SOIL PHYSICS 101

Soil health, defined as the sustainable capacity of soil to support vital living systems, often focusses on soil biology. While the role of microbes, critters and organic matter is well-documented and indisputable, we cannot only focus on the inhabitants and ignore the house. Soil structure (the house) is also critical for soil health. By Paulette Baumgartl

KEY POINTS

- Taking care of the physical properties of soil is crucial for sustainable and profitable potato farming.
- Soil physics examines the abiotic characteristics of soil and how solid, liquid, and gas components interact.
- Soil composition is key - the proportion of fine particles determines how the soil behaves.
- The composition and characteristics of soil aggregates significantly influence interactions among soil, water, and gases.
- Soil texture and structure determine the water-holding capacity and infiltration rate of the soil, impacting its ability to provide water to plants.
- **Field capacity** is the maximum amount of water that a soil can hold
- **Permanent wilting point** indicates the lower limit where water becomes unavailable to plants.
- The range between field capacity and the refill point is known as the **readily available water (RAW)** zone, which is essential for optimal plant growth.
- Infiltration, runoff, and erosion are influenced by various forces such as gravity, adhesion, cohesion, and capillary rise.
  - **Adhesion** and **cohesion** allow soil to retain water within its pores
  - **Capillary rise** enables water movement upwards in narrow spaces, particularly in clay soils.
  - Monitoring **infiltration rates** provides valuable information about soil structure and the impact of soil management practices on water movement into the soil.
- **Compaction** occurs when external forces press soil particles together, reducing pore space and increasing soil density.
  - Factors like clay content and moisture level influence the ease of compaction.
  - Compaction limits root penetration, reduces water-use efficiency, reduces nutrient retention and availability, increases fuel consumption and decreases machinery effectiveness.
  - Compacted areas can be restored through mechanical and biological approaches.

Coyne et al. (2022) compared a soil ecosystem to a neighbourhood; soil physics concerns itself with the infrastructure (aggregation) and services (aeration, hydration), while soil chemistry focusses on the catering. Microbial residents interact with, and shape, both the physical and chemical properties of the soil they inhabit.

Understanding and managing the interacting components of soil health - physical, biological and chemical factors - is essential to create robust and productive soils that are able to sustain commercial potato production.

The following article examines some aspects of soil physical properties and how they impact agricultural practice (and how agricultural practices impact soil physical properties).

SOME BASIC THEORY FOR A COMPLEX TOPIC

Soil physics studies the abiotic characteristics of a soil ecosystem and how they interact. These include the solid, liquid and gas components of the soil, referred to in science as soil phases. The interaction among these phases determines the behaviour and functionality of soil, and therefore the soil's ability to support life.

A well-structured soil under a cover crop at Mulgowie Farm in Queensland's Lockyer Valley

Soil solids include mineral and organic particles. Typically, soil solids occupy 50% of the soil volume, however solids can range from 40 to 70%.

Mineral particles are grouped into fine (sand, silt and clay, less than 2mm) and coarse (gravel, stones etc and greater than 2mm) fractions. The proportion of fine solids determines soil texture and, ultimately, the way the soil behaves.

Organic materials, including living fungi and plant residues, together with ions such as calcium, glue and bind mineral particles together to form aggregates. The composition and characteristics of these aggregates has a large impact on soil, water and gas interactions.

Soil aggregation and structure

Soils can be grouped broadly into structureless and aggregated.

Structureless soils lack visible aggregates. They are dominated by sand or clay, limiting bonding and/or resulting in poor water infiltration.

Structured soils consist of distinct aggregates that can be characterised by their shape and size.

A well-structured soil has sufficient pores (good pore volume) of differing sizes (good pore size distribution) between and within aggregates. This allows water and air to enter easily. Structured soils drain easily, while still holding enough moisture to maintain plant growth.

Poorly structured soil lacks aggregates and has few pores between soil particles.

