
AgriCapture CO2
Healthy Soil
5
Principles of
Regenerative
Agriculture
Healthy Crops
Healthy Businesses
AGROFORESTRY
MODULES: MAINTAIN LIVING ROOTS & BIOLOGICAL DIVERSITY
AgriCapture CO2
GWCT
THE ALLERTON
PROJECT

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1. Biological Diversity
Maintain wide, healthy rotations and encourage beneficial flora & fauna through reduced artificial inputs
5 Principles of Regenerative Agriculture
Healthy Soil
Healthy Crops
Healthy Businesses
5. Integration of Organic Matter
Utilise livestock and cover crops to build soil organic matter
2. Maintain Living Roots
To boost soil biology, build soil structure and increase water infiltration
3. Soil Protection
Utilise crop residues and cover crops to provide biological armour to the soil surface and reduce water loss
4. Reduced Soil Disturbance
Reduce and optimise mechanical and chemical inputs to improve soil health and structure

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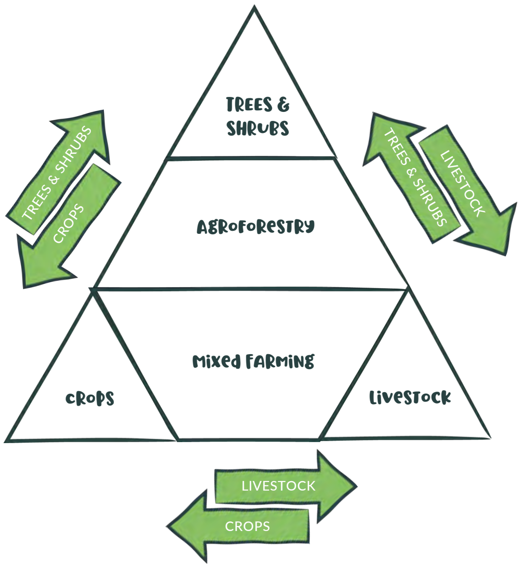
WHAT IS AGROFORESTRY?

- 'The practice of deliberately integrating woody vegetation (trees or shrubs) with crop and/or animal systems to benefit from the resulting ecological and economic interactions' (Burgess & Rosati, 2018)
- An attempt to replicate natural ecosystems to enhance the functionality & sustainability of the farmed system – to build resilience
- A polyfarming system
- A key characteristic of successful agroforestry is that trees must use resources that the crop would not itself acquire



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WHAT IS AGROFORESTRY?

Agroforestry systems have four common characteristics:

INTENTIONAL	INTENSIVE	INTERACTIVE	INTEGRATED
Combinations of tress/ shrubs & agriculture are intentionally designed & managed as a whole unit rather than as individual elements occurring in close proximity	Agroforestry practices are intensively managed to maintain productive & protective functions, e.g. cultivation, fertilisation, irrigation	Systems seek actively manipulate the biological & physical interactions between the separate components. Goal to enhance the production of more than one component at a time while providing conservation benefits, e.g. wildlife habitat	Agroforestry systems are structurally & functionally combined into a single, integrated management unit. Utilises more productive capacity of the land to balance economic production with conservation.

(Association of Temperate Agroforestry)

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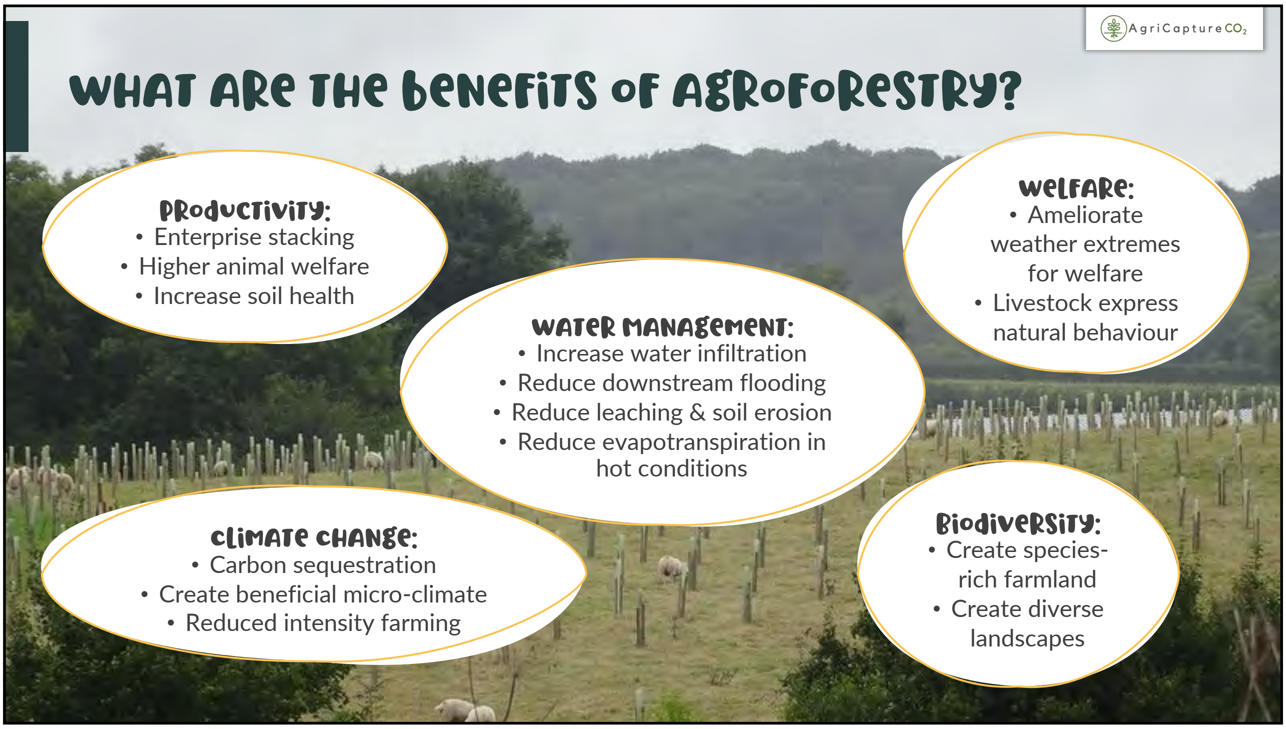
What are the benefits of agroforestry?



Productivity:
- Enterprise stacking
- Higher animal welfare
- Increase soil health

Welfare:
- Ameliorate weather extremes for welfare
- Livestock express natural behaviour

Water management:
- Increase water infiltration
- Reduce downstream flooding
- Reduce leaching & soil erosion
- Reduce evapotranspiration in hot conditions

Climate change:
- Carbon sequestration
- Create beneficial micro-climate
- Reduced intensity farming

Biodiversity:
- Create species-rich farmland
- Create diverse landscapes

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Types of agroforestry

Silvopastoral	Silvoarable	Boundary	Homegardens
• Trees & livestock • Livestock integrated into woodland or trees integrated into pasture. Includes forest farming	• Trees & crops • Arable/horticulture generally grown between wide alleys of long-term trees	• Hedgerows, shelterbelts & riparian buffer strips	• Trees & food production in domestic setting




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Agroforestry in UK & EU

Based on the LUCAS dataset, den Herder et al, 2016

All agroforestry	UK	EU
Arable agroforestry		
Area ('000ha)	2.0	358
% land area[11]	0.0	0.2
Livestock agroforestry		
Area ('000ha)	547.6	15,102
% land area	3.3	8.7
High value tree agroforestry		
Area ('000ha)	14.2	1,050
% land area	0.1	0.6
Total ('000 ha)		
Area ('000ha)	551.7	15,421
% land area	3.3	8.8

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Benefits: Productivity - 1

- Complementarity in resource capture: i.e. trees use spatial/temporal resources that monocultures would not (Cannell et al, 1996)
- Niche differentiation – different species use resources from different parts of the environment
- Tree roots extend deeper than crop roots to access nutrients & water
- Capture nutrients leached from crop rhizosphere

- Nutrient then recycled by defoliation onto soil surface for benefit of crop
- Variegated tree/crop canopy heights with trees harvesting sunlight for longer than most crops
- Greater nutrient capture & higher yields from combined system than sole monocrops (Sinclair et al, 2000)
- Cycle organic carbon into the soil increasing SOM

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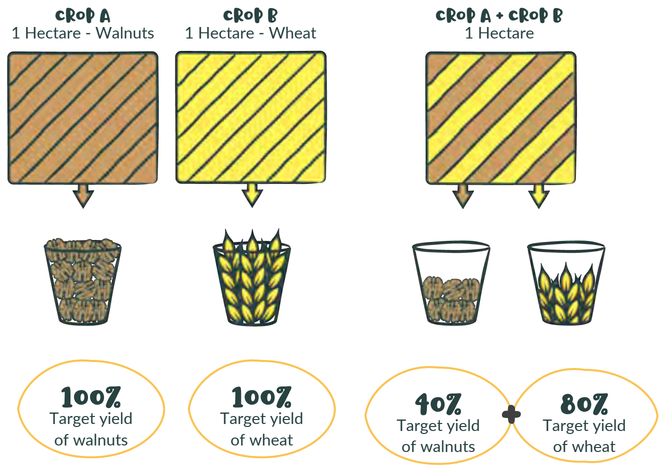
Benefits: Productivity - 2

- Land Equivalent Ratio (LER) to compare polycultures & monocrop systems
- The ratio of the area needed under monocropping to the area of polycropping at the same management level to obtain a particular yield
  - LER 1 = no advantage
  - LER 1.1 = 10% yield advantage
- LER values generally found to be highest in agroforestry systems vs other polycrops due to the significant differences in spatial/temporal spaces between crops & trees



Adapted from the Agroforestry Handbook

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Benefits: Productivity - 2

LER Land Equivalent Ratio = Combined Yield (100) / Solo Crop Yield A (100) + Combined Yield (100) / Solo Crop Yield B (100) = 2

