to better manage irrigation in my Southern California vineyard.

Soil moisture monitoring systems have been around for decades, but they are costly to purchase, customize, and maintain.

I needed something rugged, scalable, and -added bonus- low cost.

The Vinduino project (Vineyard + Arduino) scope has broadened to sharing this project with a wider audience. This includes making it open source, affordable, and fast & easy to build.

Overall, 36 countries are now classified as severely drought affected. Hopefully this contribution will inspire and help you saving water too.

### DETAILS

Project goals

2018  
**Call for Makers**  
denver.makerfaire.com



# Open-Source Technology

---



# Open-Source: Making Technology Accessible to the Masses

Journal of  
open hardware

Pearce, JM 2017 Emerging Business Models for Open Source Hardware. *Journal of Open Hardware*, 1(1): 2, pp.1-14, DOI: <https://doi.org/10.5334/joh.4>

CHAPTER 1

ISSUES IN OPEN HARDWARE

## Emerging Business Models for Open Source Hardware

Joshua M. Pearce<sup>\*†</sup>

The rise of Free and Open Source models for software development has catalyzed the growth of Free and Open Source Hardware (also known as "Libre Hardware"). Libre hardware is gaining significant traction in the scientific hardware community, where there is evidence that open development creates both technical and financial benefits for scientific equipment development.

## Introduction to Open-Source Hardware for Science

### 1.1. INTRODUCTION

By any standard, the process of development and licensing for free and open-source software, which is discussed in Chapters 2 and 3, has been a success. Because of this success, the method is now being applied to hardware. Thus,

*Modern Instrumentation*, 2012, 1, 8-20  
<http://dx.doi.org/10.4236/mi.2012.12002> Published Online April 2012 (<http://www.SciRP.org/journal/mi>)



## Open-Source Hardware Is a Low-Cost Alternative for Scientific Instrumentation and Research

Daniel K. Fisher<sup>1</sup>, Peter J. Gould<sup>2</sup>

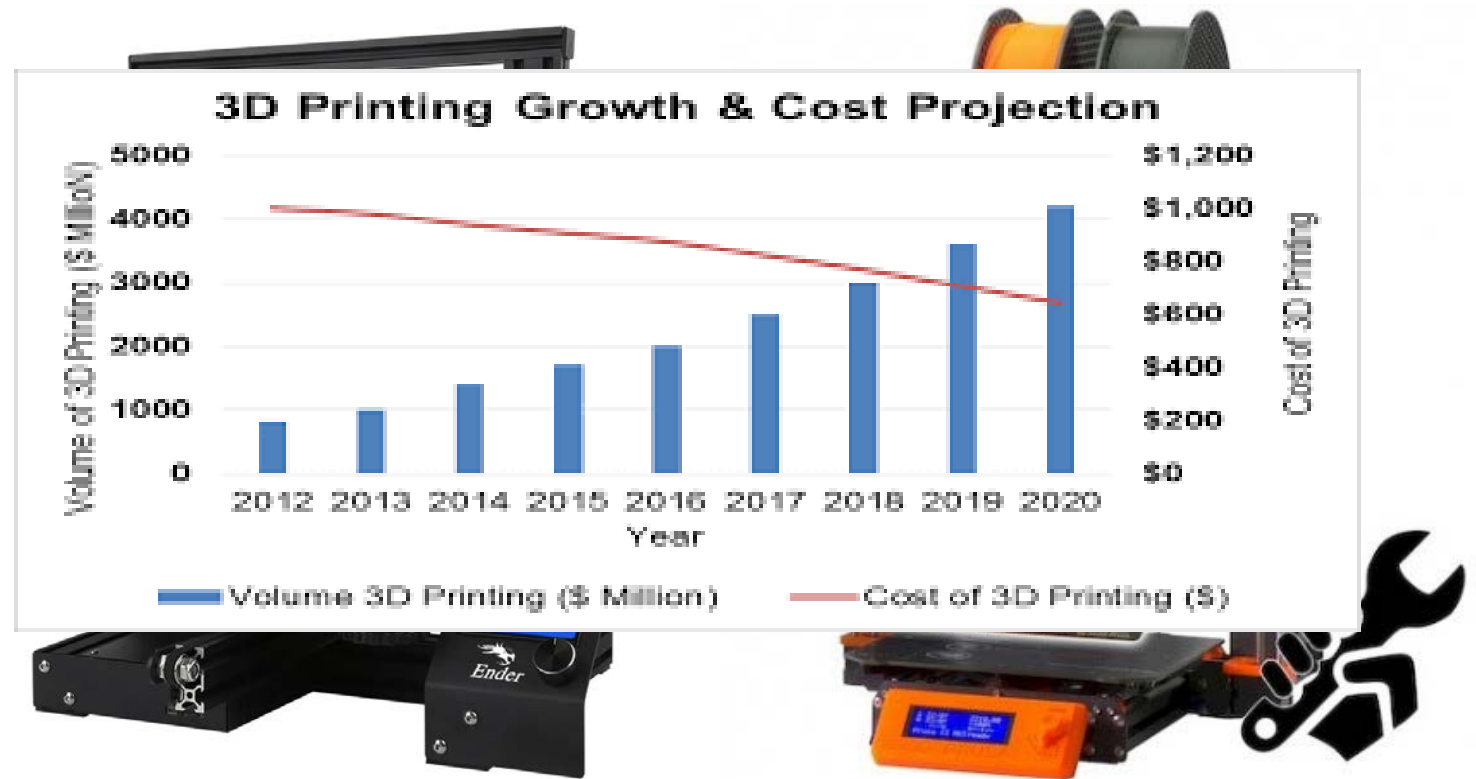
<sup>1</sup>USDA Agricultural Research Service, Stoneville, USA

<sup>2</sup>US Forest Service, Pacific Northwest Research Station, Olympia, USA  
Email: [daniel.fisher@ars.usda.gov](mailto:daniel.fisher@ars.usda.gov), [pgould@fs.fed.us](mailto:pgould@fs.fed.us)

Received January 29, 2012; revised February 28, 2012; accepted March 9, 2012

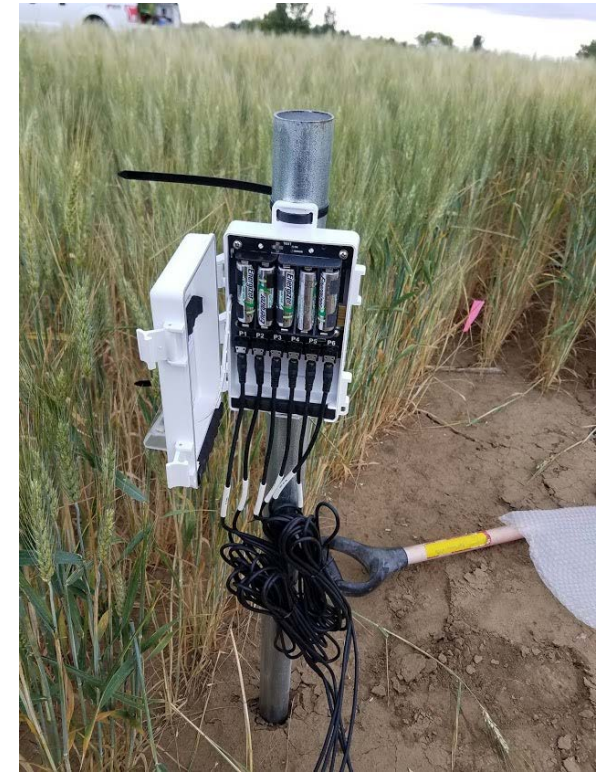
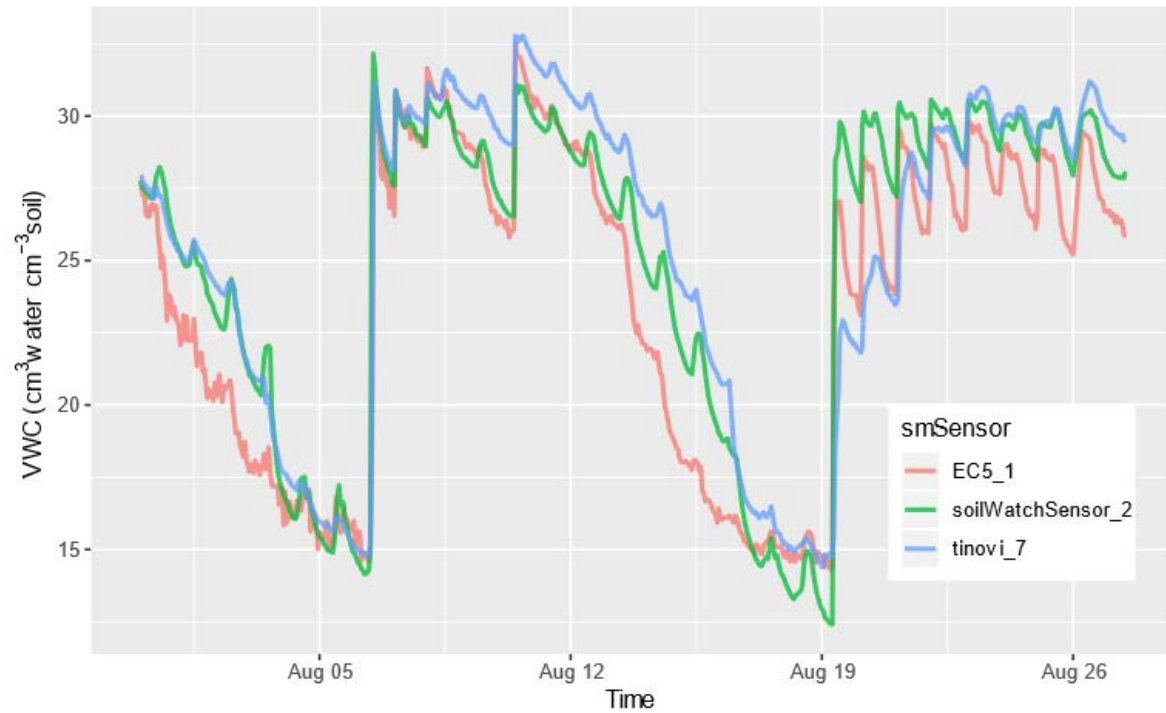
# Open-Source: 3d printing

- Modern 3-d printing technology exemplifies the benefits of open-source development.
- The last decade has seen rapid advancement in 3-d printer technology as popularity increases and the cost of manufacturing decreases.



# Open-Source: Making Technology Accessible to the Masses

---



J Jay ham



AGRICULTURE

## Smart Agriculture - More sleep for growers

bosch.com

Add comment

J Jay ham



BOULDER

## CU Boulder researchers lead team using drone technology to map soil moisture

By Charlie Brennan Staff Writer

University of Colorado Boulder students and faculty make the claim

Add comment

J Jay ham



FARMING

## Moo-ve fast and break things: Farmers are finding tech talent crucial for business

Lynsey Barber

Tech talent is becoming crucial for business, but its not just the hottest startups and forward thinking giants that are hankering after ...

Add comment

J Jay ham

QUANTUM MECHANICS

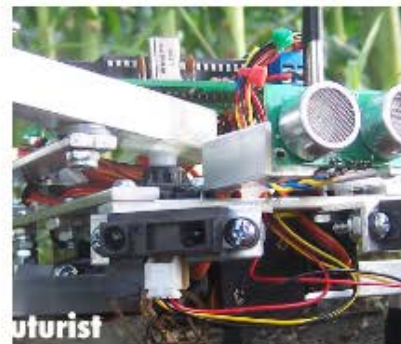
## A wheeled robot to monitor grape growth

phys.org

Just like great wine needs time, great grapes require continuous

Add comment

J Jay ham



AGRICULTURE

## Farmers in the future will "shepherd herds of robots"

Matthew Griffin

WHY THIS MATTERS IN BRIEF Robots sat in the doldrums for years without much happening but now, fuelled by AI and advance Machine vision capabilities ...