Aggregation begins when tiny, highly reactive clay particles interact with organic residues. These bind larger sand and silt particles together to form microaggregates. Fungal hyphae and fine plant roots then bind soil micro-aggregates together into the macro-aggregates visible to the naked eye (Figure 1).

The remaining 50% of soil is pores, which are filled with water or gas. While the amount of liquid in soil can vary between <1% (completely dry) to approximately 50% (saturated, with all pores filled with liquid), in ideal conditions liquids occupy 25% of the total volume of soil, with the remaining 25% of pores filled with air.

Soil chemistry and soil structure

Just as soil biology will impact the physical structure of a soil, so too can soil chemical properties, particularly sodicity and salinity.

As the name suggests, sodicity is the presence of a high proportion of sodium relative to other cations. As sodium salts are leached through the soil, a high proportion of sodium (Na) ions (relative to other cations) remain. Some soil tests show and compare the CEC with sodium (Na^+) levels to determine whether soils are sodic.

Excess sodium weakens the bonds between soil aggregates, leading to dense, cloddy and structureless soils. Sodicity can lead to dispersion at the soil surface, causing crusting and sealing. This then impedes water infiltration and accelerates erosion.

Salinity, measured by electrical conductivity (EC) levels for salts (sodium chloride, calcium and magnesium bicarbonates) can have similar effects on soil as sodicity. High salinity disrupts the soil's osmotic potential, inhibiting the plant's ability to uptake water and nutrients.

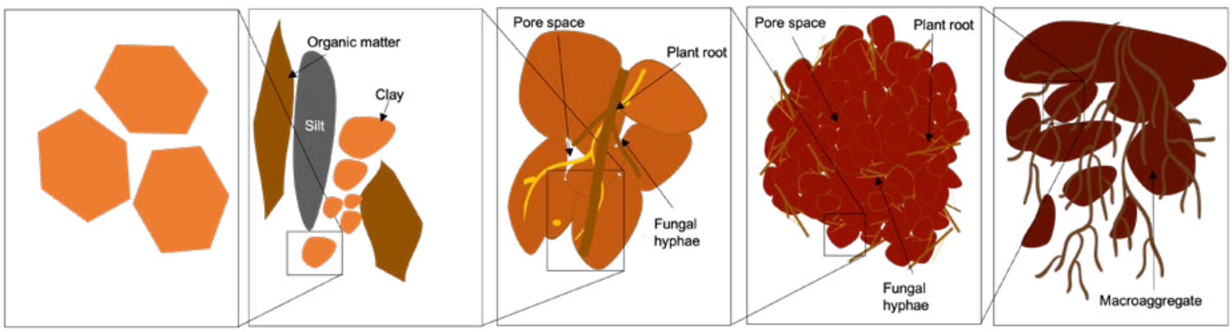


Figure 1. Aggregate formation across different scales. (Adapted from Brown et al (2021) under a creative common licence)

SOIL PHYSICS AND WATER MANAGEMENT

With their relatively shallow root zone, potatoes are very sensitive to water stress. Too much water increases disease and reduces quality, while too little water reduces productivity, yield and nutrient uptake.

The relationship between water and soil structure determines how much water is available to the plants it supports.

Like sponges, soils can only hold a certain amount of water, and absorb water at a certain rate, depending on their texture and structure.

Measuring soil water is a useful tool to understand the condition of the soil at each stage of irrigation and crop use: from **saturation point** (when all pores are filled with water, leading to anaerobic conditions, run-off and ponding), to **field capacity**, **refill point**, and finally **permanent wilting point** (Figure 2).

The maximum volume of water that a soil can hold is called field capacity, while the lower limit is the permanent wilting point, whereby the only water remaining in the soil is unavailable to plants (also known as hygroscopic water).

After saturating rain or irrigation, there is a continuous rapid downward movement of water due to gravitational force. The rate at which the water moves through the soil is related to the soil structure and texture (i.e., drainage is faster for sandy soils compared to clay soils).

After some time drainage becomes negligible. This is when the soil has reached **field capacity**. Over-irrigation that exceeds field capacity will result in drainage and/or deep percolation, wasting water.