In reality, as above, each crop likely to be below monocrop potential BUT with a joint LER above 1 = overall gain

An LER of 2 would indicate an bi-cropping system where both crops yield 100% of potential when planted together

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Benefits: Productivity - 3

- Agroforestry for multiple outputs through a rotation – stacking of enterprises, e.g. fruit/nuts trees in a silvopastoral system
- Reduced risk (market, disease, climate) from polycrop systems vs monocultures
- Use of tree products themselves: fodder, wood for construction, chippings for bioenergy, resins
- Generally requires farms to get closer to consumers, e.g. direct marketing of produce in farm shops
- Additional labour/machinery/processing costs must be considered

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Benefits: Productivity - 4

- Agroforestry establishment costs may be high, but supported under EU Rural Development programmes
- Normal 'farming' income continues until tree element matures
- Trees may provide income in long arable off-seasons
- Thorrold et al, 1997, demonstrated that New Zealand silvopastoral systems produced higher long-term profits than open pasture
- Fernandez-Nunez et al, 2007, found that over a 30 year period in Western Spain, profitability/ha was higher in agroforestry systems by 17% over pasture & 53% over forestry
- Reduced risk of field drought/extended growing season under canopy

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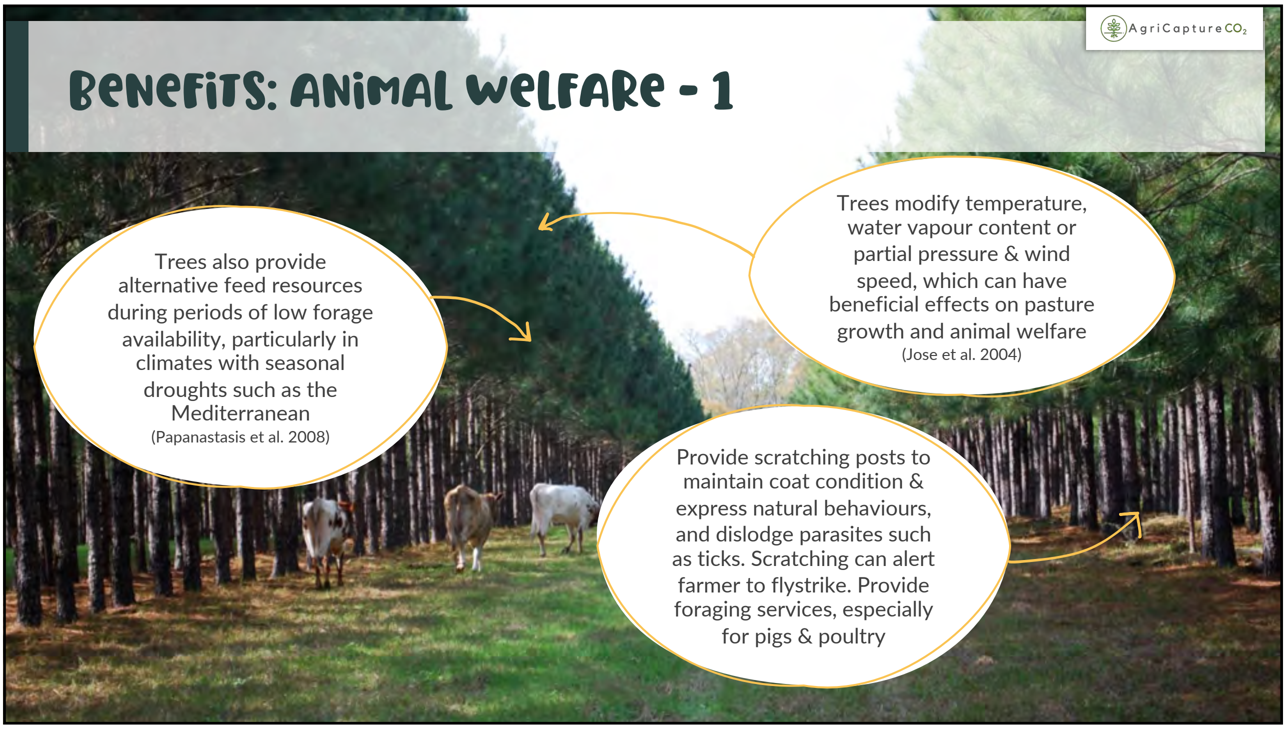

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Benefits: Animal Welfare - 2

- Trees offer shade in summer helping livestock regulate body temperature & maintain condition
- Mitlohner et al, 2006: cattle provided with shade reached target weight 20 days faster
- Research at Bangor University (UK) demonstrated sheep fleece temperature reached up to 60°c at field temperatures of 30°c
- Shade from silvopasture can reduce solar radiation by 58%
- Trees also offer shelter from winter rain & wind: at 2°c/24kph wind speed effective temperature becomes -7°c
- At 6°c, 100 sheep required 1/8ha spring grazing just to offset energy loss from keeping warm
- Minimum grass temperatures can be raised by 6°c under tree cover to extend the grazing season
- Shelter beneficial for newborn survival & parent bonding
- Shelter belts perpendicular to prevailing wind/field-scale silvopasture
- Insufficient shelter can cause overcrowding, welfare issues & soil damage

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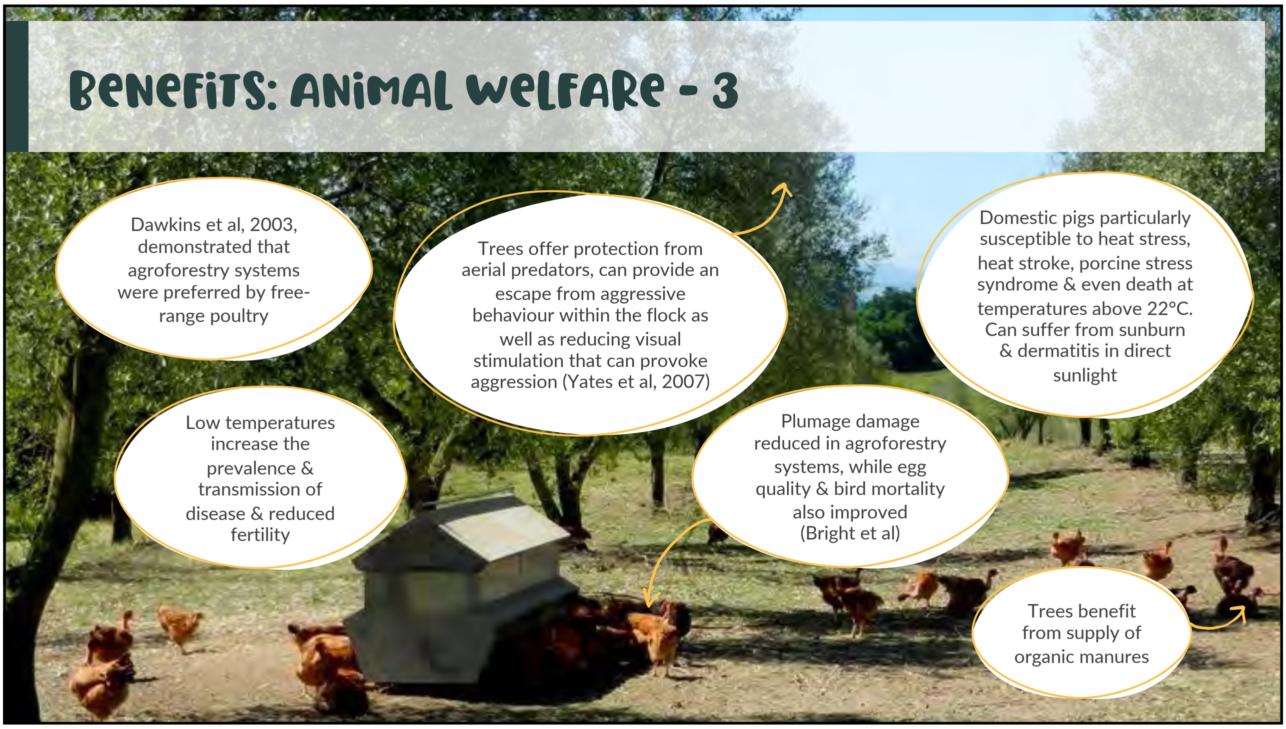

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Benefits: Biodiversity

Lampkin et al, 2015, studied biodiversity in UK agroforestry systems and found:

- Higher abundance & species richness of invertebrates (silvopasture)
- Higher abundance & species richness of airborne arthropods (silvoarable)
- Higher abundance of spiders & small mammals (silvoarable)
- Higher abundance & species diversity of butterflies & pollinators
- Torralba et al, 2016: "Our analysis shows a strong positive effect of agroforestry on [European] biodiversity".
- Diversity of habitat within an agroforestry system
- Agroforestry sites as 'stepping stones' in the landscape, especially for migratory species


A Greenfinch

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Benefits: Water Management - 1

- Evapotranspiration controlled by solar radiation, temperature, wind speed & humidity: hot & windy landscapes dry rapidly
- Use of shelterbelts to conserve moisture: porosity & height dictate level of protection given (Gardiner et al, 2006)
- A shelterbelt <40% porosity will reduce wind speeds by as much as 90% & protect an area up to 10 times the height of the shelter
- Tall shelterbelts with an optimum porosity 40–60% protect an area up to 30 times the height of the shelterbelt creating shelter suitable for crops
- Shelterbelts composed of native deciduous trees are a good choice as they are well adapted to local conditions
- During drought periods, tree roots access deeper soil horizons for water, reduce evapotranspiration from the understorey vegetation & provide shade for crops and livestock

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Benefits: Water Management - 2

- Tree roots access deeper soil horizons & a larger area than surface crops
- Under soil saturation, trees work like ’pumps’, removing water from the upper soil layer quicker than from land cropped with monocultures
- Roots also act as easy channels for water infiltration
- Improved soil organic matter levels in agroforestry systems may also help improve soil structure & porosity
- Dupraz et al; access to land for agricultural purposes after flooding events can be 7-14 days sooner under agroforestry than for land cropped as a monoculture
- Lee et al, 2003, found that tussocky grass/woody buffers retained 97% sediment runoff, 94% N and 91% P