Add comment

J Jay ham

AGRICULTURE

## Transforming the bush: robots, drones and cows that milk themselves

The Guardian: Australia News - Paul Daley

Rural Australia is being progressively hollowed out of its people. Will it be reduced to a vast mechanised place of scant human

Add comment

# Irrigation

---

- ~20% of total crop land is irrigated
- Irrigated land accounts for almost half of total crop production (~47%)
- ~60% of cereal production



# Why should we care?

---

A few quick stats:

- 0.02% of Earth's total water supply is available as fresh surface waters
- 70-80% of the world's freshwater withdrawal is used for agriculture
- 25-30% of U.S. soils are affected by drought
- 40% of annual crop losses in the US are attributed to drought and water limitation

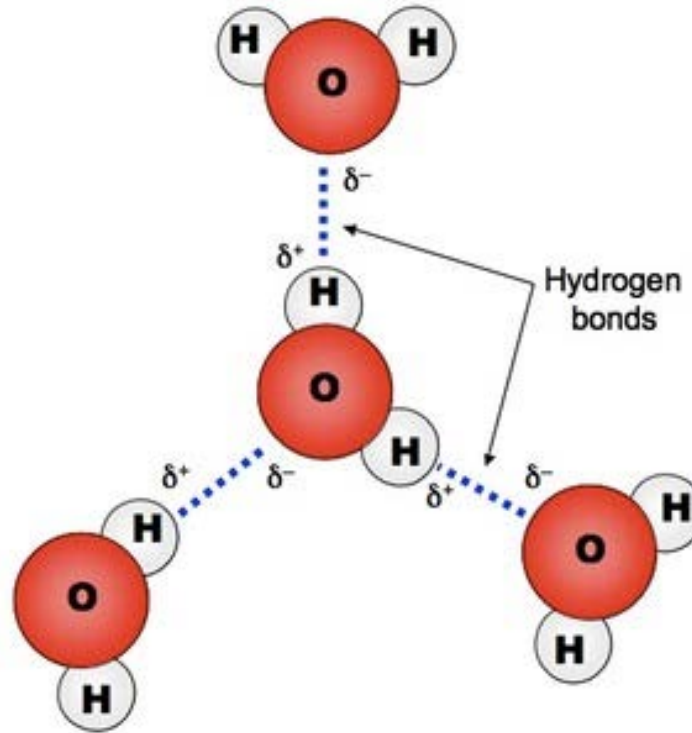




# PROPERTIES of Water

# Properties of Water

- Water's unique chemical properties make it essential for life on Earth.
- Polarity (unequal distribution of charge) causes water molecules to stick together and form strong hydrogen bonds (called cohesion).
- Water molecules are also attracted to other charged surfaces (adhesion).



## Hydrogen Bonding

A hydrogen bond is the attractive force between the hydrogen attached to an electronegative atom of one molecule.



## Water's Thermal Conductivity

Water expands as it freezes while other liquids contract. High thermal conductivity.



## High Heat Capacity

Water is able to absorb a high amount of heat before increasing in temperature.



## Cohesion

Holds hydrogen bonds together to create surface tension on water. Water is attracted to other water molecules.



## Surface Tension

Water molecules cling to each other. They create a strong tension on the surface which allows certain organisms to walk across it. Ex. Basilisk lizard



## Adhesion

Water is attracted to other molecules. Ex. Water droplets sticking onto leaves.



## Heat of Fusion

The energy required to change a gram of a substance from the solid to the liquid state without changing its temperature.



## Polarity

Unequal distribution of charge. Opposite charges are attracted to each other, so when there are lots of water molecules, they stick together.



## Heat of Vaporization

The quantity of heat that must be absorbed if a certain quantity of liquid is vaporized at a constant temperature.



## Solvent

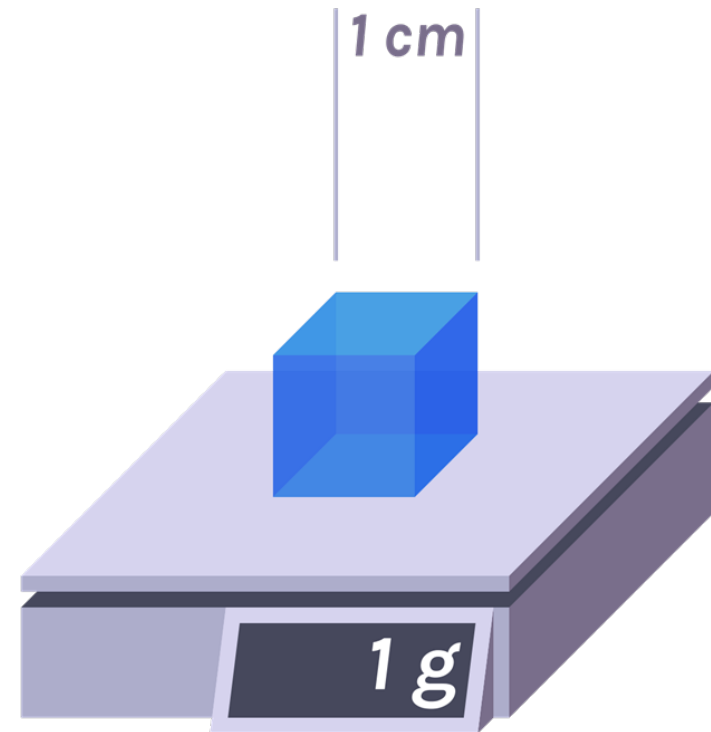
Water can dissolve lots of different substances which so it is considered a good solvent. Water is polar, which allows it to interact and dissolve many substances.



# Properties of Water

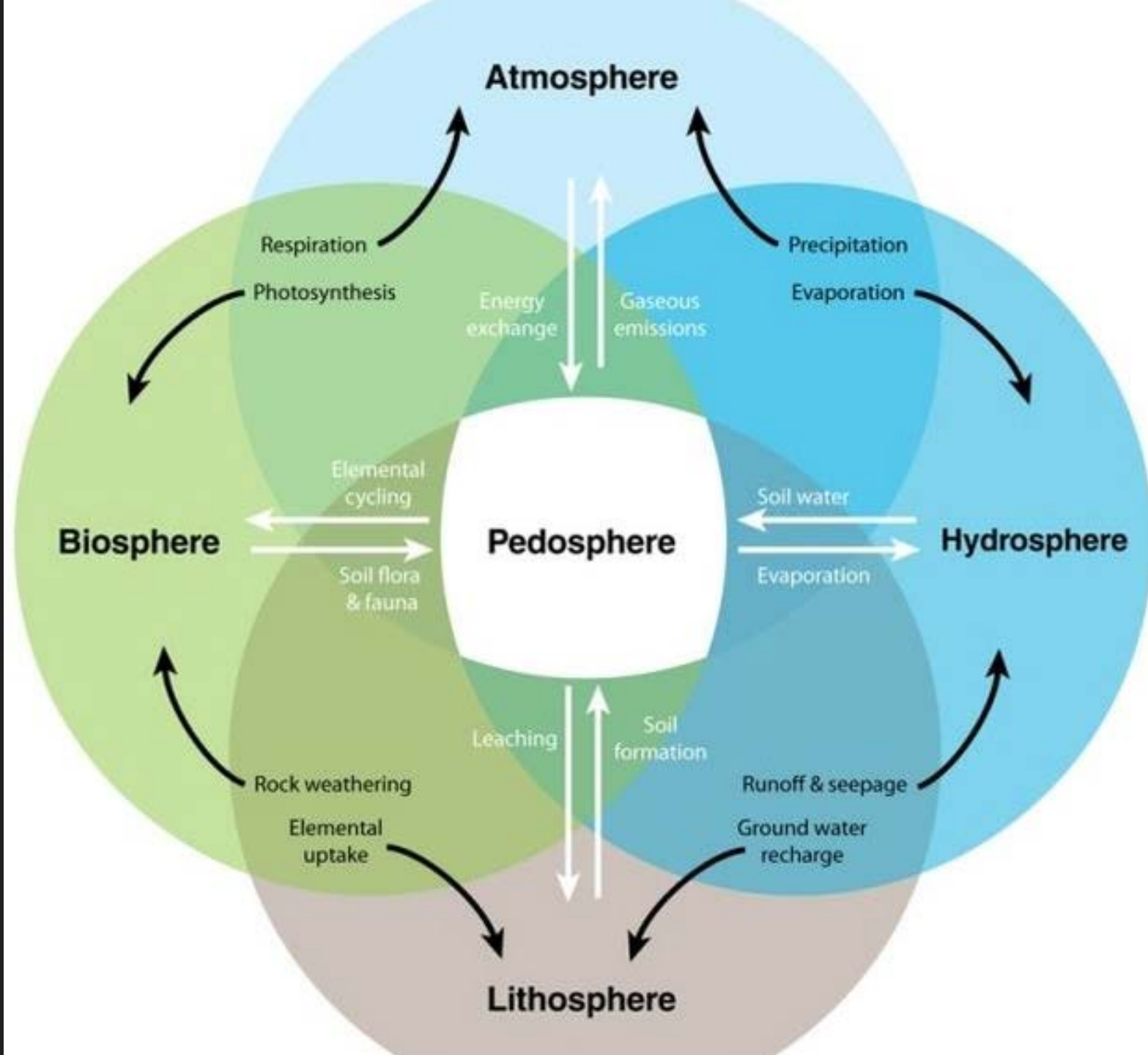
---

- Water has a density of  $1 \text{ g/cm}^3$
- One gram of water occupies one cubic centimeter of space
- $1 \text{ cm}^3 = 1 \text{ mL}$



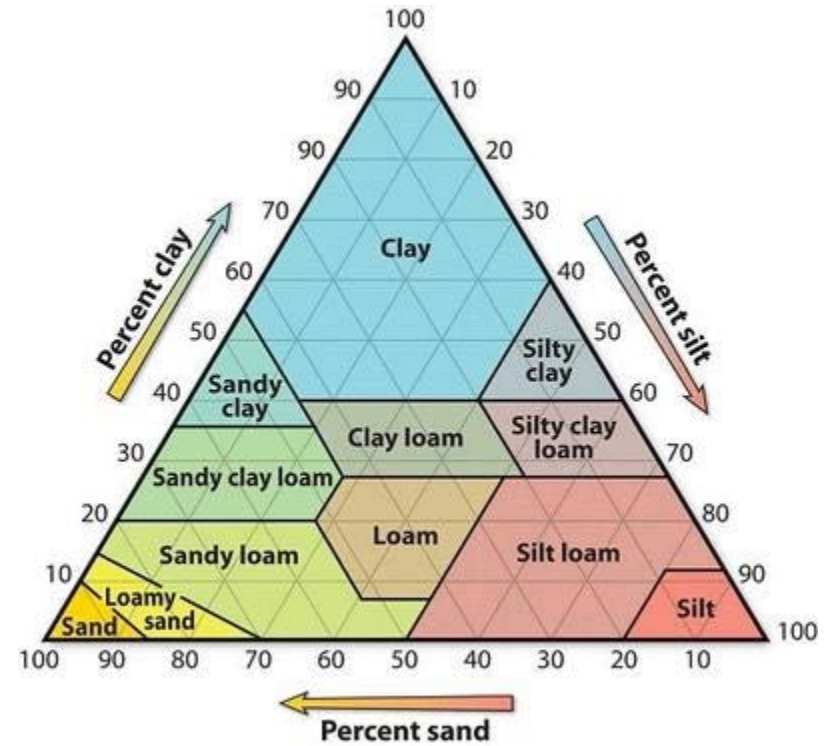
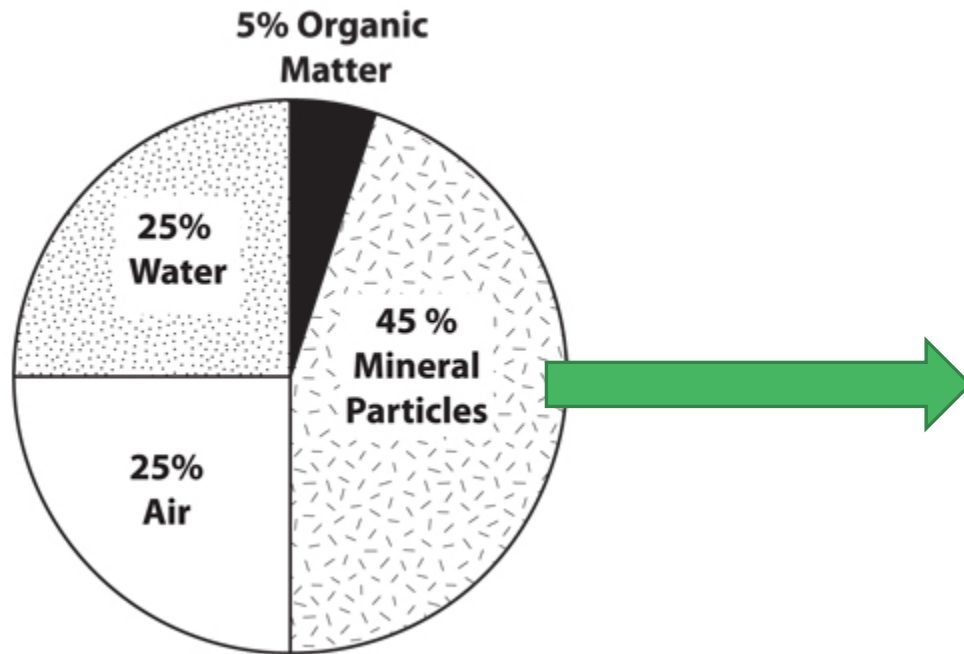
# What is Soil?