As a plant cannot use all of the water held in the soil, irrigators must calculate the water that can be readily removed from the soil by the plant. This is called **readily available water (RAW)** and is the zone for best plant growth between **field capacity** and the **refill point**.

RAW, (measured in millimetres per metre (mm/m)) indicates the depth of water (mm) held in every metre (m) of soil depth that can be taken up by plants. RAW varies with soil type, crop, rooting depth and irrigation system and can be calculated for the total profile depth, or just the depth of the plant's effective rootzone.

Information on how to determine RAW can be found here http://bitly.ws/KZy7

The **refill point** occurs when plants have removed all RAW. The refill point is when used water needs to be replaced.

Soil moisture probes can help determine water-holding capacity and the point at which the soil profile should be refilled.

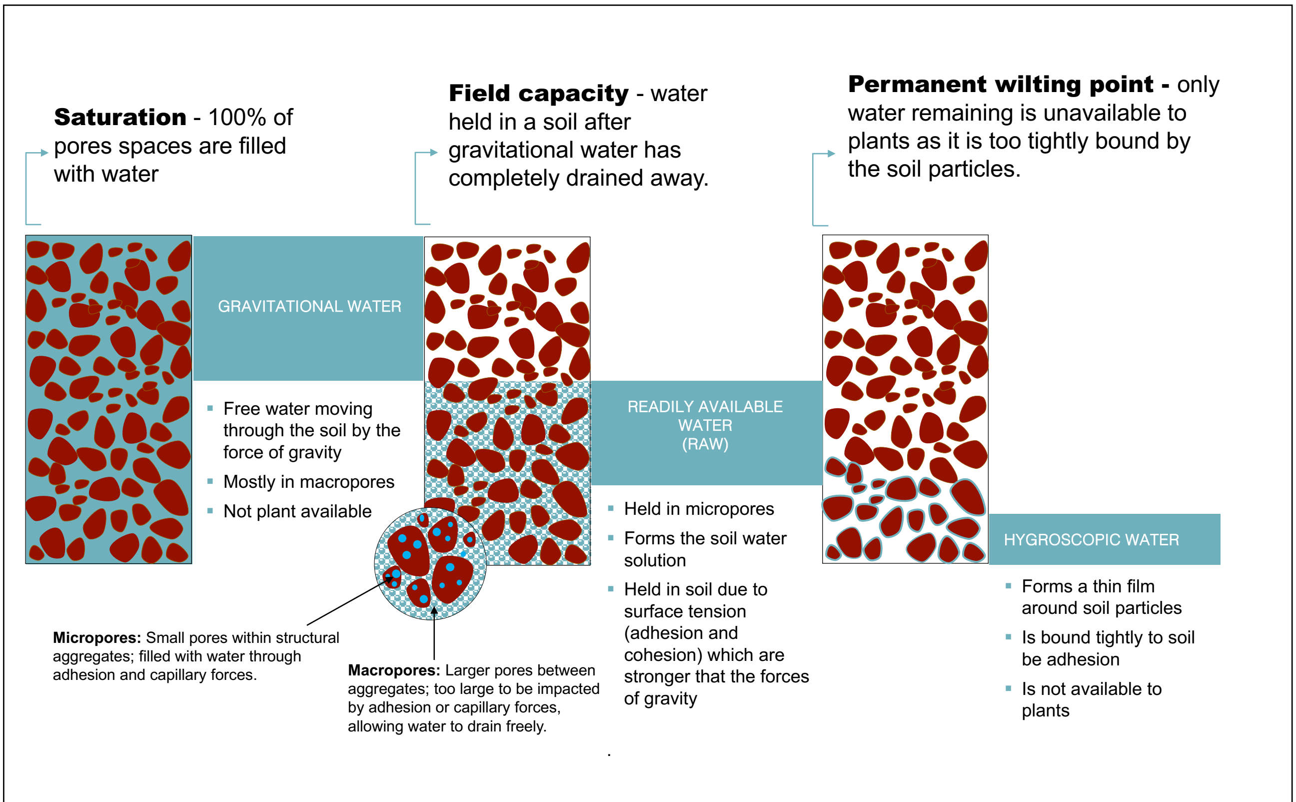


Figure 2. The different forces at play moving and holding water through the soil.

