Soil and Food Security

Demand for food

The potential number of people to be fed by the world follows from balancing demand against supply. This approach may be simple and adequate from a global perspective, but is somewhat illusive when disregarding regional imbalance between supply and demand, resulting in the present coexistence of 1 billion undernourished against 1 billion obese people.

Food demand towards mid century is not just met by simple redistributing food, but also by a compelling need for stepping up production. A rapidly growing population to over 9 billion people is one reason, richer diets following increasing incomes, are another. Additionally non-food purposes, like cotton for clothing or wood for construction, claim agricultural land. And so may the growing interest in renewable resources towards a bio-based economy. This increased pressure on land as a resource base is further aggravated by soil degradation and climate change, both curbing cultivatable acreage and land productivity.

The demand side of the equation is deduced from the population size and their diet habits. For convenience sake demand is expressed in grain equivalents as measure of overall calorie intake by all food sources combined, which are generally dominated by grain crops.

The marked increase in global population set off in the past century up to date (i.e. 7 billion people in 2012) is unprecedented. At medium growth the world may inhabite over 9 billion people to be fed, still a 30% increase within half a life time only.

Despite uncertainty on future population size, changes in dietary needs show a much larger impact on overall projected demand, as illustrated by comparing a vegetarian, moderate and affluent diet assuming medium population growth. Considering diets become more affluent with increasing wealth, currents trends (as noted in China), suggest demand to increase much faster than would be deduced from population growth only. Moreover, non-food uses like building materials (wood).

Soil water for food supply

Soils provide a medium for anchoring crops through their roots, keeping stems and leaves in an upright position, and enabling crops to capture solar energy in the process of photosynthesis. Water lost during this process by transpiration from the leave surface, is replenished by roots as they draw water from the soil. Although within reach of roots, soil water is not entirely available to crops as some water is retained within soil pores: clay soils, with more and smaller pores than sand, are characterized by a higher water holding capacity. As such clay may sustain crop water requirement over longer periods of drought. Crop yields are proportional to water uptake implying the need for supplementary water through irrigation in drier regions. Soil type is an important factor in tuning water management to realize more crop per drop while mitigating salinization as potential threat to soil degradation.

Water makes up 70-90% of the cropss fresh weight. This corresponds with roughly 40,000 litres of water incorporated in a mature field crop on 1 hectare of land (or an average sea container on a soccer field). During a dry, windy summer day, however, more than the entire water content of the crop is easily lost by transpiration.

Transpiration protects leaves from overheating when they are necessarily exposed to sun light, energizing the fixation of CO2 from the air into organic components as stored in a.o. grains and tubers. While CO2 enters small pores (stomata), at the leaf surface in this process, known as photosynthesis, water from the moist leaf tissue interiors is inevitably lost into the drier air.

Transpiration losses are normally replenished through soil water taken up by plant roots. Concurrently, dissolved soil nutrients are taken up and transported along with the water flow towards the leaves to be incorporated in the plant's tissue. Finally, water sustains rigidity of herbaceous crops (turgor), holding up leaves to effectively capturing sun light.

Soil water demand in crop production is not limited to transpiration. Water is also lost directly from the soil surface by evaporation, especially when the canopy of a young crop is not fully covering the soil yet. This unproductive loss of soil water competes with water availability for crop transpiration and associated production.

As canopy closes during the growing season, a smaller share of soil water is evaporated. Crops which quickly close their canopies will more efficiently use soil water through transpiration. Adequate availability of soil nutrients also improve Water Use Efficiency (WUE) by speeding up crop growth and associated canopy closure. This notion is of particularly important in prudent use of irrigation water.

The amount of water available to plants depends on soil water content and soil characteristics. The soil water content follows from a water balance keeping track of water flows entering (+ a.o. rainfall, irrigation) or leaving (- a.o. transpiration, evaporation) the rooting zone. Soil characteristics modify the rate of flow, as illustrated here for a clay and sandy soil (next slide).