- A porous mixture of decomposing rock and organic matter that exists at the intersection of the atmosphere, hydrosphere, lithosphere and biosphere.



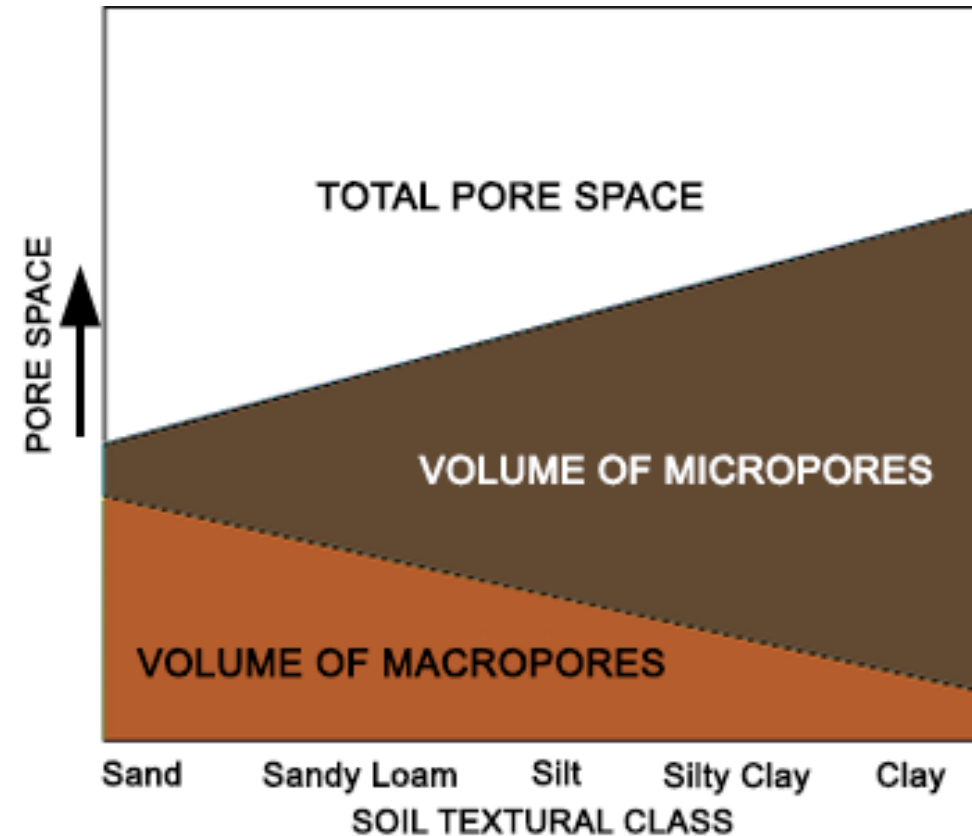
# Soil Composition

---



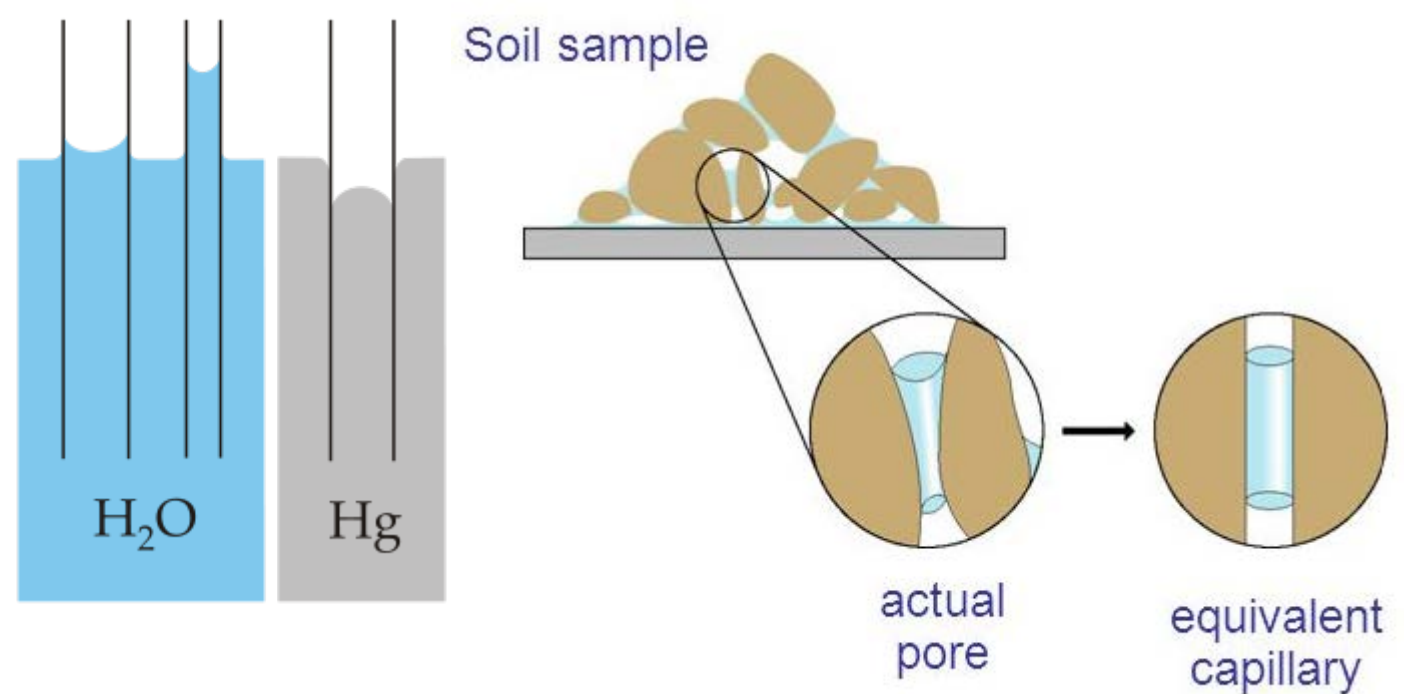
# Soil Texture – Pore Space Relationships

- Soil texture is a measure of particle size distribution in the soil; the relative amounts of sand, silt, and clay-sized particles that makes up a soil's mineral component.
- Texture is one of the most important soil properties that influences soil water storage and movement.

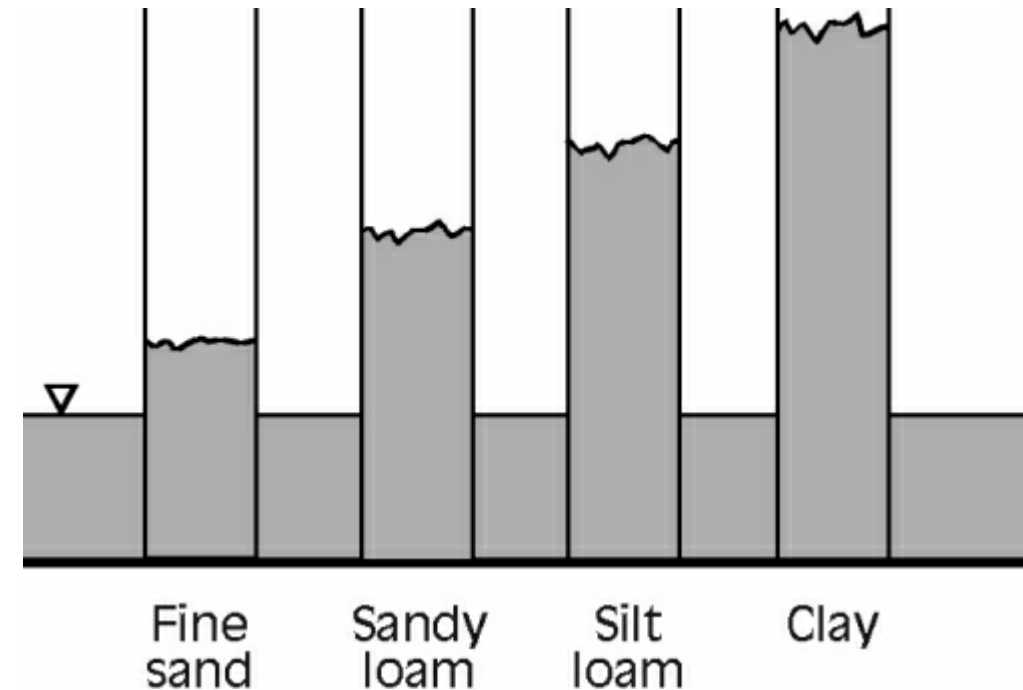


# Soil Pores

- Soil pores are the void spaces in between soil particles.
- We can think of soil pores like a bundle of cylindrical capillary tubes.
- Height of rise in the capillary tube is inversely proportional to the tube's radius.



$$h = \frac{0.15}{r}$$



# Bulk Density

---



Texture Class	Bulk Density (g cm <sup>-3</sup> )
Sand	1.65
Loamy sand	1.6
Sandy loam	1.55
Loam	1.5
Sandy clay loam	1.5
Silty clay loam	1.5
Silty loam	1.5
Clay loam	1.45
Silty clay	1.45
Sandy clay	1.4
Clay	1.35



# Particle Density

---

$$\text{Particle Density} = \rho_p = \frac{\text{mass of solids}}{\text{volume of solids}}$$

Typically 2.65 g/cm<sup>3</sup> for mineral soils (the density of mineral quartz, an abundant mineral in soils)



# Porosity

---

$$\text{Porosity (\%)} = \varphi = 1 - \frac{\text{bulk density}}{\text{particle density}}$$

Example: You have determined the bulk density of a soil to be 1.3 g/cm<sup>3</sup>, what is its porosity?

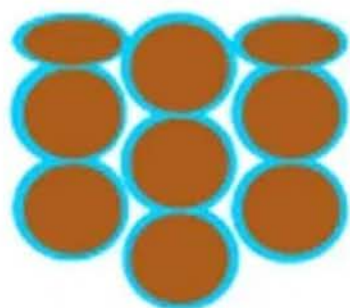
Follow-up: What is this soil's volumetric water content at saturation?