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Benefits: Water Management - 4

- Jackson et al, 2008, demonstrated that 5-year plantations of native broadleaves in Wales demonstrated soil infiltration rates between 13-67x greater than ungrazed/grazed control plots
- Attributed to changes in soil macropore structure & was associated with a reduction in soil bulk density in the upper soil horizons – improved soil structure
- Reduced surface runoff, erosion & nutrient loss
- Careful placement of small strips of trees within a hillslope can reduce magnitudes of flood peaks by 40% at the field scale as streams become less 'flashy' & flood peaks reduce

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Case Study - Pontbren Project, Wales

- 10 farm cluster group, 1000ha from 2001 with the UK Woodland Trust
- Aimed to improve efficiency of upland livestock farming within one of the wettest areas of the UK
- Planted >10 miles of hedges & 120,000 trees & shrubs to provide shelter for livestock: 5% of catchment now forested
- Utilised local tree stock & created own nursery to ensure correct species for upland climate
- Waste wood chipped to provide livestock bedding & mulches/composts
- Shelterbelts & woodlands created for native sheep breeds to overwinter outside
- Soil water infiltration 60x greater in established woodland vs grazed pasture, due to surface capping & one-dimensional root structure
- Improvements in landscape biodiversity & water quality

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Benefits: Climate Change & Environment - 1

- European agriculture a major source of NH_3 ammonia (c.94%)
- Trees are effective scavengers of both gaseous & particulate pollutants from the atmosphere: increasing tree cover at source can reduce NH_3 pollution

Defra UK research 2007-11 demonstrated that:

Shelterbelts around livestock housing could reduce NH_3 emissions by 28%

Reduce understory emissions (e.g. free range poultry) by 60%

Establishing woodland downwind of housing caused reductions of 10-25%

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Benefits: Climate Change & Environment - 2

- Combined food & energy systems, incorporating crops, livestock & energy crops such as willow coppice, can compare favourably in term of energy use to conventional modes of production (Reith & Guidry, 2003)
- Agroforestry has the potential to reduce climate pressure by increasing afforestation of agricultural lands, reducing resource use pressure on existing forests & producing both durable wood products & renewable energy resources (Dixon, 1995)
- Reduced field intensity in some agroforestry situations – i.e. no longer practical to utilise broadacre techniques such as applying PPPs, synthetic fertilisers

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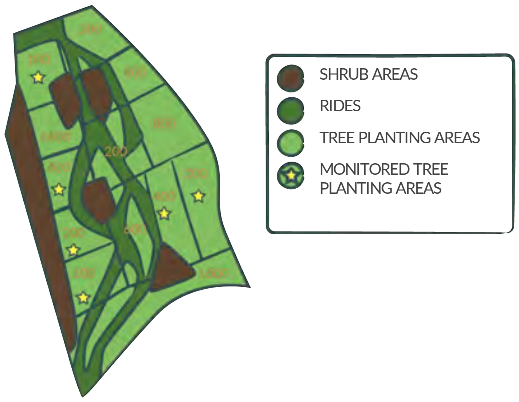
Benefits: Climate Change & Environment - 3

- Agroforestry can increase the amount of carbon sequestered compared to monocultures of crops or pasture due to the incorporation of trees and shrubs
- More growing days in perennial plants, with less C lost as it's sequestered in permanent growth
- Woody perennials store a significant amount of carbon in above ground biomass & also contribute to below ground carbon sequestration in soils. Volume dependent on:
  - system design
  - tree density per unit area
  - species composition & age
  - environmental factors, e.g. climate
  - management & end product/use



- The 25 year agroforestry trial at the GWCT Allerton Project, established 2016
- A range of systems established in one 5ha pasture field to discover optimum design

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Benefits: Climate Change & Environment - 4

- Estimated average carbon storage by agroforestry system, biomass & soil organic carbon (Schroeder, 1994)
  - Semi-arid: 9t/ha
  - Sub-humid: 21t/ha
  - Humid: 50t/ha
  - Temperate: 63t/ha
- Higher rates in temperate regions reflecting longer rotations/longer-term storage
- Sharrow & Ismail, 2004, found a Douglas fir/ryegrass/clover mix stored more carbon than either pasture or woodland
- After 11 years, the silvopasture had sequestered 740kg/C/ha more than forest, 520kg/C/ha more than pasture
- Result of higher biomass production & active nutrient cycling patterns within the silvopasture vs tree & pasture monocultures
- Peichl et al, 2006, recorded larger total C pools in
  - poplar/barley agroforestry (96t/C/ha)
  - spruce/barley agroforestry systems (75t/C/ha)
  - vs barley monocrops (68t/C/ha)
- Gupta et al, 2009, observed increases in soil organic carbon, from 0.36% in monocropped cereals to 0.66% in poplar/cereal agroforestry soils, amounting to 2.9-4.8t/C/ha more soil organic carbon in agroforestry soils
- Multifunctional spatial/temporal nature of polycrops = higher potential for C sequestration
- Possible offsetting of carbon-heavy forms of building material/fuel

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CASE STUDY: FEEDING WILLOW AT THE GWCT ALLERTON PROJECT

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- Digestibility of tree leaves is relatively low compared to grass, but crude protein & mineral levels of some species are relatively high, showing the potential value of tree leaves as an additional feed source
- Willow a source of tannins, which reduce protein degradation in the rumen & increase protein flow to intestine
- Sheep fed 200g/day of willow leaves to assess impact on ammonia, nitrous oxide & carbon dioxide emissions from urine
- All emissions were lower vs control group. Suggested methane from belching is also reduced
- Tannins also have an anthelmintic affect, reducing intestinal parasites
- Also a significant source of micronutrients such as zinc & copper
- However, an excess of tannins can be toxic to livestock
- Can willow & similar species be effectively integrated into agroforestry systems to reduce GHGs & improve livestock health?

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CASE STUDY: FEEDING WILLOW AT THE GWCT ALLERTON PROJECT

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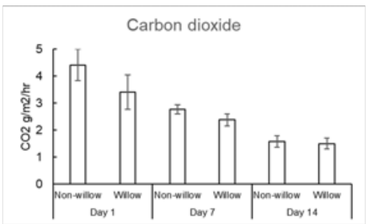
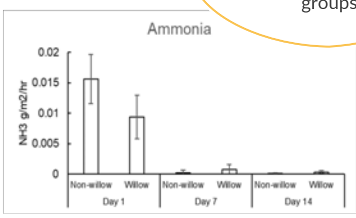
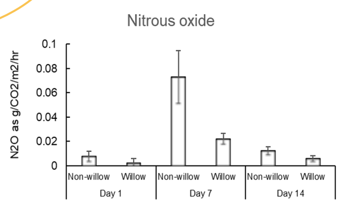
- Leaves stripped directly from cut branches

Across all gasses emissions clearly reduced vs control groups







CO_2 emissions from urine patches more prolonged than emissions from both ammonia & nitrous oxide

Game & Wildlife Conservation Trust

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Bedankt
Efharisto poli
Hvala vam
Merci
Danke
Dziękuję wam
Thank you
gilab
SatAgro
One Carbon World
EEB
European Environmental Bureau
GWCT
THE ALLERTON PROJECT
planet.
ELGO - DIMITRA
mellow yellow
EnvirometriX
Lancashire County Council
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ARTHUR'S LEGAL

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Application of Compost

MODULES: INTEGRATION OF ORGANIC MATTER

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COMPOST

- Amendment/conditioner used to improve soil fertility & mechanics. Provides:
  - Nutrients
  - Organic matter
  - Beneficial microbes
- Made from controlled biological decomposition of either green waste (leaf/woody material) or mixture of green waste & food waste in the presence of oxygen
- Combines available organic waste to create a uniform & stable product
- Reduces bulkiness of organic materials, stabilises soluble nutrients & speeds formation of humus
- EU Landfill Directive aims to reduce organic biodegradable waste sent to landfill: compost & anaerobic digestate are one sustainable outlet

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COMPOST

- Quality compost requires a mix of ‘greens’ (N-rich feedstock such as prunings/food waste) & ‘browns’ (carbon-rich woody materials, straw)
- Composting aided by shredding plant matter, adding water (40-60% water content while composting) & aerating in windrows
- Fungi, earthworms & other detritivores further fragment OM
- Aerobic bacteria & fungi produce heat, CO2 & ammonium
- Decomposes into humus-like material
- Mature compost typically 50-60% OM

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COMPOST

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- Composting: **an aerobic method of decomposing organic solid wastes**
- Composting organisms require:

CARBON	NITROGEN	OXYGEN	WATER
Microbial oxidation of carbon produces heat needed to compost	essential to synthesis proteins/amino acids required for growth of microbial biomass	essential for oxidation & decomposition; >5% required	an essential catalyst in correct quantities to avoid anaerobic conditions

- Active management (turning) required to aerate & wet the material
- Essential to maintain composting temperature of 50-70°c
- Carbon:Nitrogen (C:N) around 30:1 – close to ideal for soil microbes

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COMPOST

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MESOPHILIC PHASE

Decomposition carried out under moderate temperatures by mesophilic microorganisms

THERMOPHILIC PHASE:

Thermophilic bacteria carry out decomposition at higher temperatures (40-60°c)

MATURATION PHASE

As high-energy compounds reduce, temperature decreases & mesophilic bacteria mature the compost. Beneficial bacterial populations increase & ammonium is converted to nitrate

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COMPOST ORGANISMS

- Chemical decomposers
- Bacteria process C & N, excreting plant available nutrients such as N, P, Mg.
- Mesophilic bacteria operate at lower temperatures & bring compost up to temperature range of thermophilic bacteria (40-60°c)
- Actinobacteria & fungi specialise in breaking down 'brown' materials rich in lignin/cellulose, making C, N & NH3 available to plants
- Protozoa contribute to biodegradation of organic material & consumer non-active bacteria & fungi
- Physical decomposers
- Organisms such as earthworms, springtails & ants break down organic materials, aerate the windrows & cycle nutrients in the compost into plant-available forms

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WHAT IS SOIL ORGANIC MATTER (SOM)?