A clay soil is characterized by tiny soil particles (with diameters less than 0.002 mm) and corresponding small pores, that impair water flow into the soil. Consequently, these soils show low infiltration rates, while little water may be lost by percolation of water below the root zone. On the other hand, the small pores promote capillary rise of water from the ground water. When, in absence of a closed canopy the soil surface becomes exposed to evaporation loss, capillary rise may thus sustain substantial water depletion from the soil profile. At the same time, salts dissolved in the upwards flowing water may precipitate at the soil surface as water evaporates. This process, known as salinization, jeopardizes germination of arable crops, rendering lands useless for agriculture.

Much water may run-off during high intensity rains on these soils and considered to be lost when diverted away from the cropping area. In some instances it may run-on into other fields and become available to other crops. Heavy clay soils may be prone to waterlogging, which blocks soil aeration thus hampering plant growth.

Sandy soils consist of coarser soil particles (texture class: ÿ 0.05-2.0 mm), and are therefore more porous with inherently high infiltration rates. As a result, evaporation losses may be smaller, although losses due to percolation to zones below the rooting depth may be higher. Supplementary water from capillary rise is low, while run-off and run-on flows are lower too.

The water balance keeps track of the overall amount of water (in mm) present in the rooting zone. Not all of this water is available to the plants, when soils become either too wet or too dry. To extract water from the soil, roots exert some force proportional to the force of suction, by which water is drawn into the pores between the soil particles, or retained by the soil's organic matter. This suction force is expressed by the Soil Water Potential (SWP) with inherently negative values, or by its logarithmical equivalent, known as the pF-value.

The pF value of a water saturated soil equals 0, as soils virtually soaking in water do not exert any suction force to retain water. Assuming all pores to be filled with water, the volumetric soil moisture content (SMC) complements the solid fraction. This is as high as 40% for a sandy soil. Absence of the gaseous fraction and thus soil aeration hampers crop growth: water uptake by the roots becomes impaired causing leaves to wilt, especially at high evaporative demand, despite abundant soil water. (Soils inundated with water are also referred to as water logged

When saturated soil is exposed to free drainage during two days, gravitation forces will cause the widest pores to drain first, allowing air to enter. The remainder of water is retained in the soil matrix. This situation known as 'Field Capacity' represents the upper limit of available soil water to plants. At this point SWP equals -100 hPa, (i.e. in absolute terms 1/10 of atmospheric pressure) or pF value 2, which is associated with a SMC of 15% in a sandy soil. Plants will perform optimally under these soil water conditions as roots have easy access to both water and oxygen in the soil.

Plants need to exercise increasing force to keep withdrawing water from the soil when the water content decreases. Transpiration demand creates this suction force, but a point may be reached during the day, at which the volume of absorbed water cannot keep up with the required transpiration rate. This induces dehydration of plant tissue, with leaves starting to wilt and stomata to close, thus depressing photosynthesis. This moment, characterized by pF values around 3 (i.e. -1000 hPa, or in absolute terms corresponding with 1 bar atmospheric pressure) differs among plants.

While plants may still recover during the night by rehydration when transpiration losses are down, plants under these conditions thus experience temporary wilting.

With continued withdrawal of water for transpiration and evaporation, narrower pores are emptied leading to a sharp decrease in SWP. As SWP approaches pF 4.2 (-16,000 hPa or in absolute terms 16 times atmospheric pressure of 1 bar), roots can no longer exert adequate suction to absorb water, which results in severe dehydration of plant tissue, stomatal closure and critical wilting. Leaves may not recuperate beyond this point, even after water application, leading to Permanent Wilting. The moment of occurrence of this irreversible situation varies between plant species, and may also be triggered by excessive dry power of the air during an extreme combination of hot, dry and windy conditions in addition to a persistent drought period.

The residual water beyond pF 4.2 can only be extracted from the soil matrix by drying in an oven at 105 ∞C (i.e. beyond the boiling point of water) up to a SWP of pF 7. The volumetric gas fraction of the soil equals the volumetric water fraction at pF 0. A SWP of pF 7 is approximated in nature by evaporation of the first millimetres of top soil when exposed during daytime to soaring heat in desert climates. At this point no plant live is possible. Dormant seeds or rhizomes in the soil await the rains to come to germinate ... The curve connecting the specified stages of soil water extraction is referred to as soil water retention curve, or pF-curve, linking SWP with SMC. The curve characterizes the water holding capacity of a soil.