# Visualizing Soil Properties with a Sponge

- Infiltration
- Wetting front
- Percolation
- Drainage
- Capillary Rise
- Surface Runoff



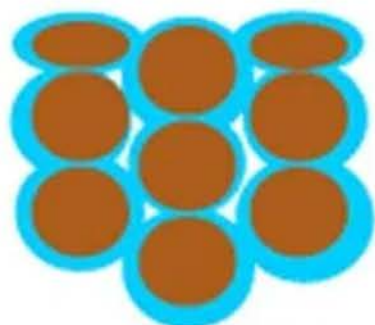
**Hygroscopic water**



Remaining water adheres to soil particles and is unavailable to plants

Wilting point →

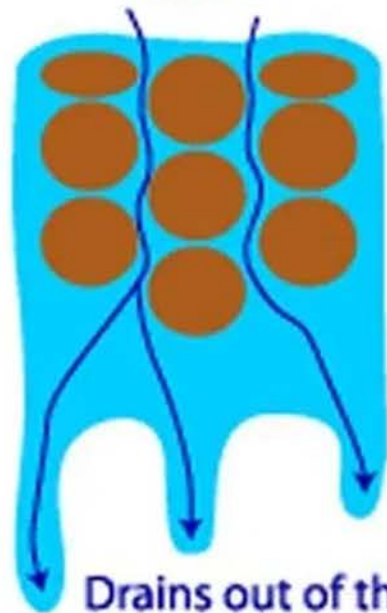
**Capillary water**



Water held in micropores

Available water-plant roots can absorb this

**Gravitational water**

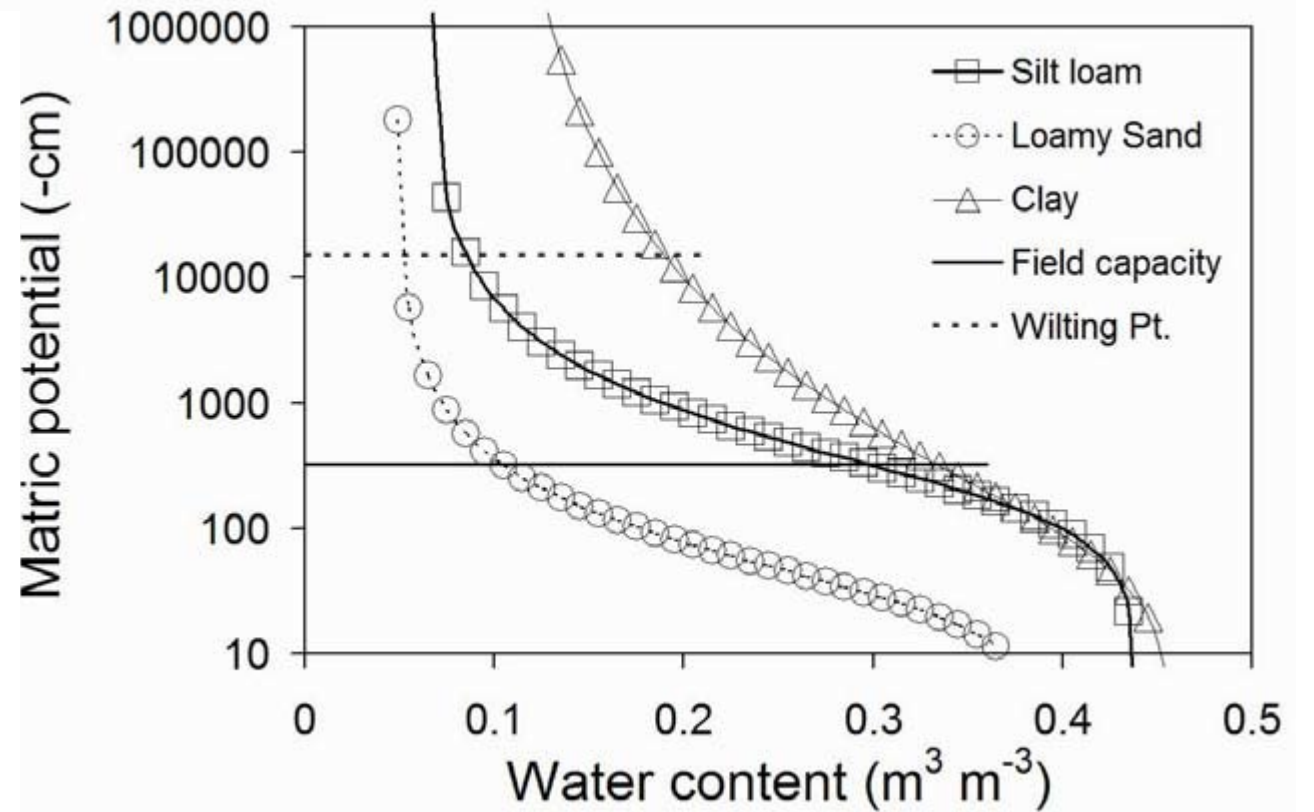
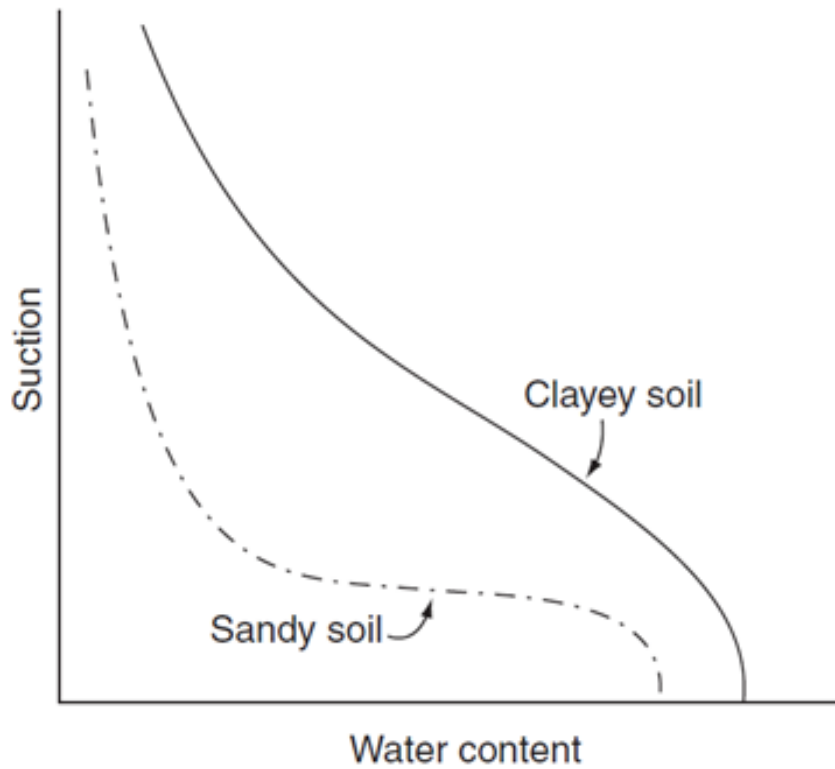


Drains out of the root zone

← Field capacity

**Available water for plant growth**

# Measuring Soil Water Status



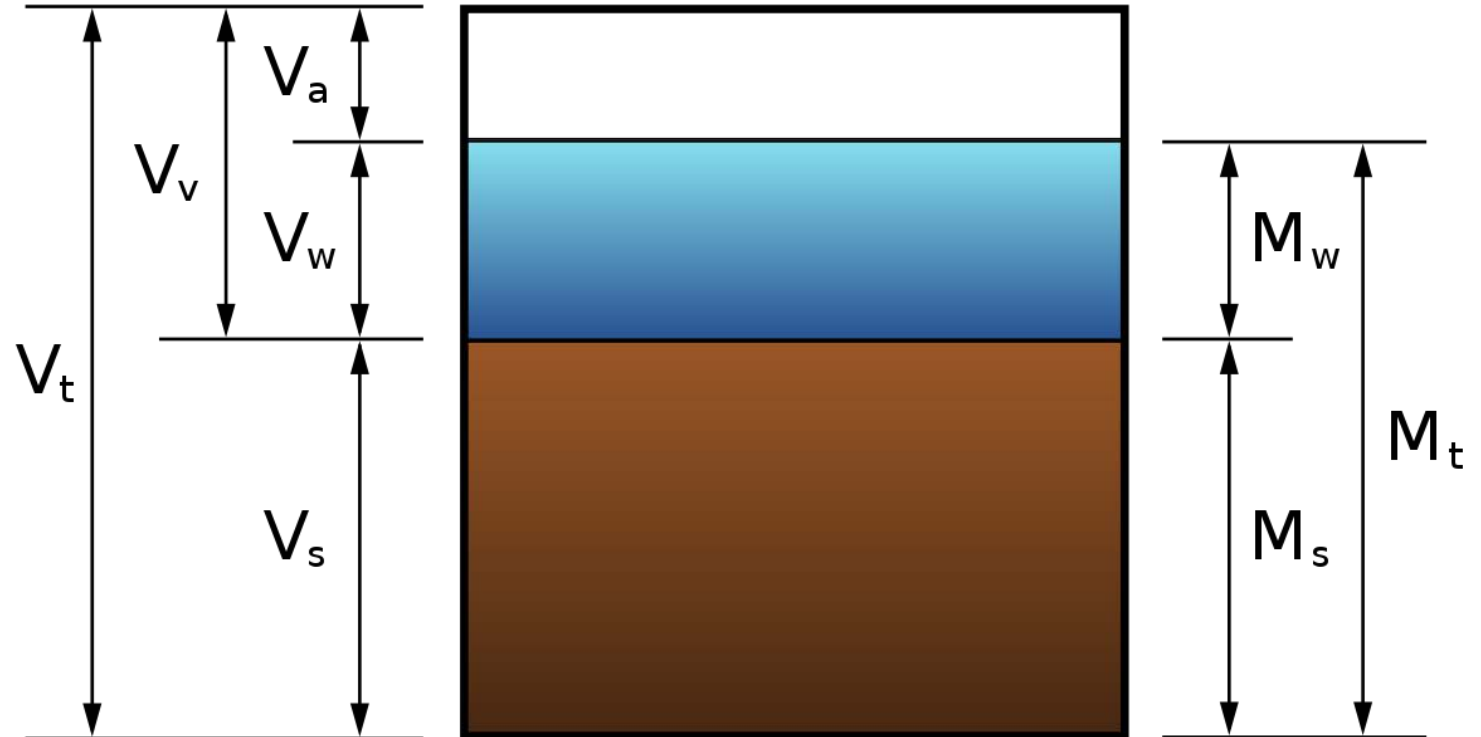
# Soil Water Content

Gravimetric water content:

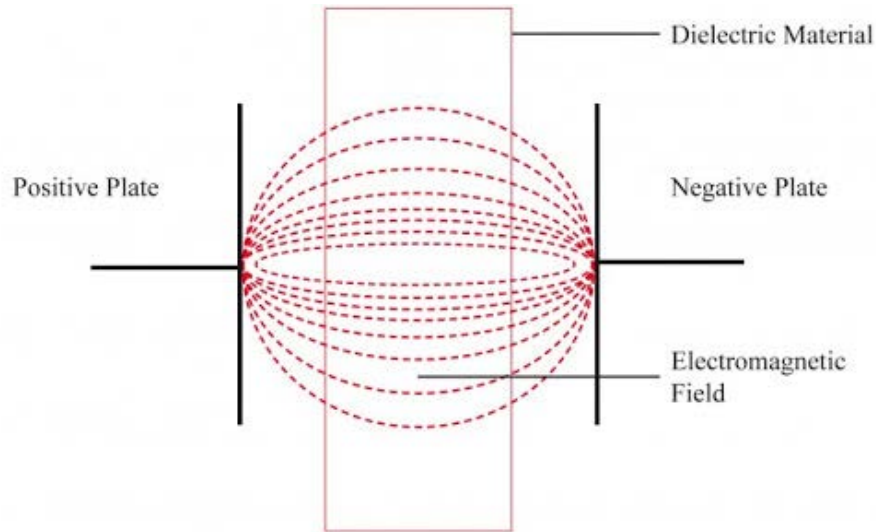
$$\theta_g = \frac{\text{mass of water}}{\text{mass of soil}} = \frac{\text{mass wet soil} - \text{mass oven dry soil}}{\text{mass oven dry soil}}$$