Infiltration, run off and erosion.

Gravity is not the only force at play as water travels through a soil matrix.

Adhesion, cohesion and capillary rise also play a role, impacting infiltration and how much water is available to plants.

Adhesion, the stronger of the two forces, describes the attraction between water and solid particles. Cohesion is the attraction between like materials, in this case water to water.

These forces make it possible for soil to hold on to water. Without adhesion and cohesion, water would simply drain out of the soil pores.

Capillary rise - the upward movement of a liquid through a narrow space - is another important physical phenomenon at play in the soil. As clays have smaller pores, capillary rise is higher, which is why a clay soil can also hold onto more water.

The infiltration rate is the rate at which water enters the soil and is measured by the depth (in mm) of the water layer that can enter the soil in one hour; it will vary with soil texture and structure. It is usually measured by a field test using a cylinder or ring infiltrometer.

In dry soil, water infiltrates rapidly. This is called the initial infiltration rate. As water fills the pores, infiltration slows, reaching a steady rate or basic infiltration rate.

If the amount of water entering the soil is more than what it can absorb at the time, the excess water will run off the surface. This **runoff** causes water erosion by carrying and redistributing soil particles down the slope and creating rills or gullies.

Soil management practices that degrade soil structure can adversely affect infiltration capacity, making monitoring of infiltration rates a good indicator of their impact on water movement into the soil.

Figure 2 illustrates the main forces acting on the different 'types' of water in soil as it moves through the soil profile. Figure 3 illustrates the movement of water in the soil profile.

Waterlogging

With a relatively shallow root system, potatoes have a low tolerance to waterlogging and anaerobic conditions.

While waterlogging cannot always be prevented, improving drainage of water away from the crop and improving the soil's physical structure can help the soil 'protect' itself against excessive water.

The best way to identify waterlogged areas is a visual assessment. If the surface is wet the soil is likely to be waterlogged.

However, sometimes the surface may appear dry but be waterlogged underneath. It is worthwhile to dig and examine what is happening beneath the surface. Dig a couple of holes to about 30cm - if water flows into them the soil is waterlogged.

For more information on managing waterlogging, read more in PotatoLink Issue 8 (http://bitly.ws/RujS)