The water holding capacity (expressed in cm3 (water) cm-3 (soil), or in %) between Field Capacity and Permanent Wilting Point reflects Plant Available Water. Within this range plants can extract water from the soil.

Plant Available Water for a sandy soil (+/-10%) is substantially less than for a clay soil (+/-25%). Clay particles have a larger water adsorbing surface area, while smaller pores retaining more water. This leads to an overall higher soil matrix forces, which implies that relatively high amounts of moisture are contained by the soil at pF 4.2 that is not available to plants. The fine soil particles in combination with the high moisture retention lead to the sticky properties of clay soils; that classifies clay as a heavy soil difficult to till, for instance. By contrast, sand is classified as a light soil.

The higher water holding capacity of a clay soil allows plants to bridge longer periods of drought compared to a sandy soil, which could easily last over 2 months considering rooting depth and transpirational demand. However, some plants favour sandy soils, due to better gas exchange properties because of the larger soil pores. From a practical perspective, harvest of root crops is easier in sandy soils.

Soil nutrients for food

For their growth crops feed on nutrients. Roots take up soil nutrients which, incorporated in the crop, make up part of our food. Soil nutrients are derived from various sources. Natural fertility, originating from slow release of nutrients by eroding bedrock or mineralizing organic matter, is associated with relatively low yields. This situation is worsened when this mineral stock can not keep pace with nutrient depletion resulting from frequent harvesting on the same piece of land. Resorting to other land (i.e. shifting cultivation) claims more soil area.

Higher yields correspond with high nutrient uptake, implying application from supplementary nutrients from manure or artificial fertilizers. Additionally, soils may be repeatedly cultivated, as long as harvested nutrients are sufficiently replenishing. However, not all nutrients applied to the soil are readily available to crops. This is amongst others determined by soil type. Clay particles in particular may fix minerals while they prevent losses by leaching below the rooting zone.

Soil water availability is a prerequisite for crops taking up nutrients: as they become dissolved, nutrients absorbed by the roots are subsequently transported to other plant parts. This implies that bóth water and nutrients should be provided simultaneously by the soil to increase crop productivity.

Biomass contains nutrients, of which nitrogen (N), phosporous (P) and potassium (K) are most notably, thus referred to as macro-nutrients. Other minerals such as iron (Fe), copper (Cu), manganese (Mn), and zinc (Zn) are present in substantially smaller quantities, and accordingly known as micro-nutrients. The range in nutrient content (i.e. kg (nutrient) kg-1 (dry matter)) varies with plant species, plant part (e.g. leaves, storage organs) and the development stage of that particular plant part. Nutrients, as intrinsic part of the harvested and subsequently consumed plant matter, play a vital role in human health. This is reflected by the nutritional properties of food in addition to its caloric value.

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Nutrients have various functions in plants. N is incorporated in the rubisco enzyme within the green chloroplast, which is essential in photosynthesis. N-deficiency is thus reflected by yellowing leaves. As integral part of proteins, N is stored in plant organs like beans. P supports energy transfer in bio-chemical processes, related to a.o. photosynthesis and subsequent conversion of sugars (CH_2O) into other components like fats and proteins. K is an important osmoticum, regulating water absorption by plant cells and thus the plant's turgidity and overall fresh weight. A fully turgid plant also maximizes light interception, with expanded leaf surfaces, optimally oriented towards the sun. A number of micronutrients has been identified in contributing to enhance resistance against abiotic (a.o. drought and frost) and biotic stesses (plant diseases).

Nutrients taken up by a plant originate from a nutrient pool in the soil, with water as solute. Yields increase as more nutrients can be absorbed. The size of the nutrient pool is a reflection of the soil fertility. Under normal conditions, i.e. without artificially supplied nutrients, natural soil fertility for N (expressed as No) may support uptake levels up to 75 kg N ha-1 in well endowed regions, but substantially less on so called marginal lands. By and large sandy soils are associated with lower fertility (thus lower yields), compared to clayey soils, as surface area of the coarser sand particles potentially adsorb less nutrients than the finer clay particles.