Volumetric water content:

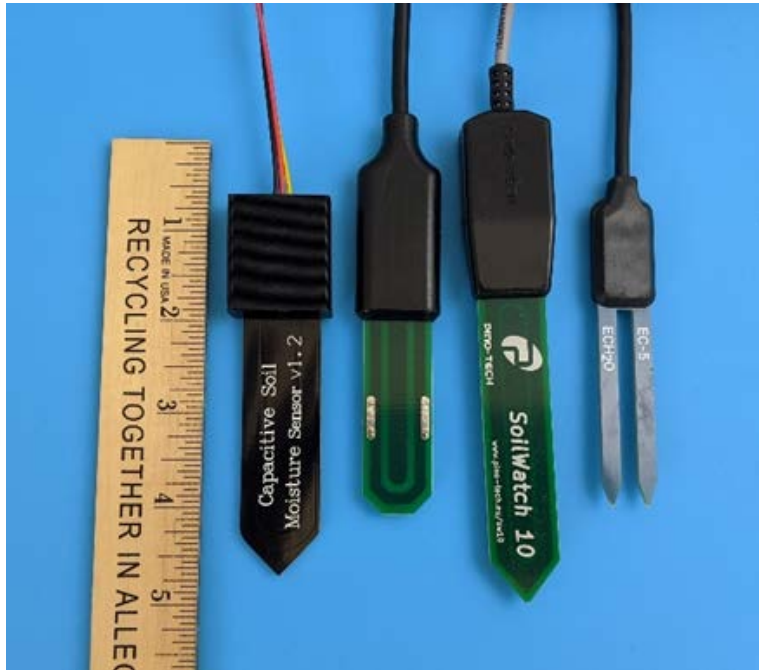
$$\theta_v = \frac{\text{water volume}}{\text{total soil volume}} = \theta_g \times \rho_b$$



# Capacitive Soil Moisture Sensors

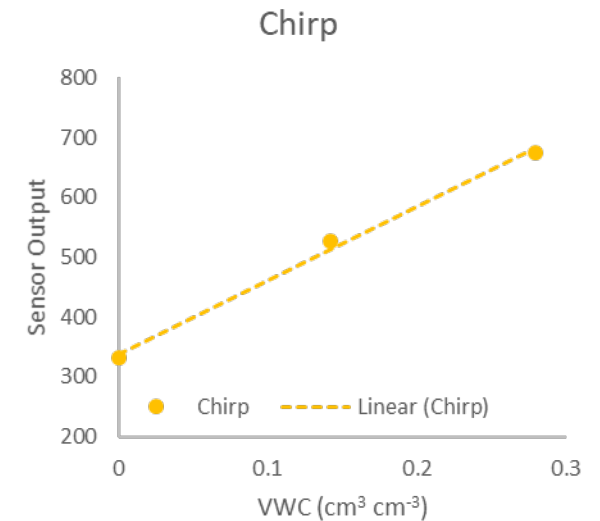
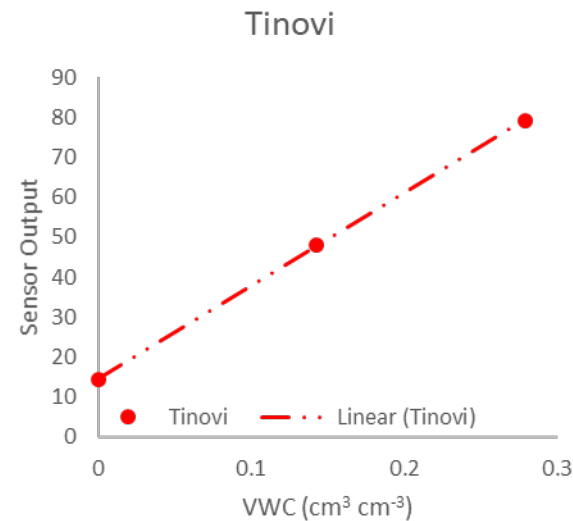
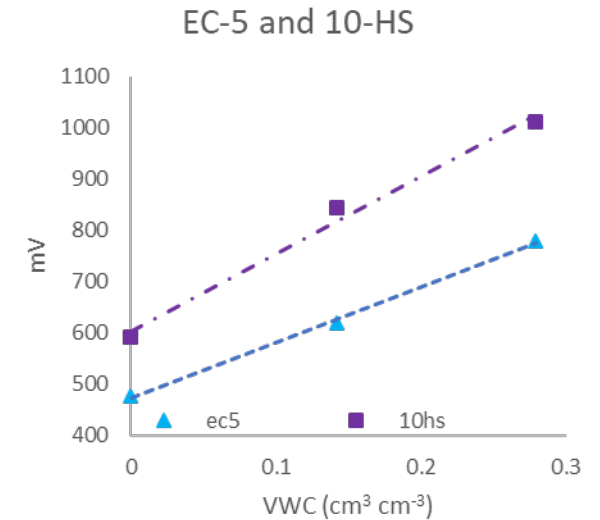
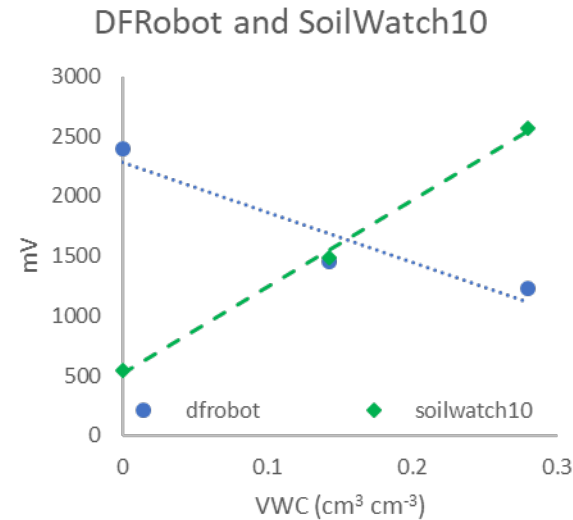


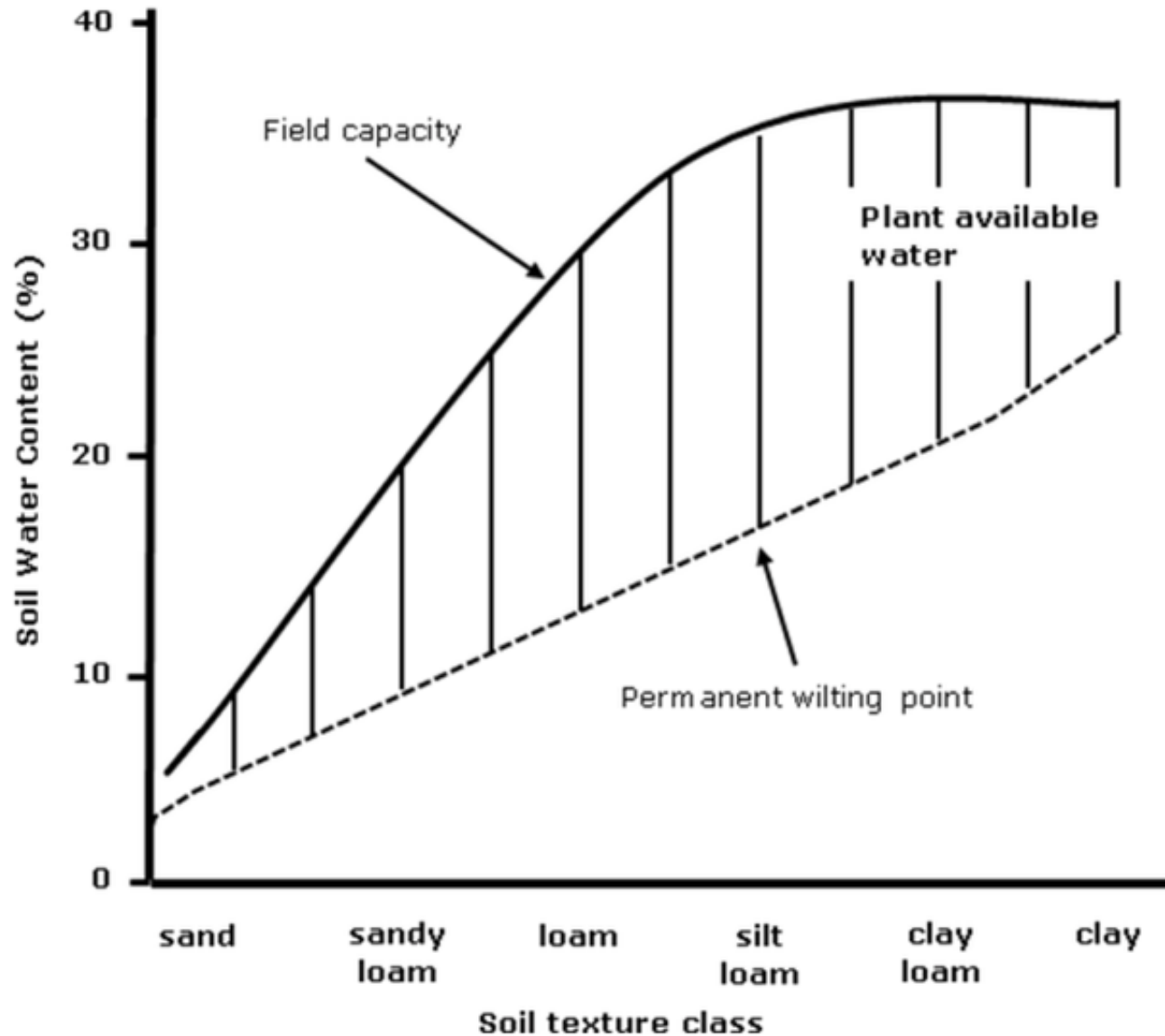
Capacitive sensors measure the dielectric permittivity of the material surrounding them—the dielectric constant of air is close to 0 F/m (Farads/meter), the dielectric constant of water is about 80 F/m



# Calibrating Soil Sensors with Direct Measurement of Soil Water Content

- Many soil moisture sensors return a voltage.
- In order to convert this voltage to a meaningful measurement of soil water content, we need to calibrate the sensors against a direct measurement (GWC or VWC).