- All living or once living materials within & added to soil
- Includes roots, crop residues, manures & composts
- Contains carbon, nitrogen, phosphorous, sulphur, potassium, magnesium, calcium & other micronutrients
- Composed of c.58% carbon
- The interaction of OM with parent geology is a key process in soil formation
- Agricultural soils typically from 1-6% SOM
- +1% SOM can increase yield by as much as 10%

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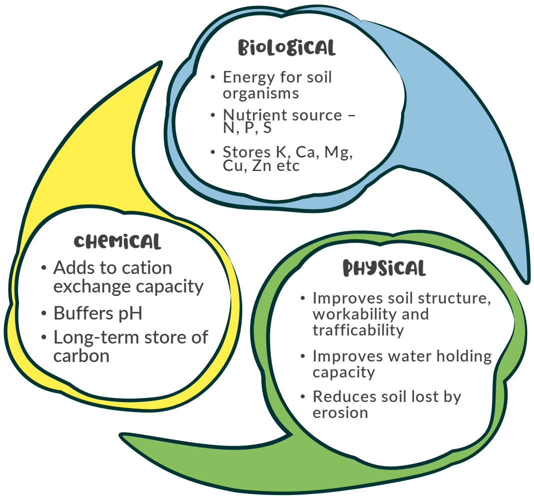
SOIL ORGANIC MATTER (SOM)

- Essential for soil biological, physical & chemical processes
- The living, the 'dead' & decomposing (detritus) & the 'very dead' (humus) – actively cycling vs stable, long-term soil organic carbon (SOC)
- Provides nutrients & energy for soil biome
- Keystone of healthy soil structure
- Boosts water holding capacity (WHC)
- Buffers pH & aids cation exchange capacity (CEC)



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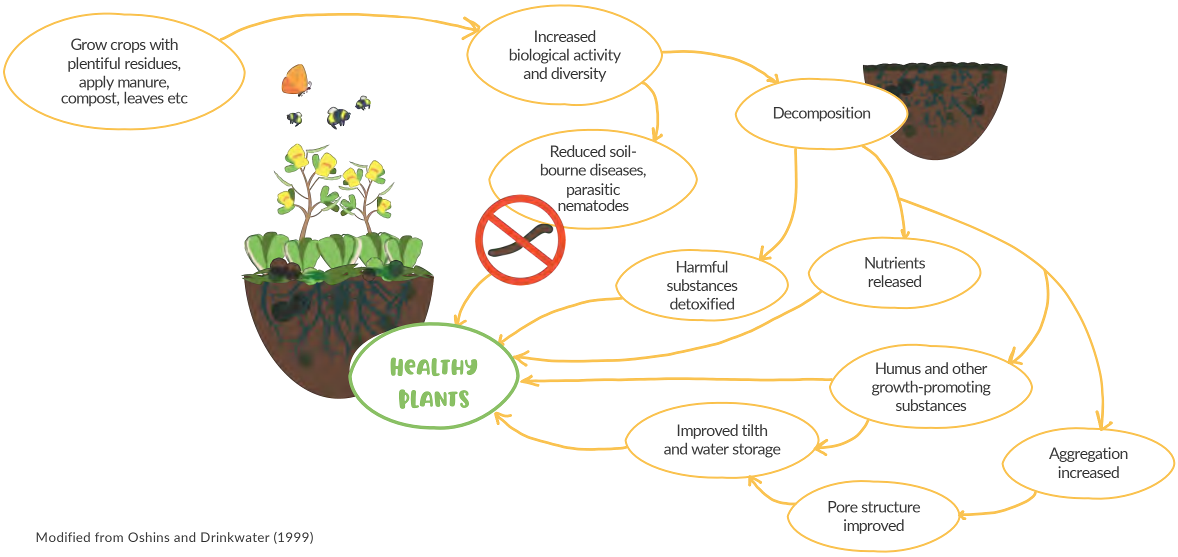
WHY IS SOIL ORGANIC MATTER IMPORTANT?



Modified from Oshins and Drinkwater (1999)

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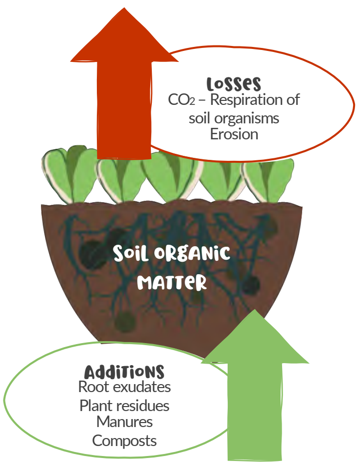
ORGANIC MATTER ADDITIONS - 1

- Levels of soil organic matter = equilibrium between inputs & decomposition of SOM by soil organisms. Inputs must exceed losses to build SOM.
- Levels of SOM present in soil can be affected by natural processes such as
  - Temperature
  - Rainfall
  - Soil type & texture
- But also human processes such as
  - Tillage
  - Removal of crops/crop residues
  - Application of artificial N
- Important to adapt management practices to reverse losses before increases can be gained



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ORGANIC MATTER ADDITIONS - 2

CARBON:NITROGEN (C:N) RATIO

- Dictates how fast soil microbes break down biomass & release nitrogen
- Microbes use carbon for energy & nitrogen for protein
- C:N of 24:1 ‘ideal’ diet for soil microbes
- To decompose high C:N microbes utilise soil N, resulting in a temporary N deficit (immobilisation)
- Manures with a lower C:N will be consumed with excess N remaining in the soil (mineralisation) - though they may also scavenge soil carbon to achieve this
- Higher C:N manures more likely to contribute to stable SOM
- Choice of manure = important
- Compost around 30:1

ORGANIC ADDITION	C:N RATIO
Micro-organism's composition	8:1
Microorganism's preferred diet	24:1
Livestock slurries	4 -10:1
Vetches	11:1
Biosolids	14:1
Farmyard manure	17-20:1
Pea straw	29:1
Green wastes and composts	30:1
Oat straw	70:1
Wheat straw	80:1
Paper waste	150-200:1

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ORGANIC MATTER ADDITIONS - 3

Impact of organic matter additions also related to:

- Loading rate: rate & frequency of application. Benefits often only seen after significant applications over many years
- Dry weight: organic materials can range in water content from 10% to 90%. Carbon is closely related to dry matter
- Economics: AHDB (UK) research indicates OM applications become uneconomic above £30/t (€35) dry matter/hectare/year (including costs of application)

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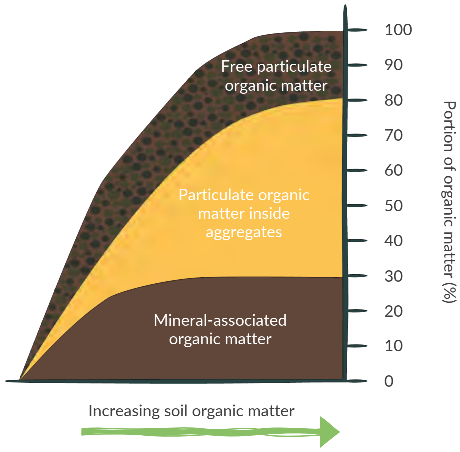
ORGANIC MATTER ADDITIONS - 4

- Easier to increase SOM in degraded soils vs additional improvements to high SOM soil
- But difficult to raise SOM levels in coarse, sandy soils (where 2% SOM might be a good level) vs fine textured clay soils (where 6% might be good)
- Degraded soils will initially see free mineral surfaces bound with OM particles
- Small aggregates will form around OM particles, in turn forming larger aggregates
- Once mineral sites & micro-aggregates are saturated, OM accumulates as free particles within larger aggregates or unaffiliated with minerals
- This unprotected free particulate OM is actively cycling
- This process goes into reverse under soil degradation



Organic matter changes in soil as practices favouring buildup are implemented.
Redrawn and modified from Angers (1992)

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COMPOST: NUTRIENTS

- Typically low in plant-available (inorganic) N, but long-term applications can build (organic) soil N supply
- High in plant-available P & K
- Typically, 50% of P & 80% of K available in first cropping year
- Potential to reduce mined mineral inputs
- Most composts have a liming value – in some cases exceeding 15% of the liming value of ground limestone. Individual batches should be tested
- Atmospheric emissions (ammonia, nitrous oxide, methane) and leaching losses (nitrate, phosphate) are very low from compost

Typical Green Waste Compost nutrient content*	kg/t (fresh weight)
Dry matter content	60%
Nitrogen	7.5
Phosphate	3.0
Potash	5.5
Magnesium	3.4
Sulphur	2.6
Readily available N	<0.2

Source: SRUC TN650: 'Optimising the application of bulky organic fertilisers' (2013)

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PAS 100 COMPOST QUALITY STANDARD (UK)

Sets a minimum compost quality baseline	The Compost Certification Scheme (CCS) provides assurance to consumers, farmers, food producers & retailers that Quality Compost produced from composting processes is safe for human, animal & plant health.	Quality Compost = compost certified under the CCS for end-of-waste & quality assured status
PAS 100 (Publicly Available Specification for Composted Materials) means that the compost is no longer subject to waste regulatory controls & has achieved 'product status'	PAS 100 applies to the centralised, on-farm & community composting of biodegradable wastes & materials that have been kept separate from those that are not biodegradable	Intended to improve confidence in composted materials & help identify products which are safe, reliable & high-performance