Natural soil fertility is normally sustained by minerals released to the nutrient pool from weathering or eroding bedrock by wind (subsequently deposited as dust) or water (e.g. sedimentation of river clay, exemplified by the fertile Nile delta). Another source originates from mineralization by micro-organisms degrading organic matter (e.g. remnants of roots, crop residues or animal excrements). Focusing on N, specialized bacteria in symbiosis with leguminous plants (e.g. bean crops, acacia trees) show nitrogen fixing properties. To some extent N_2 can also be oxidized into plant available N during lightening. Additionally, in regions with predominant dairy and pig farms, adjacent crop fields may benefit from deposition of N components volatilized by urine and animal dung.

Soil nutrients, not absorbed by crops, are exposed to losses. Whereas erosion is important to release nutrients from parental rock, the downside is that nutrients may be blown away or washed out especially when nutrient rich topsoil remains unharnessed by vegetation. Surplus water may additionally leach out nutrients beneath the reach of plant roots, especially in sandy soils. Micro-organisms in the soils temporarily immobilize minerals by incorporating these into their bodies. Nitrogen in particular may be lost by soil bacteria through denitrification into N_2 or volatilization into ammonia gas (NH_3) depending on soil conditions, such as high water content and resulting limited soil aeration.

At harvest plant parts, and storage organs in particular, are removed from the land, including the incorporated nutrients taken up from soil. These nutrients need to be replenished to maintain soil fertility.

Initial yields based on natural fertility can be relatively high yields. However, yearly cropping without fertilization results in dwindling yields since processes like mineral erosion and mineralization, cannot keep pace with nutrient extraction by the harvested produce (i.e. draining the nutrient pool). Hence, fallow periods are required, allowing natural soil fertility to recover.

To step up yields well beyond levels attainable under natural soil fertility, additional external input of nutrients are essential, and must be applied every season to keep up the high production. These external nutrients may be derived from artificial fertilizers, manure or other organic fertilizers. Application rates of 100-200 kg of N per ha as artificial fertilizers correspond with approximately 15,000 ton (100 fold!) of manure in terms of N-equivalents.

Keeping track of the dynamics in nutrient in- and outflow, helps to formulate nutrient applications per crop for various soil types under different climatic conditions, resulting in high recovery rates, i.e. efficient nutrient use. Optimal recovery fractions may be as high as 0.9, whereas values for agriculture in the Netherlands vary around 0.7. Under poor growing conditions recovery rates may drop below 0.3 (!) for nitrogen. Although non-recovered nutrients are subject to various losses, some remain protected against those losses, when temporarily immobilized as part of the soil's organic matter (e.g. plant residues, soil organisms). Nutrient release by subsequent mineralization renders soil organic matter as a useful nutrient buffer.

Combining the nutrient response curve by the crop (i.e. yield to uptake relation, yellow quadrant) with the recovery data from the soil (i.e. uptake to application relation, brown quadrant) results in the commonly known yield response to fertilizer applications (green quadrant). Grain yield at zero application reveals the degree of (natural) soil fertility as starting point, implying lower intercept values under marginal soil conditions. The curve reaches saturation, reflecting that higher application rates result in lower nutrient use efficiency. Despite a well defined relation between yield response and nutrient uptake per crop (yellow quadrant), common 'yield response to nutrient application' (green quadrant) may differ considerably among locations and different seasons.

According to Liebig's 'law of the minimum' nutrient limited crop yield is dictated by the availability of the most limiting nutrient, exemplified by the shortest stave of the barrel which represents achievable yield. Supplementing the most limiting factor would increase crop yield to the next limiting factor. The yield response, however, also depends on the ratio between nutrients in a crop: assuming N being the most limiting factor, while P is abundantly available in a soil, a small increase in N would lead to a larger yield increment, compared to a situation where P levels are relatively low too.