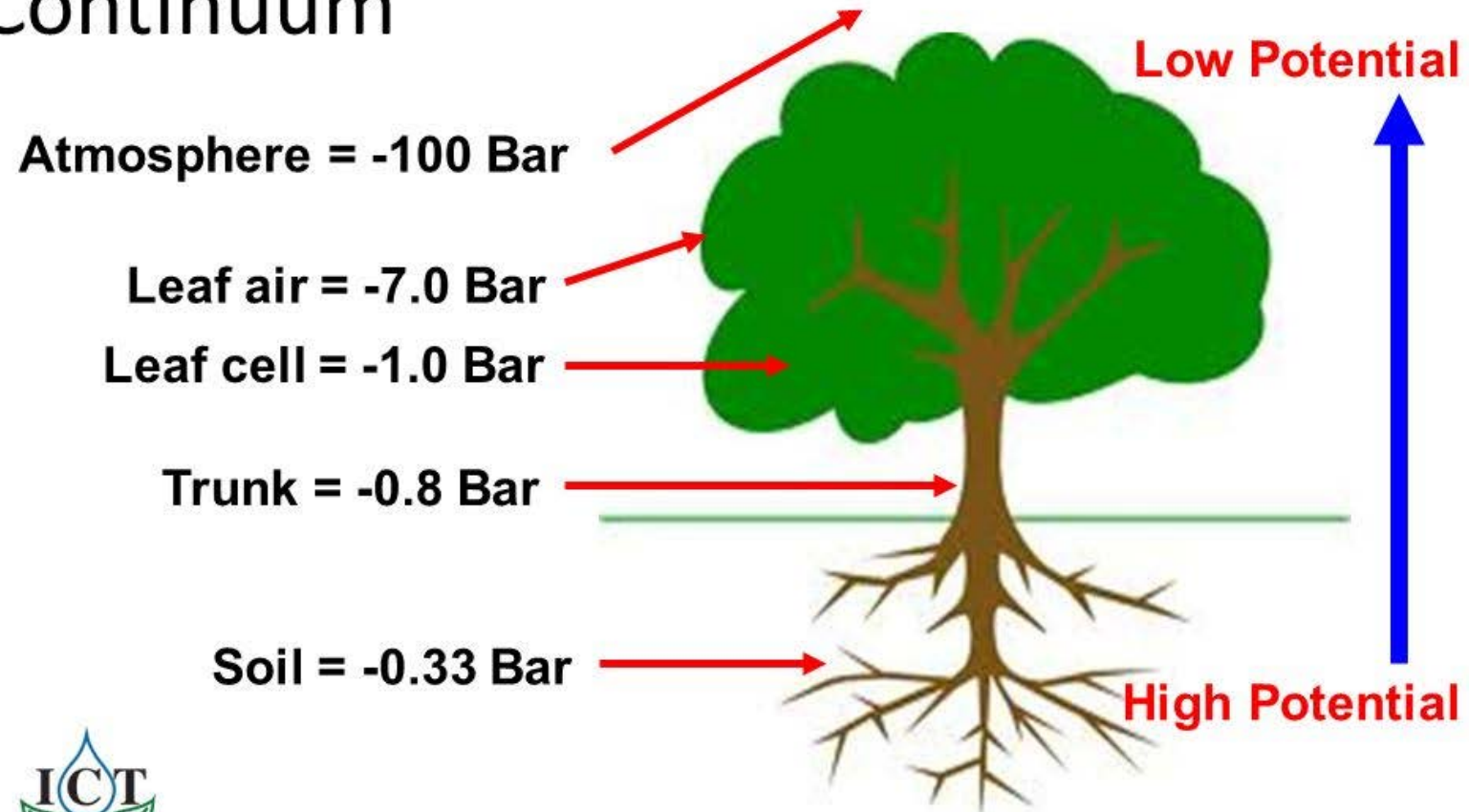
# Plant Available Water

- Plant available water, or available water content (AWC), is the amount of water held in soil between field capacity (FC) and permanent wilting point (PWP)
- $AWC = FC - PWP$

# Evapotranspiration

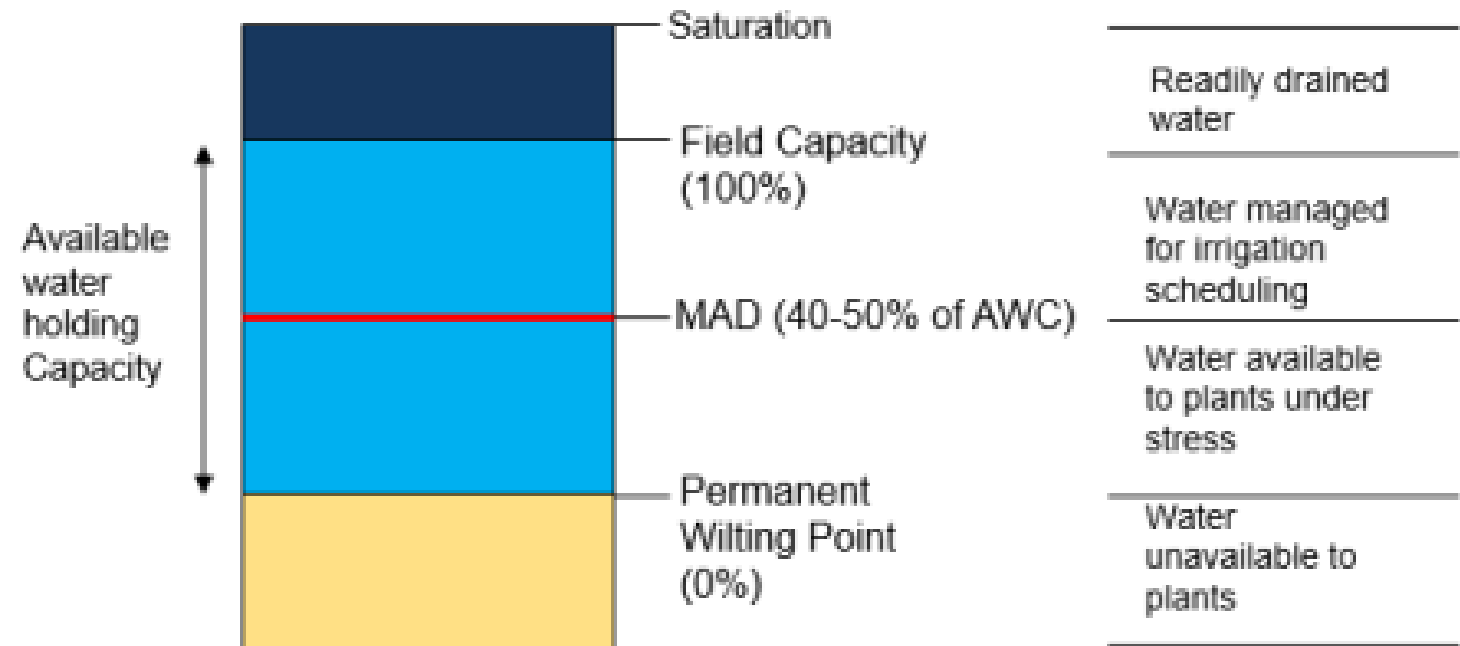
- The sum of water lost from the soil by evaporation and transpiration processes
- Soil-Plant-Atmosphere continuum: Water moves along a gradient from high potential (wet soil) to low potential (dry air).

## Soil-Plant-Atmosphere Continuum



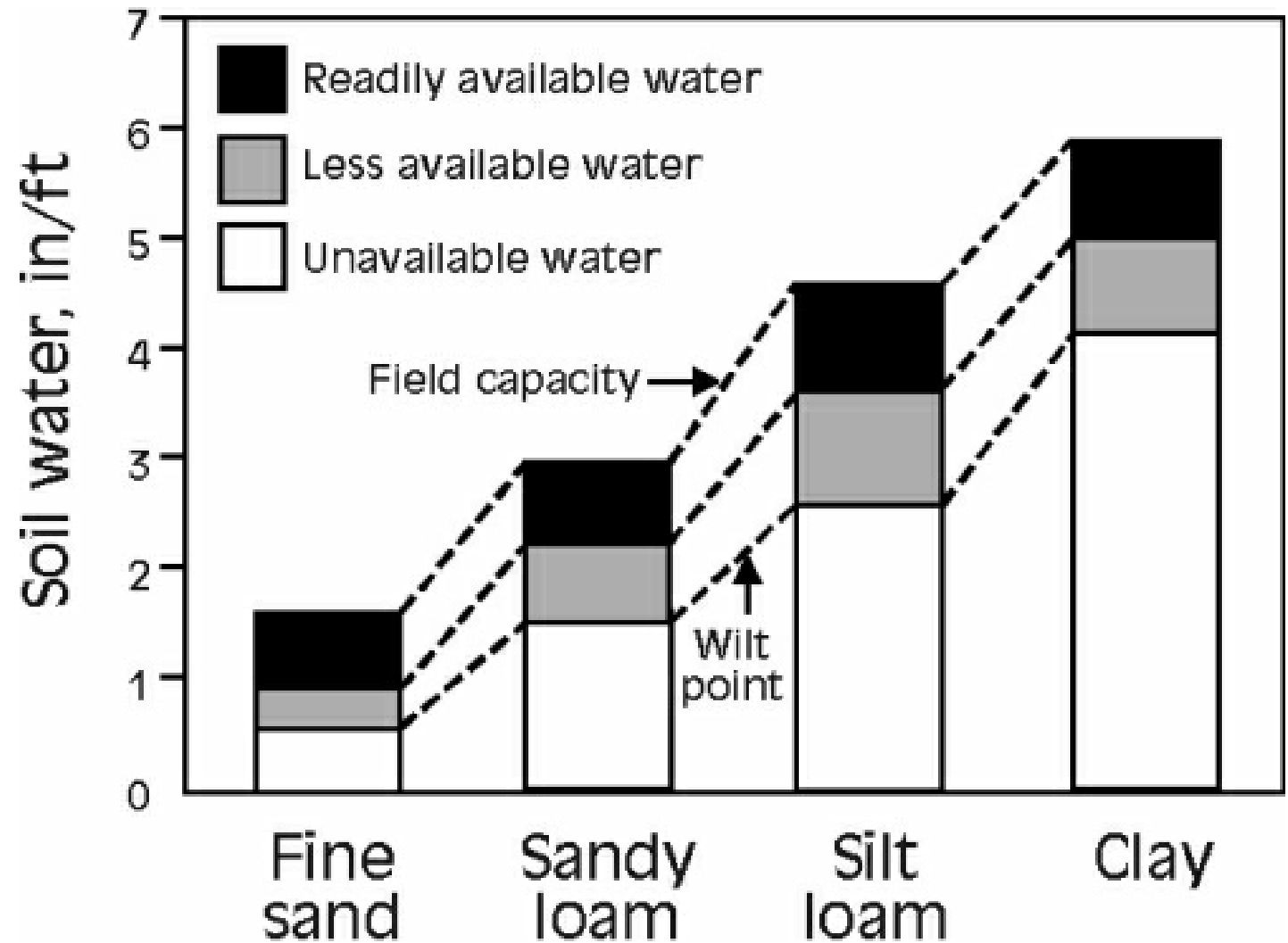
# Management Allowable Depletion

- Management allowable depletion (MAD) is the amount of water that plants can extract from the soil before incurring a yield penalty from water stress.
- MAD is typically between 30-60% of field capacity, depending on plan species.
- [FAO table for MAD by crop type](#)