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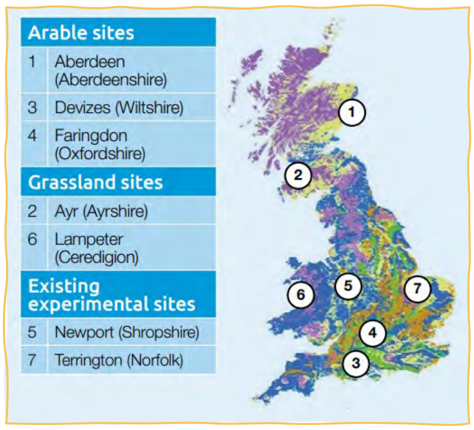
CASE STUDY: DC-AGRI PROJECT

- AHDB (UK) research to create the evidence base for the safe, confident use of digestate & compost
- Impact of different regimes over 7 sites & a range of soil/climate types
- 3 year trial
- 2 sites had a prior history of organic matter inputs



AHDB

wrap

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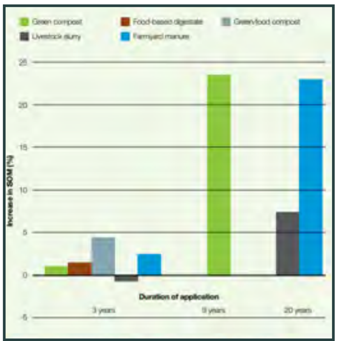
Case Study: DC-Agri Project

- No significant change in soil OM after 3 years – long term additions necessary
- Significant >20% increase from compost after 9 years
- Suggestion that compost builds OM faster than FYM
- Retention of compost OM twice that from FYM: 70% of compost OM comprised of more stable lignin, versus 55% for FYM
- Compost already more decomposed into humus-rich material



Source: AHDB/WRAP 'Field experiments for quality digestate & compost in agriculture' (2016)

AHDB
wrap

Material	Application rate (tonnes/hectare)
Synthetic fertiliser control (no organic matter)	To address crop need
Quality green compost	16
Farmyard manure (FYM)	16
Quality green/food compost	11
Livestock slurry	8
Food-based digestate	2
Manure-based digestate	3-6 (depending on N content)

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Case Study: DC-Agri Project

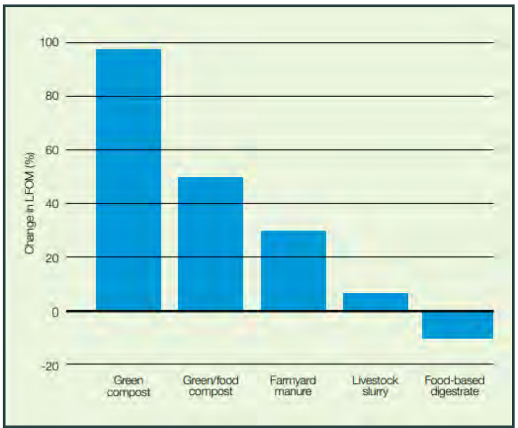
- Soil microbial biomass & earthworm numbers also increased in 9-year compost plots – though less than in 20-year FYM plots (FYM has more readily decomposable OM)
- Decreased soil bulk density demonstrated in long-term plots leading to improved soil structure & health
- Compost plots more resilient than control plots in drought years
- Benefits of bulky organic manures to improve soil health & structure (vs e.g. slurry/digestate)

AHDB
wrap

20

CASE STUDY: DC-AGRI PROJECT

- Building SOM a long-term commitment
- However, even after 3 years Light Fraction Organic Matter (LFOM) demonstrated to have doubled in compost plots
- LFOM – the active fraction of OM – a potential indicator of longer-term SOM benefits



Source: AHDB/WRAP 'Field experiments for quality digestate & compost in agriculture' (2016)

21

BEDANKT EFHARISTO POLI

HVALA VAM MERCI

DANKE DZIĘKUJĘ WAM

THANK YOU

22

Healthy Soil · Healthy Crops · Healthy Businesses

5 Principles of Regenerative Agriculture

Application of Biochar

MODULE: INTEGRATION OF ORGANIC MATTER

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1

2

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WHAT iS biOCHAR?

- A charcoal produced through pyrolysis of biomass under controlled temperature in a low oxygen environment
- Characterised by a fine texture & high surface area
- Highly stable, carbon-rich solid also containing residual mineral matter & organic matter
- Particular properties of biochar vary by feedstock – wood, straw, manures, tree prunings…

3

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WHAT iS biOCHAR?

- Resists decay
- Particle size 2-10mm
- Feedstock:biochar yield of 5-50% depending on burning conditions & feedstock
- Higher temperatures/shorter burns produce less char BUT of an even more stable nature
- High mineral feedstocks (e.g. chicken litter) = even higher mineral biochar with loss of volatiles during pyrolysis
- Conversion of biomass carbon to biochar sequesters c.50% carbon vs 3% from burning/c.20% from biological decomposition
- Valuable as a soil amendment

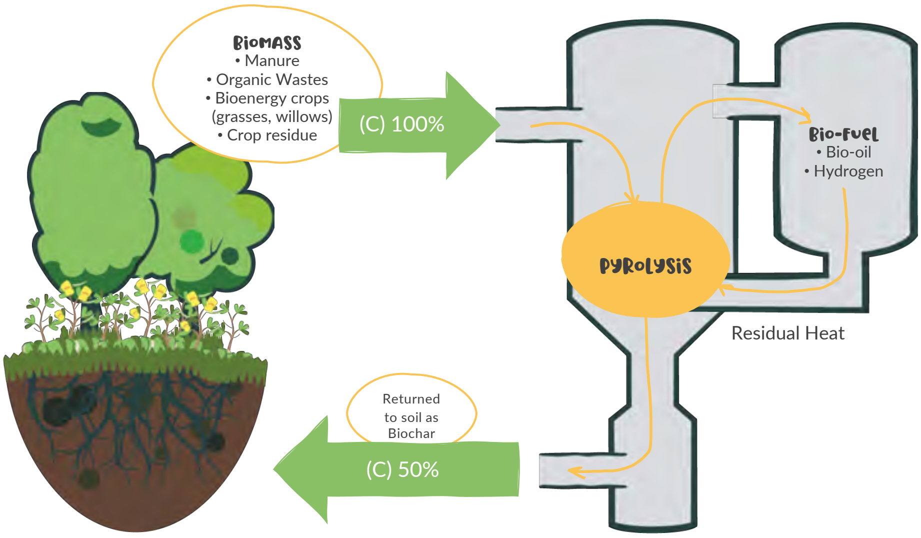
4

PYROLYSIS

- Thermal decomposition of biomass at controlled temperatures in a low/no-oxygen environment (preventing combustion)
- Produces a mixture of solids (biochar & some ash) liquids (bio-oil) & gas (syngas) products
- Biomass typically burned at 4-500°c for around 8 hours
- Must be cooled before exposure to oxygen to avoid combustion
- Water completely removed, with many organic molecules (e.g. cellulose, lignin) broken down & driven off as volatiles
- Emission of carbon dioxide/hydrogen/carbon monoxide
- Non-volatile residues become richer in carbon
- Scales from household to industrial

5

PYROLYSIS



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Biochar as a Soil Conditioner

What is a Soil Conditioner?

- A product added to soil to improve its physical qualities, primarily:
- Fertility
- Nutrient availability
- Cation exchange capacity (CEC)
- Soil biological activity
- Mechanics
- Soil structure
- Water holding capacity (WHC)
- Biochar demonstrated to possess all these attributes (dependent upon feedstock/pyrolysis technique/soil type)

7

Biochar: Inoculation & Charging

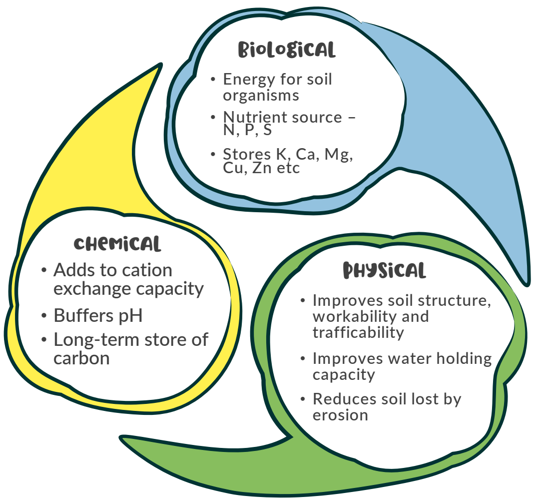
- For biochar to act as a soil improver, it must be inoculated/charged or both (activating) to fill its pores with nutrients
- Inoculation: addition of microbes to biochar (via aerobic compost tea?)
- Charging: addition of nutrients (via organic matter/inorganic fertilisers)
- Mix biochar with manure/compost for dual activation
- Raw biochar can make soil nutrients immobile, creating a short-term deficit for soil microbes & growing crops
- Mixing with manure can also reduce odour & ammonia emissions – often in layers in housed bedding to ensure good mixing

8

Benefits: biochar

Soil carbon

- Chemical structure of biochar characterised by poly-condensed aromatic groups that provide prolonged chemical & biological stability against microbial degradation
- Highly stable form of soil organic carbon which can endure for centuries
- Ability to sequester 2.1-3.6t CO2e per tonne of biochar added to soil according to UK trials by Arla
- 'Pyrogenic carbon capture & storage' as a means to sequester atmospheric carbon from photosynthesising biomass while improving soil health & fertility



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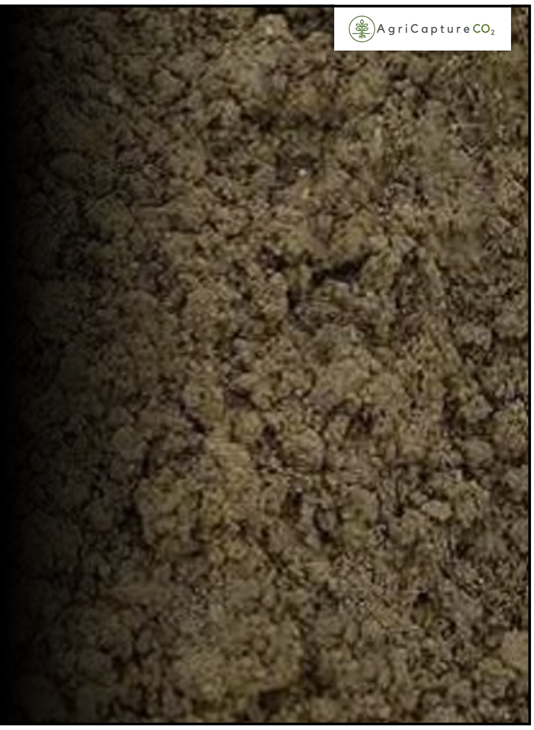
Benefits: biochar