Nutrient availability, and associated recovery also depends on soil acidity. As shown in the diagram, iron (Fe) availability is increased at lower pH-values, which may imply a higher recovery for this nutrients, unless concentrations become toxic.

Therefore, rather than applying a deficient soil mineral, such as P, supplements with lime (Ca), as socalled soil improving measures in acid soils may improve the P-recovery. Gypsum ($CaSO_4$) additionally promotes stability of soil organic matter and soil aggregates, which improve both water penetration and soil water retention, together faciliating seed emergence.

Potential production and yield gap

Assuming no limitation by water and nutrients on one hand, and a field free of weeds, pests and diseases on the other, crops attain their potential yield level as defined by their genetic make up and climatic conditions (solar radiation and temperature).

Actual yields, especially in Africa and SE Asia, are substantially lower than potentially attainable. Understanding these 'yield gaps'' by using crop simulation models based on both plant, soil and climatic factors, will help to formulate measures to step up actual production (apart from socio-economic considerations). African soils in particular have shown to be poor in nutrient content, implying that even in drier parts productivity could be increased by fertilization rather than irrigation. Models also help to understand the impact of climate change on crop production by various soils world wide.

For sake of simplicity three yield levels are distinguished according the production situations, and associated production factors by which they are realized. The highest yield or potential production is defined by ambient climatic conditions and crop genetics. These factors are not simply modified under common outdoor situations. When factors like water and nutrients become limiting, yield increasing measures like irrigation of fertilizer application may bridge the yield gap, provided that weeds, pests and deseases are not further reducing yields, as they would under actual production situations. Finally, roughly 30% of harvested global crop production becomes avoidably (!) wasted.

The previous classification indicates to which extend yield gaps can be bridged by applying yield increasing (fertilization or irrigation), or yield protecting measures, as recommended in Africa and some parts of Asia. In some Western countries, where yield gaps become practically closed, further production gains require unconventional techniques, including biotechnology and soilless cultures in greenhouses.

Yield gaps for various parts of the world are analyzed through crop simulation modelling. Potential production is proportional to the amount of absorbed sun light which is converted into plant matter through photosynthesis. As the leaf area increases during the growing period, gradually more light becomes intercepted for dry matter which is distributed over the various plant organs as regulated by plant development. As canopy closes, maximum light interception associated with maximum growth has been reached, during which built up dry matter becomes gradually more allocated to storage organs, such as the grains.

The previous model can be extended by adding limiting factors: lack of water and nutrients, which are also related to soil factors curb photosynthesis. Additionally remaining dry matter may be distributed in favour of root extension (enlarging the rooting zone to compensate for insufficient water and nutrient availability at the expense of the storage organs.

To simulate actual production models also include yield reducing factors: weeds may compete with light interception (higher canopies than those of crops) or water and nutrients withdrawal (e.g. by a more extended root system).

Simulation models enable calculation of potential and actual crop yields and associated yield gaps for virtually every spot on earth using information on ambient climate and local soil conditions. Aggregating to global scale, crop modeling provides insight on overall agricultural production harvested from globally available arable land area. Concurrently overall water and nutrient requirement at different yield levels is indicated.

Crop modeling helps to analyse differences in crop production for different parts of the world using soil and climate data, as exemplified here for Portugal and the Netherlands. Whereas potential yields may be higher in Portugal due to a longer growing season and associated overall light absorption, actual yields are lower following substantial water limitations, particular when crops are grown on sandy soils.

It is only since the last century that fertilizers are applied, in combination with introducing high yielding varieties and other measures. This has resulted in striking changes in production trends for the important grain crops, marking the 'Green Revolution'. Starting in Western countries, green revolutions have subsequently reached the East and presently take off in Africa, resulting in higher land productivity to meet increasing food demand.