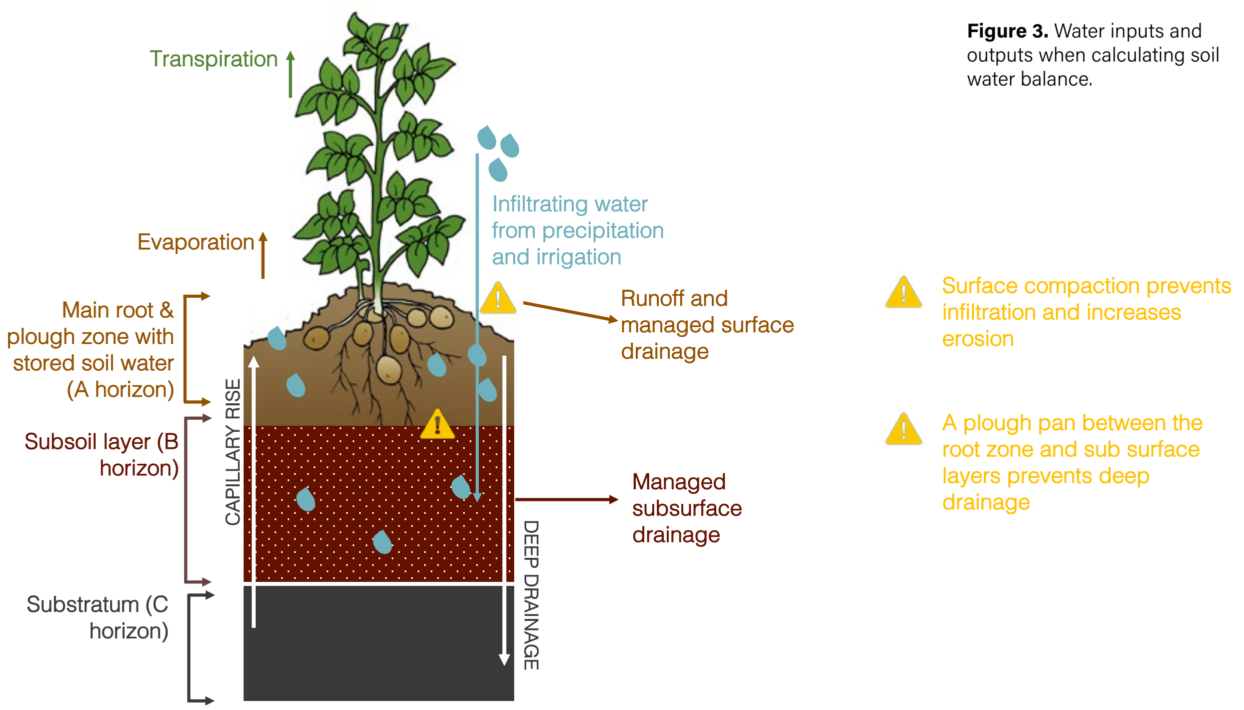


Figure 3. Water inputs and outputs when calculating soil water balance.

MAINTAINING GOOD VENTILATION

Soil holds a mixture of air and other gasses in the macropores. These should comprise the remaining 25% of the total soil volume. The composition and movement of gasses in soil are dynamic.

Pores provide a pathway for gasses to move through the soil. In the root zone good aeration is required to allow plant roots to respire, taking in oxygen and releasing carbon dioxide.

Anaerobic conditions, often a result of waterlogging, have many consequences:

- Reduces the ability of plants to take up nutrients.
- Limits the soil's biodiversity, as microbes need good aeration to efficiently cycle organic matter and nutrients.
- Lenticels on tubers become puffy and swollen as the tubers struggle to get enough oxygen.
- Plants are more susceptible to infection from a range of fungal and bacterial pathogens.
- Results in a build-up of carbon dioxide and ethylene, impacting growth.
- Leads to nitrogen loss through de-nitrification.

Not only are air and water dynamic parts of soil, but both are often inversely related. Maintaining the balance between aeration and soil water availability is a critical aspect of soil management.

SOIL COMPACTION

Compaction is caused by applying stress, for example from heavy machinery traffic, to a soil with a moisture content wetter than its plastic limit (see break out box). When soil particles are pressed together by external forces, bulk density increases and soil porosity decreases. The result is an increase in mechanical resistance or strength of the soil.

Many soil properties affect how easily the soil compacts. These include clay content, due to its ability to hold water.

Compaction has many adverse impacts on potatoes including:

- Plant roots are unable to penetrate compacted layers to access water.
- Water-use efficiency is greatly reduced; rain or irrigation water is unable to penetrate the compacted layers to re-fill the subsoil, increasing run-off and evaporation.
- Compacted soil requires more fuel to cultivate.
- Machinery can become blunt and less effective.
- Fertiliser efficiency is reduced as compacted soils provide few surfaces to retain and release nutrients for crop growth.

While most compaction occurs in the top 20–30cm of the soil, repeated tillage at the same depth can form a hardpan—a dense, impenetrable layer beneath the tilled soil.

Symptoms of surface compaction include:

- Surface clods that are hard to break apart.
- Water ponding in tracks and headlands
- Wheel tracks with a smeared appearance
- Soils that appears to have no structure.

RESTORING COMPACTED AREAS

Avoiding compaction by reduced tillage, controlled traffic, and avoiding, as much as possible, tillage when the soil is wet, is obviously preferable,

Top: compacted soils. Bottom: soil from under cover crops (left) versus intense cultivation (right) however it is not always practically possible.