Soil structure

- Porosity of biochar structure increases soil bulk density & aeration/infiltration
- Stability of biochar = reduced mineralisation vs non pyrogenic biomass: fragmentation into micro particles of SOC which help formation of soil micro-aggregates
- Formation of micro-aggregates improves soil structure & stability (pore spaces) leading to improved soil biome & formation of macro-aggregates & enhanced nutrient cycling
- Reduced compaction, erosion, runoff & leaching



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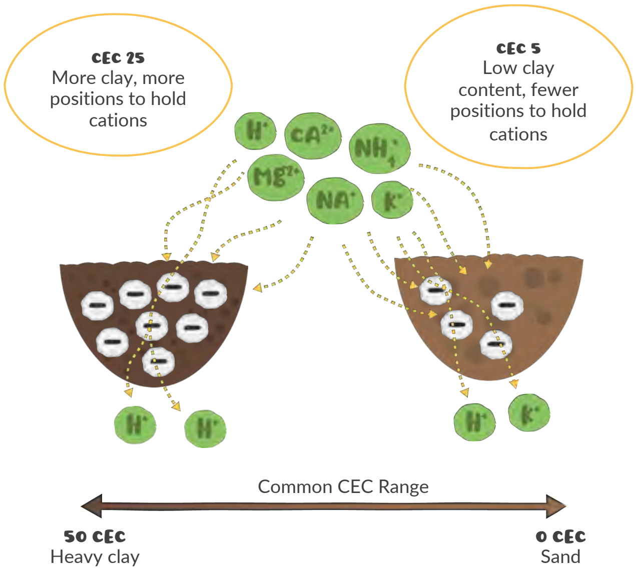
Benefits: biochar 1

Cation exchange capacity (CEC) & nutrient availability

- Clay mineral & organic matter components of soil have -ve charge sites on their surfaces which adsorb & hold +ve charge cations by weak electrostatic force
- Critical to supply of plant nutrients as many exist as cations (Mg, P, Ca, Na, NH4)
- Soils with large –ve charge tend to be more fertile as they retain more cations (higher CEC) vs leaching in low CEC (sandier) soil
- The lower the CEC, the faster pH will also decline



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Benefits: biochar 2

- Microscopic structure of biochar key to its soil conditioning properties
- Hugely increased surface area due to the thermal decomposition of feedstock and elimination of volatiles
- Remaining structure consists of highly concentrated carbon chains
- High CEC – especially at higher pyrolysis temp
- Carbonaceous surface covered in oxygen groups with ion exchange properties
- Related to large number of pore spaces & significant surface area to hold –ve charged sites (but pores collapse at very high char temps)
- Effective at retaining soil nutrients & reducing leaching/increasing fertiliser use efficiency

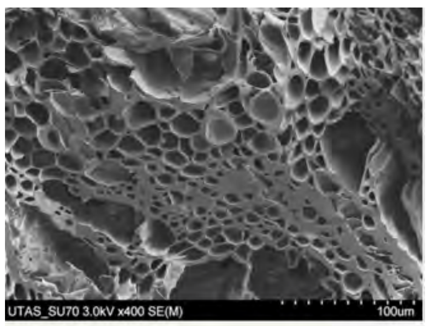

Image courtesy of Dr Jocelyn of Biochar Industries / Biochar Projects and Friends of the Char

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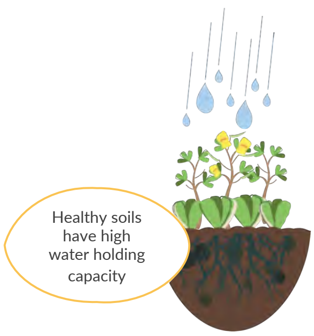
Benefits: biochar 4

- Structure of biochar also key to increasing water holding capacity (WHC) of soils, mitigating against drought/increasing productivity
- Reduces nutrient loss & leaching, makes nutrients more available to plants
- Related to significant number of pore spaces & high CEC
- Biggest impact on light, sandy or degraded soils
- Ok-Youn Yu et al, 2013, found a doubling of WHC in a loamy sand soil using a 9% mixture (195t/ha) from wood feedstock
- Beneficial to increase WHC in small-scale high value crops, e.g. olives



Every **1%** increase in organic matter can result in up to **20,000** gallons of available soil water per acre*

Healthy soils with high organic matter will equate to higher water holding capacity
*USDA-NRCS

13

Benefits: biochar

- Increases soil pH
- Depends on feedstock & pyrolysis conditions
- Biochar generally alkaline due to conversion of base cations into oxides, hydroxides & carbonates during burn
- Concentrated in ash element
- Mineral-rich, high-temperature biochar most likely to be high pH

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Benefits: biochar

- Soil biological activity
- Microscopic structure of biochar provides safe habitat for soil micro-organisms, boosting microbial biomass (Xiaona Li et al, 2020)
- Microbial diversity more dependent on soil type
- Increases greatest in degraded & sandy soils, especially with regular additions
- Inoculation of biochar pre-application
- Micropores serve as habitat for fungal hyphae, protected from saprophytes
- Application of SOC creates wider conditions beneficial to soil biological activity
- Alkaline nature of biochar improves soil pH to favour microbiology

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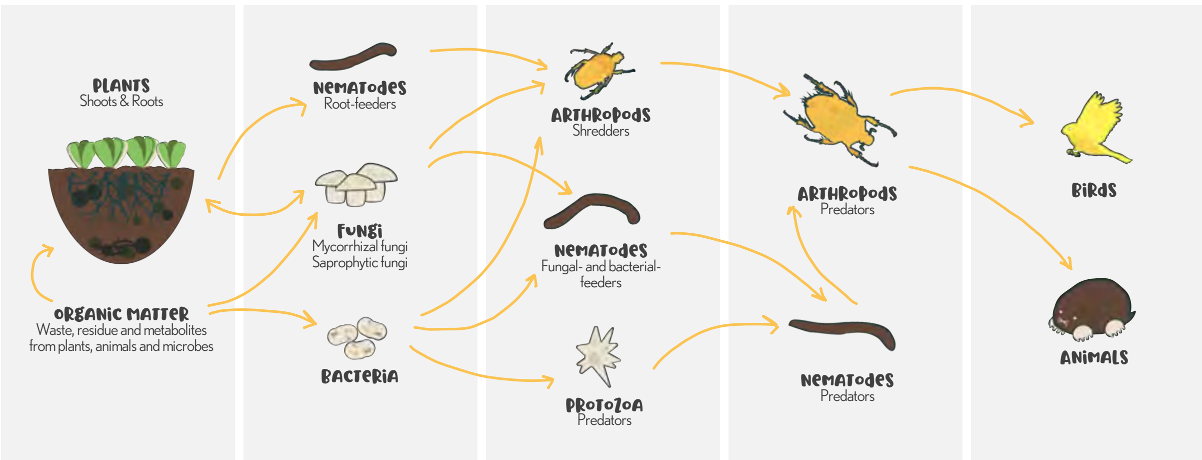
Benefits: biochar



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Terra preta de indio

- 'Indian black earth' – biochar + organic manures
- Practiced by pre-Columbian native Amazonian cultures
- Addition of biochar to deforested land either intentionally or as a result of slow-burning of residues in tropical climate
- Up to 70x the soil organic carbon of surrounding natural soils!
- Rich in N, P, K, Ca
- Up to 6ft deep & self-propagating: high SOC levels sustain rich soil full of beneficial soil organisms
- Historic char also present in many prairie soils as a result of natural fires

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Challenges of biochar

- Currently commercially limited – very large quantities/ha potentially required in broadacre operations
- Variable impact dependent on soil type, feedstock, char temperature
- Method of application & incorporation
- Possible nutrient immobilization from raw biochar
- Rick of carbon leakage in biochar production: e.g. feedstocks sourced from non-sustainable sources
- Potential to immobilize some residual herbicides

18


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Bedankt
Efharisto poli
Hvala vam
Merci
Danke
Dziękuję wam
Thank you
gilab
SatAgro
One Carbon World
EEB European Environmental Bureau
GWCT
THE ALLERTON PROJECT
planet.
ELGO - DIMITRA
mellow yellow
EnvirometriX
Lancashire County Council
AGRICULTURAL UNIVERSITY OF ATHENS
ARTHUR'S LEGAL

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5 PRINCIPLES OF REGENERATIVE AGRICULTURE

HEALTHY SOIL · HEALTHY CROPS · HEALTHY BUSINESSES

COVER & CATCH CROPS

CONTRIBUTION OF ORGANIC MATTER (ON-FARM)

MODULES: BIOLOGICAL DIVERSITY, MAINTAIN LIVING ROOTS, SOIL PROTECTION, REDUCE SOIL DISTURBANCE, INTEGRATION OF ORGANIC MATTER

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1

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WHAT IS A COVER/CATCH CROP?

A fast growing, non-cash crop grown primarily for the purpose of protecting and improving soil between periods of regular crop production

FOUR MAIN TYPES:

GRASSES/CEREALS	BRASSICAS	LEGUMES	'OTHERS'
• Oats • Rye • ryegrass	• Radish • Mustard • Turnips	• Vetch • Clover • Lucerne	from different taxonomic groups to those in a normal arable rotation (buckwheat/phacelia/ herbs)

3

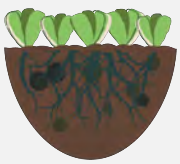
WHAT IS A COVER/CATCH CROP?