Soil productivity vs acreage

A substantial acreage of land has already been put into cultivation to feed mankind today. Although globally additional land, suitable to agriculture, may still be exploited, claiming more soils competes with bio-diversity. Feeding future populations demands choices on increasing productivity on a smaller acreage (with prudent use agro chemicals) or expanding land area with less productive agriculture. Additionally, marine agricultural may be explored, producing a.o. seaweeds for food (protein) and non-food (bio-materials) purposes. Similar produce is also supplied by growing algae, which does not depend on agricultural land. More than half of humanity today lives in cities. Therefor urban farming, based on soilless culture, is considered, particularly to provide for fresh produce like fruits and vegetables.

Global agricultural production follows from the overall acreage covered with a green, photosynthesizing canopy. Global land acreage makes up close to 30% of the earth surface.

Only part of the land acreage is suitable for agricultural production. Areas without top soils (e.g. barren rocks) or soils permanently covered with ice, or areas which are too cold or too hot, as well as urban areas (presently 0,2 Gha) are all unsuited for terrestrial agriculturl production. (1 Gha, or Giga hectare equals one billion hectares, or roughly the surface area of Canada).

Presently over 10,7% of global land area is used for crop land (dark green) and about 23% is suitable as pasture (light green), together yielding about 7 Gton of grain equivalents (1 Gton = 1 billion tonnes = 10^12 kg).

To meet the demand of a growing and wealthier population by 2050, production need to be stepped up towards 10 Gton of grainequivalents or more. The additional production may be realized by increasing acreage at the expense of land, reserved for biodiversity (yellow surface). Sacrificing biodiversity might turn counterproductive on the long run. Alternatively, mismanaged lands, amongst others caused by salanization might be reclaimed using crops with either natural or inbred higher salt tolerancy.

The other option is increase production per unit area, thus preserving land, allocated for biodiversity purposes. Considering the yield gaps in Africa and South Asia, there is plenty opportunity for this approach. However, increasing landproductivity also requires more water for irrigation, particularly during drier seasons, thus drawing heavily on fresh water supplies. Likewise increased fertilizer inputs are expected, of which phosphates in particular may become scarce.

Alternatively in addition to expanding agricultural land, or increasing land productivity also exploration of the earth water mass should be considered, which represents a vaster area than land.

The world is urbanizing and already half of the growing world's population lives in cities. In a few decades the urban share will approach three quarters of the predicted 9 billion people. These typical large metropolitan areas often usurp the space most suited for agricultural production with urban land use. Therefore ideas are developed towards metropolitan farming, focusing especially on fresh products (vegetables and fruits).

Technologies supporting agricultural production in urban areas make use of LED-lighting and soil-less culture, using artificial rooting media like rockwool. Within cities nutrients retrieved from sewage systems may thus be recycled for plant production.

Alternative forms of agriculture independent of arable land might include production of algae, which can be used for cattle or fish feed, thus contributing to the increasing demand for proteins. Algae are also considered for biofuels or feedstock for biomaterials towards a bio-based economy.

Diet patterns and other alternatives

Apart from increasing production, we need to rethink our consumption. First, we need cutting down waste, presently amounting to over 30% of all farm produce, representing a sizable amount of land (and other inputs) as well. Likewise overconsumption of animal protein should be brought down, especially when animals are fed with farm produce from arable land. In view of the high conversion rate in terms of grain equivalents used to produce one kg of beef, alternative sources for proteins, like insects could be considered. With a more favorable conversion rate, pressure on agricultural land is decreased. Finally, to prevent land becoming deprived of soil minerals, which may trigger exploitation of soils elsewhere, nutrients need to be recycled to sustainably secure food for future generations.

Currently on average over 30% of the global agricultural production is wasted. This number is considerably higher when considering fresh produce with a shorter shelf life. While this problem is world wide, countries show different opportunities to cut waste, when analyzing their supply chain. Reducing waste also implies less pressure on land use.

Production of 1 kg of beef requires 6-10 kg of feed. Thus alternative protein sources, with more profitable conversion rates may enrich our diets, while sacrifycing less land: 1 kg of insects requires less than 1 kg of feed.

By and large our entire food supply chain needs to be examined to close cycles to make more efficient use of our resources, including soils. This is in a nutshell the focus towards a circular economy.

By closing the cycle and thus regenerating resources and cutting down emissions the objectives of Sustainable Global Food Security is served best.