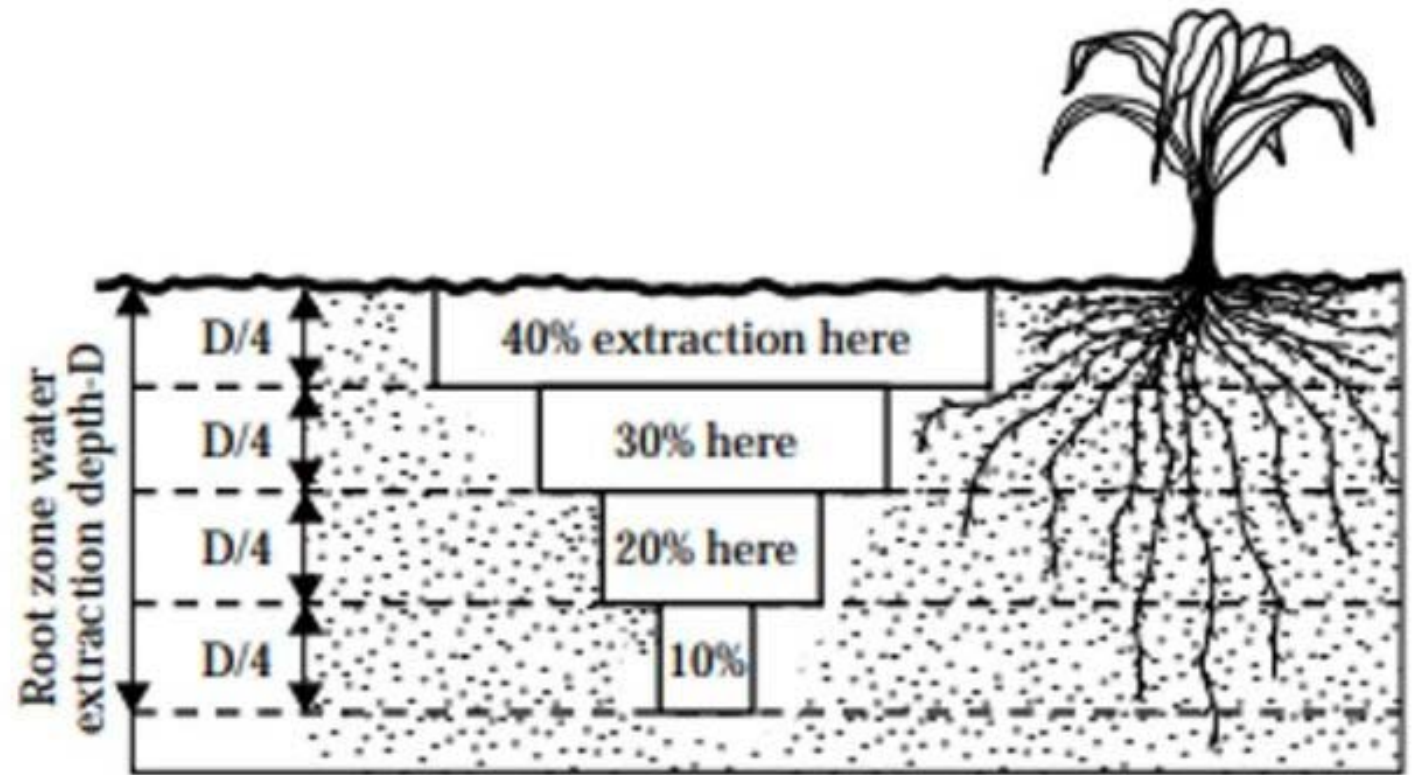
# Readily Available Water

- Readily Available Water (RAW) is the fraction of AWC that a crop can extract from the root zone without suffering water stress (FAO)
- $RAW = MAD \times AWC$



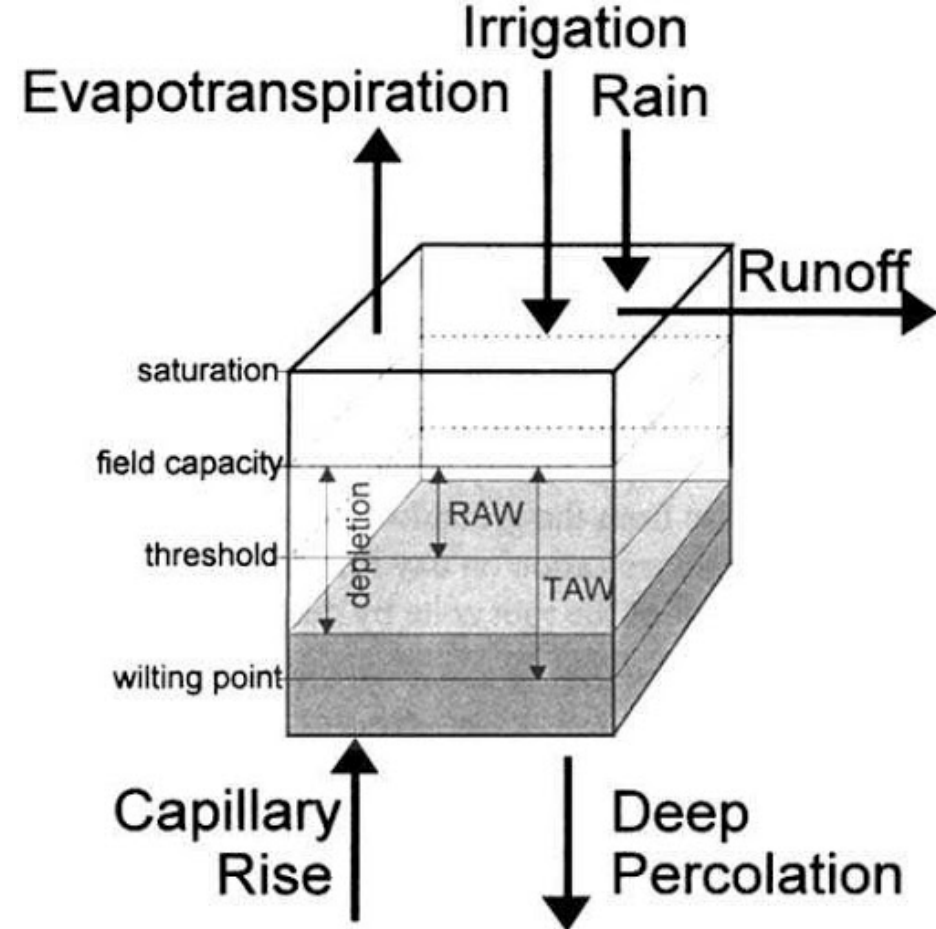
# Gross Irrigation Water Depth and Root Zone Depth

- Gross irrigation water depth (IG) is how much water needs to be applied during irrigation to replenish the soil profile. IG is measured in length units (in/ ft or cm/ m)
- Root Zone depth is measured in length units (in/ ft or cm/ m) – [FAO Table](#)
- $IG = MAD \times AWC \times RZ$
- $IG = RAW \times RZ$



# Irrigation Scheduling

- Typically, we try to estimate soil water content using a water balance approach that is based on weather data.
- This approach works well if the weather data is accurate, but spatial variability in weather patterns (especially precipitation) leads to errors.



$$D_{r,i} = D_{r,i-1} - (P - RO)_i - I_i - CR_i + ET_{c,i} + DP_i \quad (85)$$

where

$D_{r,i}$  root zone depletion at the end of day  $i$  [mm],

$D_{r,i-1}$  water content in the root zone at the end of the previous day,  $i-1$  [mm],

$P_i$  precipitation on day  $i$  [mm],

$RO_i$  runoff from the soil surface on day  $i$  [mm],

$I_i$  net irrigation depth on day  $i$  that infiltrates the soil [mm],

$CR_i$  capillary rise from the groundwater table on day  $i$  [mm],

$ET_{c,i}$  crop evapotranspiration on day  $i$  [mm],

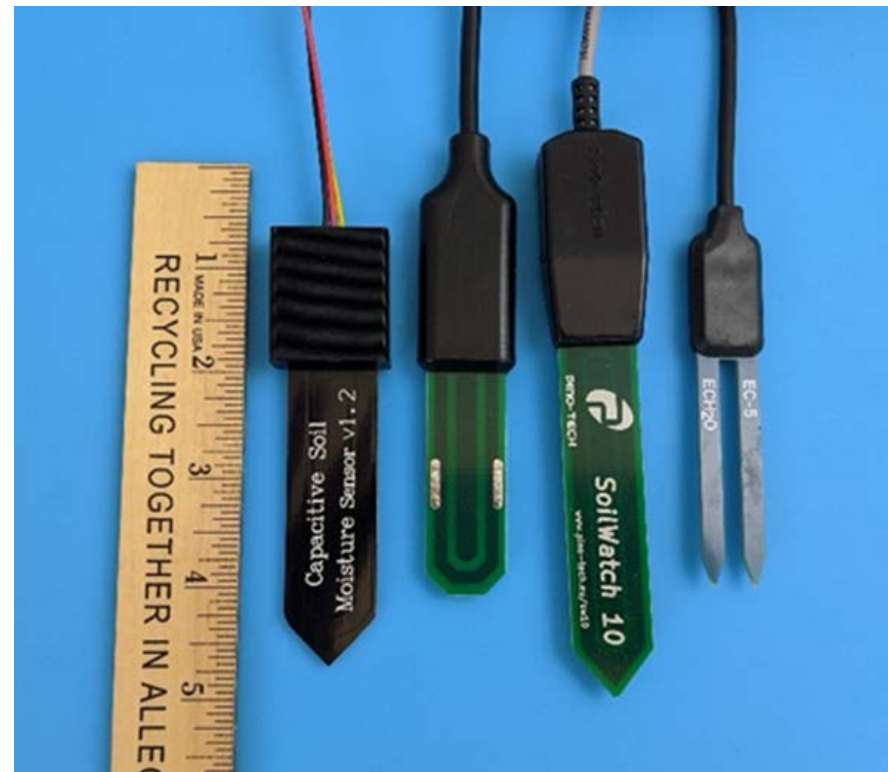
$DP_i$  water loss out of the root zone by deep percolation on day  $i$  [mm].

# Why not just measure soil moisture?

- Soils are spatially and temporally heterogeneous, so many soil moisture sensors are needed to get a good estimate of soil moisture in a field.
- Sensors have historically been too expensive to be able to instrument fields with them in adequate numbers.

**“Controlling an irrigation system without soil moisture sensors is like driving a car without a gas gauge” – Dana Lonn, Toro**

**“You can’t manage what you can’t measure!” - Peter Drucker**



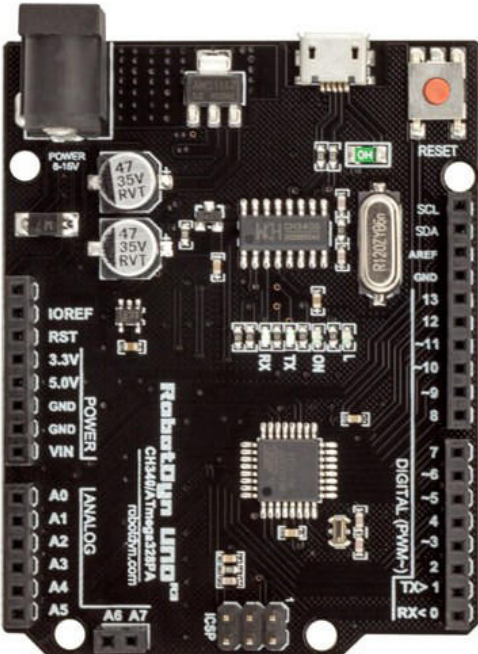
These sensors range in price from \$1/unit to \$120/unit.

We have found that mid-range sensors (\$20) compare well with research grade alternatives.