Compacted areas can be restored or managed with both mechanical and biological approaches.

Biological management takes time, using cover crops with different rooting patterns that can break through the soil.

Cultivation when the soil is dry will also hasten the natural breakdown of clods. However tillage needs to be shallow to avoid compaction of deeper (and usually wetter) soil.

It is therefore important to check the soil moisture profile in relation to cultivation depth. Only cultivating dry soil ensures that it will fracture rather than smear.

Deep ripping breaks up compacted soil layers mechanically using strong tines working down to 35-50cm depth. These loosen hard layers of soil.

Before deep ripping, it is important to consider tine spacing, working depth, use of shallow leading tines or discs, soil moisture content, timing and soil type.

More information about the science of deep ripping is available here (http://bitly.ws/KZyk).

CONCLUSION

Potato cultivation, by necessity, is a constant cycle of building up a soil structure then smashing it down, undoing years of good, regenerative work.

Moreover, rarely will soil have exactly the same structure and other properties across all paddocks, complicating management further.

Being aware of the physical properties of soil in each paddock can help avoid destructive practices. It can also help identify and implement regenerative soil management strategies, keeping the potato farming enterprise sustainable and profitable.

PLASTICITY

The plasticity of a soil is its ability to deform without cracking and it is an important characteristic of fine-grained soil, especially clay soils.

At the lower plasticity limit, the soil will crumble when rolled into threads of 3.2mm in diameter.

To assess if your soil is suitable for vehicle traffic or cultivation, perform the following test:

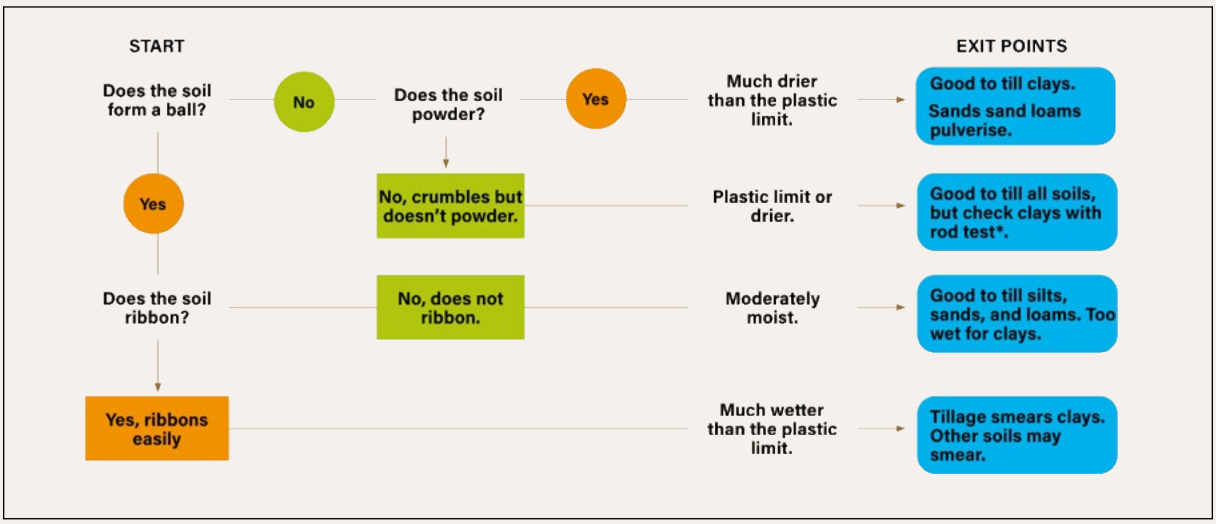
1. Rapidly squeeze a small lump of soil into a ball.
2. Attempt to roll the soil ball into a 3mm diameter rod.
3. If you can easily make a cohesive rod, the soil is too wet and should not be worked with machinery.
4. If you cannot make a rod at all, the soil is only suitable for cultivation if it is clay. If it is loam, this indicates that the soil is too dry to cultivate.