FOUR MAIN MODES OF ACTION:

- Improving soil fertility
- Improving soil structure
- Managing weeds & pests
- Environmental management

BUILD SOIL HEALTH & QUALITY

RETAIN SOIL FROM EROSION



SUPRESS WEED GROWTH

IMPROVES BIO-DIVERSITY

4

Cover vs Catch Crops

Catch Crops

- short term (6-8 weeks)
- fast growing
- planted between two regular crops grown in consecutive seasons, generally in the autumn

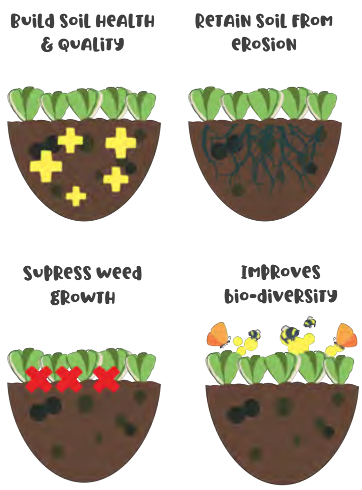
Cover Crops

- longer term (up to 6 months)
- planted between main cash crops, generally over wintered

5

Primary benefits of cover/catch crops

- Increase soil organic matter
- Reduce soil erosion (wind & water)
- Fix & cycle soil nutrients
- Build soil fertility
- Boost soil biology
- Improve soil structure
- Improve soil water infiltration/reduce soil transpiration
- Managing weeds and pests
- Habitat creation & biodiversity
- Cover crops as forage



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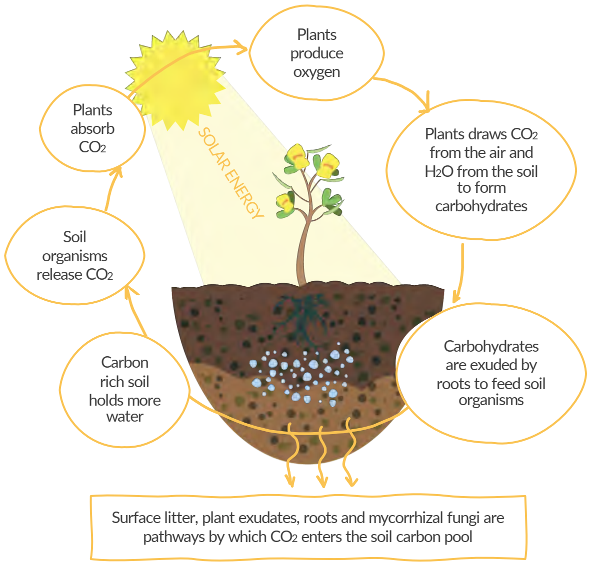
Benefits: Increase Soil Organic Matter - 1

- OM >50% carbon
- Adds to soil fertility & health by enhancing physical, chemical & biological properties
- Increasingly important to build soil climate resilience

3 main pools of soil OM:

- Fresh plant residues (litter, decaying roots) and soil organisms
- Decomposing (active) OM
- Stable OM, often bound to clay minerals (humus)



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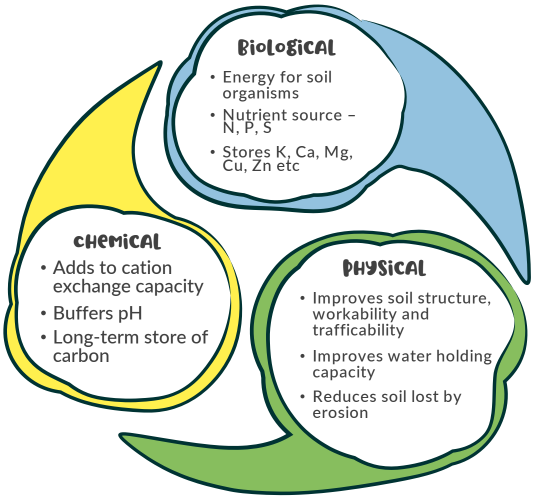
Benefits: Increase Soil Organic Matter - 2

- Fresh plant residues fuel soil biome
- The amount of decomposing OM impacts on soil biology, nutrient cycling & structure
- The amount of humus alters the physical and chemical properties & processes in the soil
- Increased SOM = improved soil structure, water infiltration & holding capacity & cation exchange capacity



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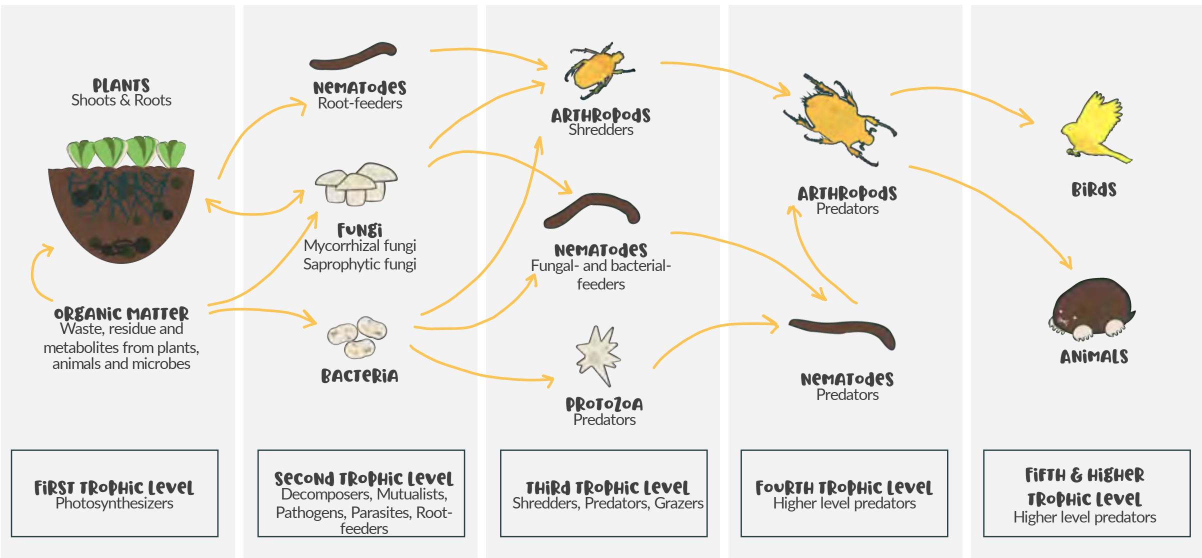
Benefits: Increase Soil Organic Matter - 3

- Cover crops produce biomass at large volumes above & below ground
- Incorporation of CCs as green manures to boost SOM
- Stimulates & feeds soil biological activity
- Living roots also secrete carbon-rich exudate fluids into the rhizosphere (the soil zone surrounding the plant roots)
- Up to 20% of photosynthetically fixed carbon is transferred via exudates to the rhizosphere, primarily as amino acids, organic acids & sugars
- Particularly important to plant-mycorrhiza symbiosis in the rhizosphere, allowing cover crops to access nutrients & water otherwise unavailable to root system

9

Benefits: Increase Soil Organic Matter - 3



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Benefits: Increase Soil Organic Matter - 4

How Plants Sequester Carbon

11

Benefits: Increase Soil Organic Matter - 5

- OM benefits of CCs dependent on varieties used: plants rich in proteins & sugars (e.g. perennial legumes) will release nutrients rapidly but leave little OM residue.
- Grains & grasses release fewer nutrients more slowly but contribute more biomass & stable OM (humus) to build SOM
- Short-term ability of CCs to boost SOM can be very limited; long term incorporation in a low-cultivation rotational system is essential

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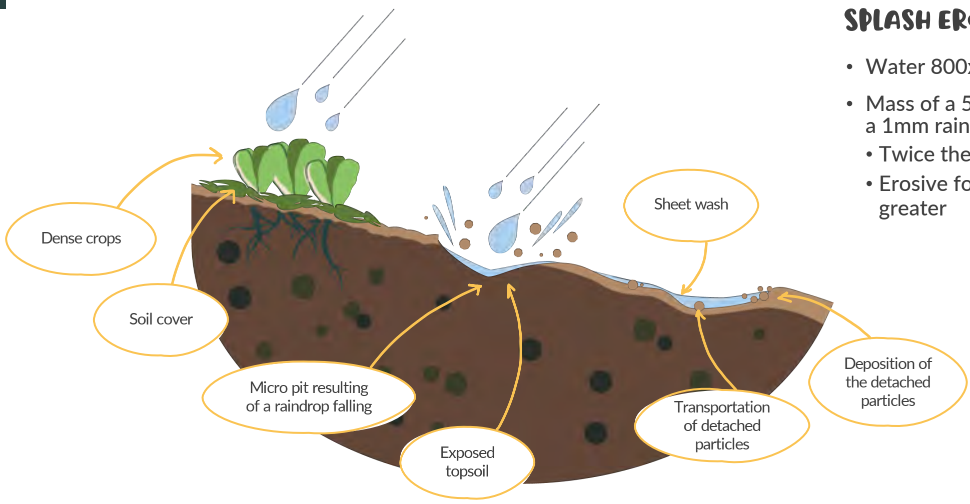
Benefits: Reduce Soil Erosion - 1



Splash Erosion

- Water 800x heavier than air
- Mass of a 5mm raindrop 125x that of a 1mm raindrop
  - Twice the terminal speed
  - Erosive force on impact 500x greater

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Benefits: Reduce Soil Erosion - 2

- Water sheet, rill & gully erosion across the field surface
- Erosive capacity of water determined by volume, speed and gradient
- Bare, cultivated & compacted soil most at risk
- Tractor tramlines greatest source of erosion/runoff

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Benefits: Reduce Soil Erosion - 3

- Wind erosion – achieved at wind speeds over 20kph
- Suspension of finer particles into dust clouds
- Saltation of coarser materials into dunes
- Dry, cultivated, bare soils most at risk