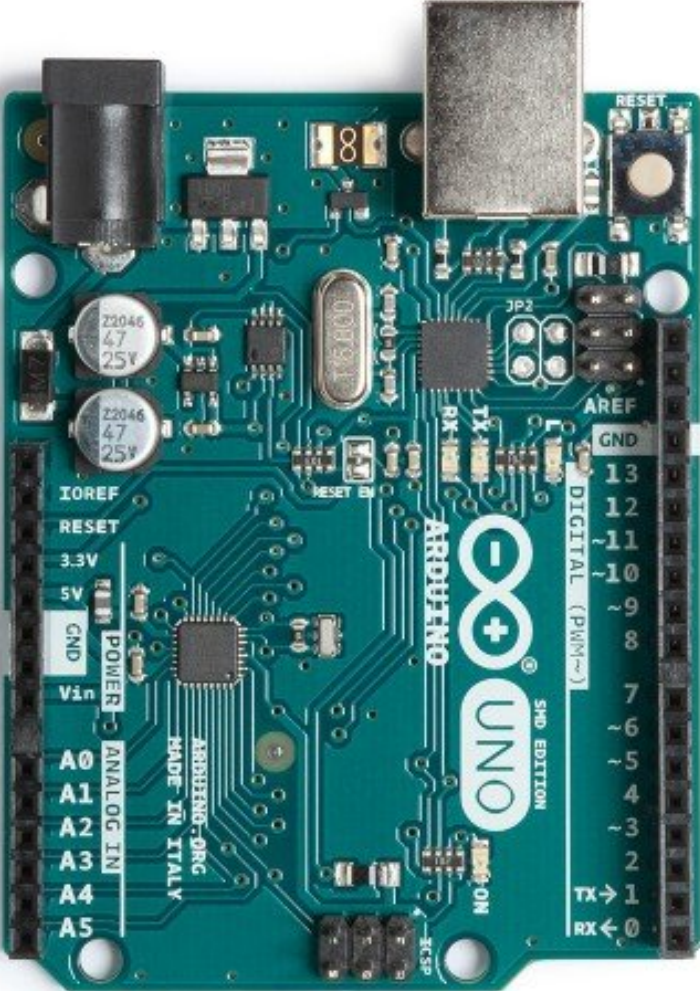
# Arduino is an Open-Source Microcontroller Platform

ATmega328

Footprint (board layout)

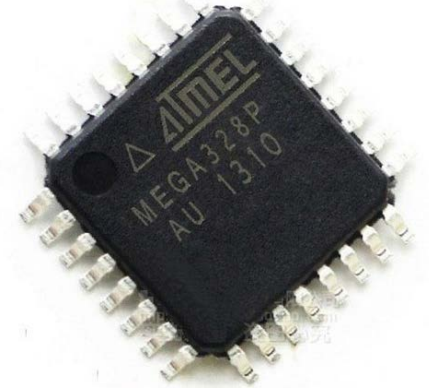
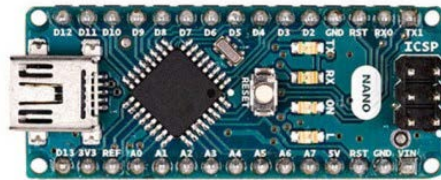
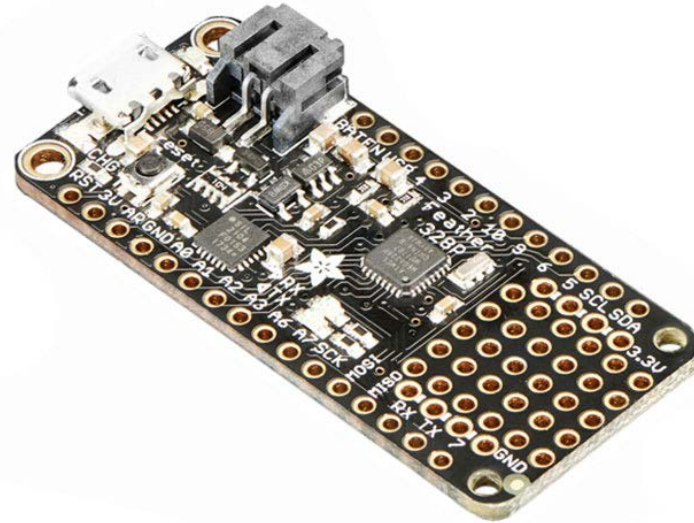
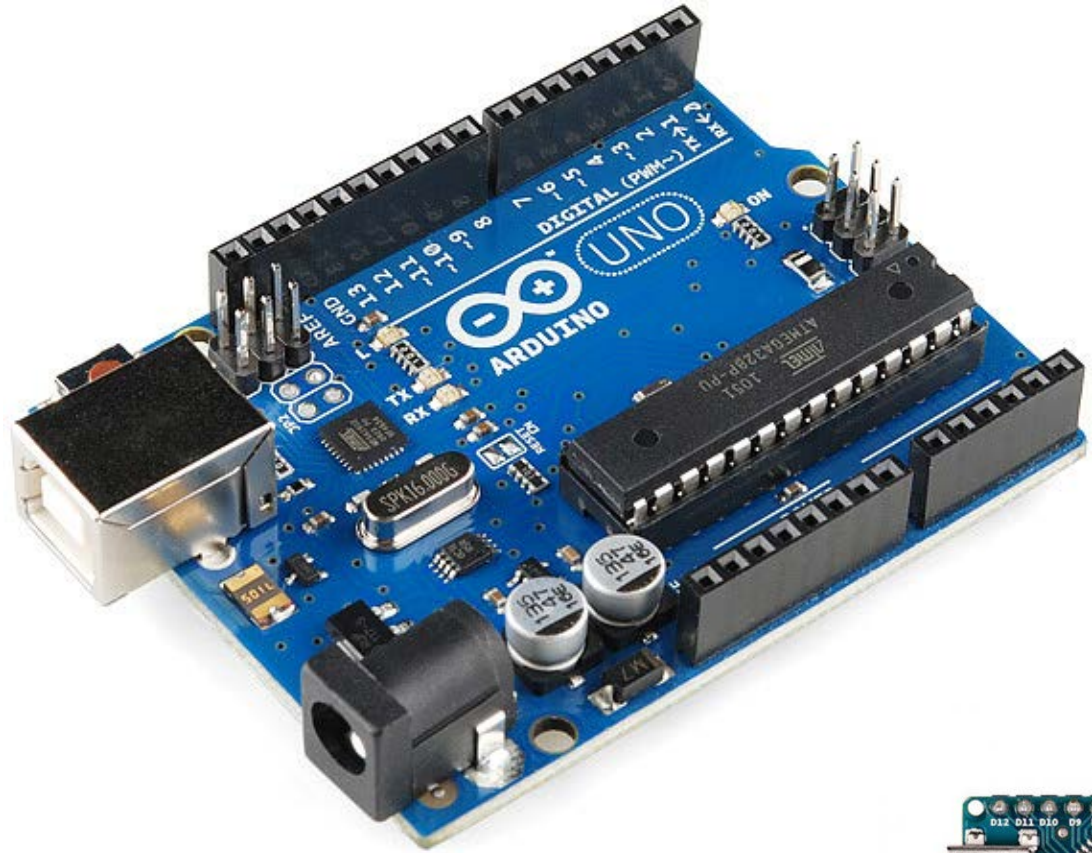


RobotDyn "Uno"

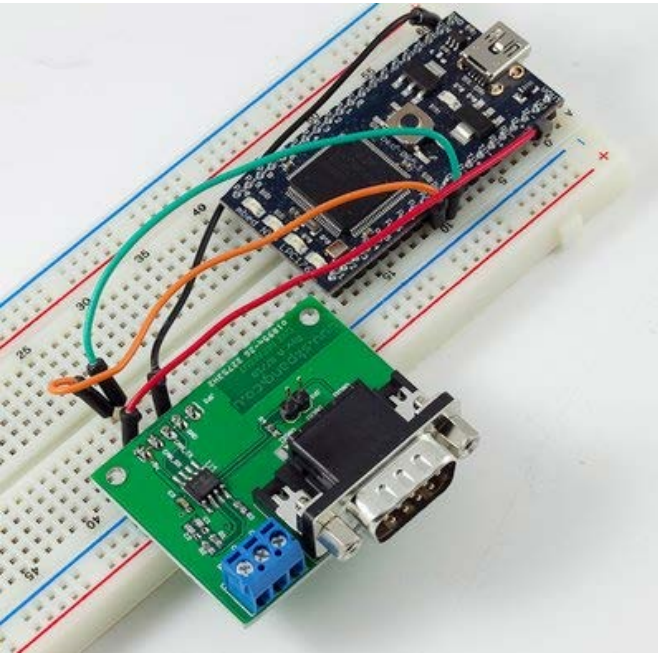
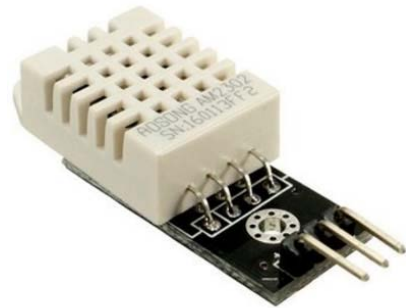
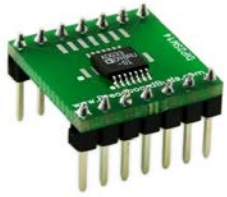


Official Uno

# Comes in Many Different Shapes and Sizes

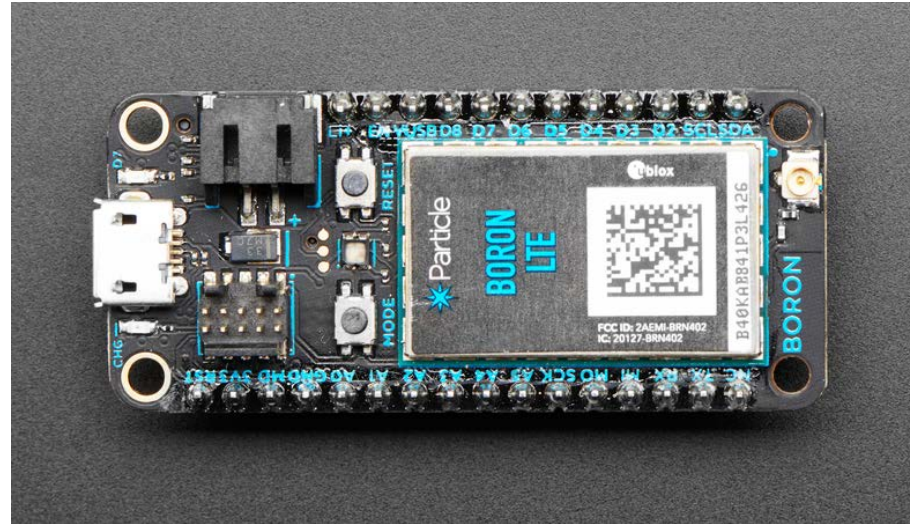


# Breakout Boards and Shields



# Connectivity Options with More Advanced Boards

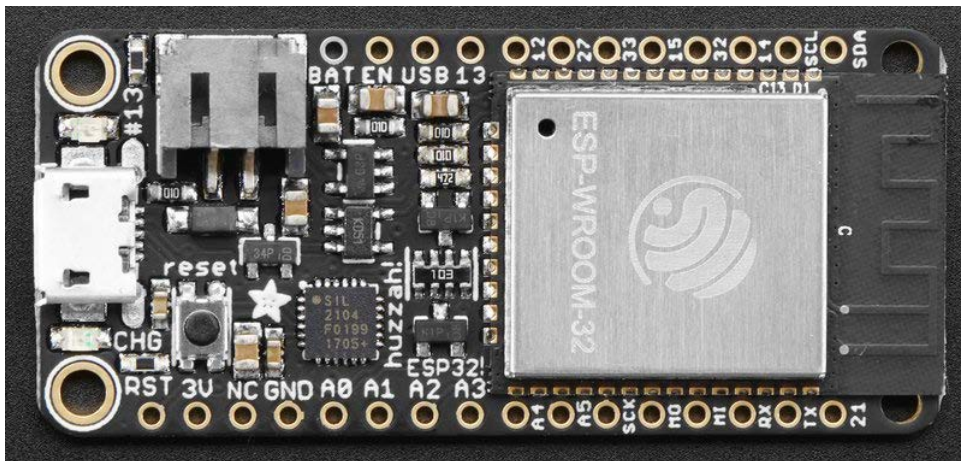
Processor: ESP32  
Footprint: Feather  
Connectivity: BLU and WiFi  
Creator: Adafruit



Processor: ATmega328p  
Footprint: Custom  
Connectivity: LoRa (Radio)  
Creator: Moteino



Processor: ARM Cortex-M4F  
Footprint: Feather  
Connectivity: Mesh and Cellular  
Creator: Particle



# Arduino Resources, References and Projects

- <https://www.adafruit.com/>
- <https://www.sparkfun.com/>
- <https://www.arduino.cc/>
- <https://www.particle.io/>
- <https://www.dfrobot.com/>
- <https://www.seeedstudio.com/>
- <https://www.hackster.io/>
- <https://www.instructables.com/>