5. If you can make a crumbly rod, the water content should be suitable for cultivating all soil types.

Soil moisture test for tillage. Source: https://www.dpi.nsw.gov.au/__data/assets/pdf_file/0020/127280/Cultivation-and-soil-structure.pdf

The ribbon test is used to estimate soil texture and the amount of clay in a soil. NSW DPI have a useful step by step guide here https://www.dpi.nsw.gov.au/__data/assets/pdf_file/0005/164615/determining_soil_texture_using_-ribboning_technique.pdf

*Rod test described in the five point step.



CLAY AND ORGANIC CARBON

Keeping carbon stable in the soil is important to improve soil health. The ability of the soil to do this depends on its physical, chemical, and biological properties. Clay minerals, which are the most reactive particles in soil, play a big role in storing organic carbon (OC).

Clay soils are good at protecting OC from microbial breakdown. The clay particles and aggregates physically protect the organic matter. The organic materials can stick to clay surfaces, get covered by clay particles, or get buried in small pore spaces of clays. This makes it hard for microorganisms to break them down.

SOURCES

Blume, H-P, Brümmer, G, Horn R., Kandeler, E, Kögel-Knabner I, Kretzschmar R., Schad P, Stahr K, Wilke B-M (2015). *Scheffer/Schachtschabel Soil Science.* Springer (https://doi.org/10.1007/978-3-642-30942-7)

Brevik, E (2018) *A brief history of the soil health concept*, Soil Science Society of America (https://profile.soils.org/posts/field-and-historical-notes/a-brief-history-of-the-soil-health-concept/)

Brown S, Biswas A, Caron J, Dyck M, Si B (2021) *Soil physics*. In M. Krzic, F.L. Walley, A. Diochon, M.C. Paré, & R.E. Farrell (Eds.), *Digging into Canadian soils: An introduction to soil science (pp100-148).* Canadian Society of Soil Science*. (https://openpress.usask.ca/soilscience/chapter/soil-physics/)*

Coyne M, Pena-Yewtukhiw E, Grove J, Sant'Anna A, Mata-Padrino D (2022) *Soil health – it's not all biology.* Soil Security, 6 (https://doi.org/10.1016/j.soisec.2022.100051)

Local Land Services, NSW. *What is healthy soil? Factsheet 11.* Accessed March 2023. (https://www.lls.nsw.gov.au/__data/assets/pdf_file/0020/1270541/11-What-is-a-Healthy-Soil_FINAL.pdf)

NDSU Potato extension *Potatoes in flooded fields.* Accessed June 2023 https://www.ag.ndsu.edu/potatoextension/potatoes-in-flooded-fields#:~:text=Anaerobic%20conditions%20can%20also%20lead,also%20will%20favor%20blackheart%20development.

NSW Department of Primary Industries. *Check your soil structure.* Accessed March 2023. (https://www.dpi.nsw.gov.au/agriculture/soils/guides/soil-structure-and-sodicity/check)

Queensland Department of Agriculture and Fisheries. *Soil health for vegetable production in Australia—Part 3: Managing common soil constraints.* Accessed March 2023 (https://www.daf.qld.gov.au/__data/assets/pdf_file/0003/57513/Soil-health-vegetable-production-Part_2a.pdf)

Queensland Department of Environment, Land and Water. *Soil sodicity.* Accessed June 2023 https://www.qld.gov.au/environment/land/management/soil/soil-properties/sodicity#:~:text=Sodicity%20in%20soil%20is%20the,of%20sodium%20impacts%20soil%20structure.

WA Department of Primary Industries and Regional Development. Accessed June 2023 https://www.agric.wa.gov.au/soil-compaction/deep-ripping-soil-compaction

WA Department of Primary Industries and Regional Development. Accessed June 2023 https://www.agric.wa.gov.au/citrus/calculating-readily-available-water?page=0%2C1%5bcreate