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Benefits: Reduce Soil Erosion - 4

- Wind erosion most likely in summer on dry cultivated land (catch crops)
- Water erosion most likely in autumn/winter when rainfall levels are high on cultivated, fallow land (cover crops)
- Sloping land most at risk
- Loss of fertile topsoil contributes to watercourse sedimentation and nutrient/pesticide pollution, impacting on water quality and biodiversity

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Benefits: Reduce Soil Erosion - 5

- Cover/catch crops provide ground cover during erosion risk periods
- Ground cover of 35-50% significantly reduces erosion risk
- Reduce wind erosion by reducing wind speed at soil surface & binding soil together
- Canopy intercepts rainfall and reduces splash erosion – especially high tillering varieties such as brassicas
- Root systems stabilise soil and increase infiltration by slowing surface flow and creating more channels/improving soil structure & porosity
- Soil cover of 30% can reduce runoff by 50% and erosion by 80% (Kainz, 1989)

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Case Study: Cover Crops in Mediterranean Orchards - 1

- 'Sustainability using cover crops in Mediterranean tree crops, olives and vines', (Gomez, 2017)
- Agronomic practices prioritise tree soil water balance to maximise yield
- Includes low tree density, canopy pruning & elimination of weeds to reduce competition for scarce water resources
- But this can lead to soil degradation, erosion and loss of biodiversity, especially in sloping areas

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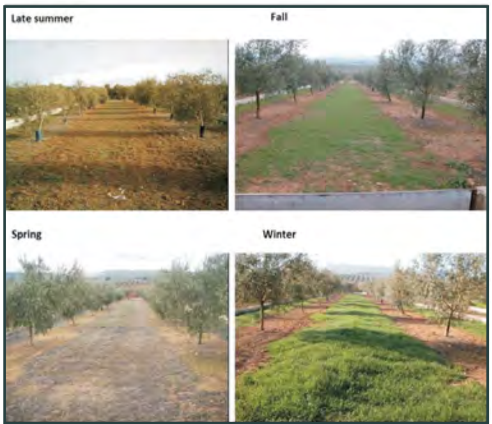
Case Study: Cover Crops in Mediterranean Orchards - 2

- Use of temporary cover crops along tree avenues can reduce soil damage & increase biodiversity.
- Planted late autumn, utilise winter rainfall & terminated in early spring to provide plant residue soil cover through summer & reduce evapotranspiration
- Timely termination vital to avoid competition via transpiration for scarce water resources in late spring/summer, especially in thinner soils
- Trials show soil runoff can be reduced by c.60% by use of cover crops



Evolution of a temporary cover crop in an olive orchard during the four seasons of the year.

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Benefits: Fix & Cycle Soil Nutrients - 1

- Leaching – the loss of water soluble nutrients from soil due to excess rainfall and irrigation
- Reducing leaching can be more important for soil fertility than fixing N – especially in winter when legumes are slow to fix
- Leaching affected by soil type & structure – light soils particularly at risk
- Heavily influenced by soil N levels
- Leaching also influenced by cultivations

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Benefits: Fix & Cycle Soil Nutrients - 2

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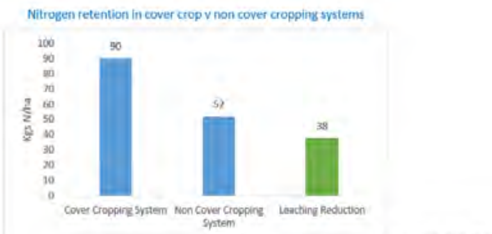
- Cover & catch crops used to assimilate nutrients, especially nitrogen (N) phosphate (P) and potash (K) in the field for the benefit of the following crop after termination
- Reduced soil erosion through cover crops key in reducing loss of P bound to soil particles
- Cover crop uptake of N reduces the risk of nitrate leaching over winter
- Fast growing species with deep root systems (grazing rye, mustard) most effective (N)
- Buckwheat particularly suited to scavenging P
- Can lead to mean N leaching reductions of 40% (Kelloggs Origins)
- N uptake typically between 30-100kg N/ha
- 10-100kg N/ha typically available to following crop after incorporation & mineralisation



Source, NIAB TAG 2016

kg/ha N	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Mean
Nitrogen – cover crop system	150	96	71	74	74	77	90
Nitrogen – no cover crop	69	39	44	44	54	59	52

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Benefits: Fix & Cycle Soil Nutrients - 3

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Average soil leaching reduction varies by cover crop type (Meisinger et al, 1991), with legumes less active scavengers of N

62% reduction from brassicas

61% reduction from grasses

25% reduction from legumes

22

Benefits: build Soil Fertility - 1

- Legume cover crops can provide N via biological nitrogen fixation (BNF) from the atmosphere
- Converts atmospheric N (N2) to ammonia (NH3) then ammonium (NH4)
- Early establishment (late summer/early autumn) is key, as fixation can take up to 6 weeks to commence
- N fixation most effective above 7°c (limited in winter in N Europe)
- Available to following crops and other soil biology after incorporation & mineralisation (short term) or increasing soil mineralizable nitrogen SMN (longer term)

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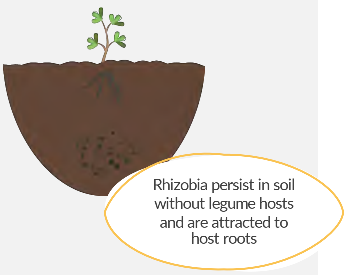
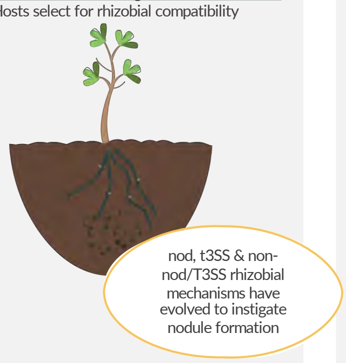
Benefits: build Soil Fertility - 2

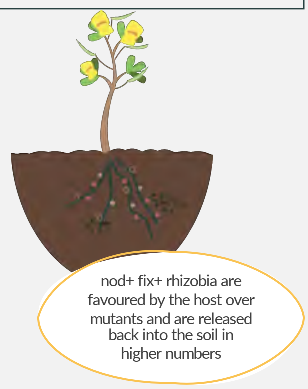
Pre-symbiosis
- Rhizobia thrive in soil
- Host seedlings must acquire symbionts in each generation



I: Nodule formation & invasion
- Rhizobia instigate nodule formation through at least three different mechanisms
- A suite of other rhizobial functions promote nodule infection and modulate host range
- Hosts select for rhizobial compatibility



II: Symbiotic nitrogen-fixation
- Nitrogen fixation requires the nitrogenase enzyme and microaerobic conditions in the nodule
- Hosts sanction ineffective rhizobia, selecting for nitrogen fixation



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Benefits: build soil fertility - 3

Many factors determine leguminous N fixation:

- Species & biomass
- Established legumes fix more N than newly established plants
- Establishment of effective root nodules via Rhizobia bacteria
- Existing levels of soil N – legumes may also scavenge available soil N before fixing it themselves (though this too will eventually be released)
- Volume of plant biomass
- Soil type
- Climate
- Carbon to nitrogen (C:N) ratio

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Benefits: build soil fertility - 4

- Carbon:Nitrogen (C:N) ratio = amount of C in biomass divided by amount of N
- Predicts how fast soil microbes break down biomass and release N to soil
- Microbes use carbon for energy and N for protein
- C:N of 24:1 considered 'ideal' for soil microbes
- To decompose high C:N microbes utilise soil N, resulting in a temporary N deficit (immobilisation)
- Crops with a lower C:N will be consumed with excess N remaining in the soil (mineralisation)
- Cover crop mineralisation must be balanced with following crop need to reduce nutrient loss

Species	C:N ratio	Above Ground N Content (%)	
Hairy Vetch	11:1	4.3	Maitland and Christie, 1989
Red Clover	14:1	3.1	Maitland and Christie, 1989
Crimson Clover	16:1	2.8	Wagger, 1987; Samson et aL,
White Mustard:late	26:1	1.5	Crowther and Mirchandani, 1931
Winter Rye: early	32:1	-	Wagger, 1987
late	38:1	-	Wagger, 1987
Annual Ryegrass	34:1	1.3	Wivstad, 1990

How Much Nitrogen Does My Cover Crop Take Up and When Do I Get It Back?
University of Nebraska, Institute of Agriculture and Natural Resources, Crop Watch, August 2020.

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Benefits: build Soil Fertility - 5

- Nitrogen fixation can vary widely
- Impacted by local and climatic circumstances
- Non legume/legume mixes observed to have higher BNF due to competition for soil nitrogen leading to more rapid conversion of N2 (Li et al, 2015)

Species	Range of N fixed	Other information	Reference
Red clover (*Trifolium pretense*)	8 – 177 kg N ha^{-1}	In the sowing year (between spring and winter crops in the same year) of several studies in Northern Temperate regions.	(Li et al. 2015; Carlsson and Huss-Danell 2003)
Crimson clover (*Trifolium incarnatum*)	77 - 111 kg N ha^{-1}	Growing period July/August to November in Denmark, the study was conducted over two years	(Mueller and Thorup-Kristensen 2001).
Persian clover (*T. resupinatum*)	100 kg N ha^{-1}		
Egyptian or Berseem clover (*T. alexandrinum*)	32 – 69 kg N ha^{-1}		
Common vetch (*Vicia sativia*)	40 – 90 kg N ha^{-1}		
Hairy or winter vetch (*Vicia villosa*)	149 kg N ha^{-1}		
	75 – 80 kg N ha^{-1}	When an autumn sown winter cover crop was killed in the spring, grown in Georgia, USA	(Nesmith and McCracken 1994).
Lucerne or alfalfa (*Medicago sativa*)	36 kg N ha^{-1}	After 12 weeks growth, sown in the spring in Canada.	(Townley-Smith et al. 1993).
Field or broad bean (*V. faba*)	150 kg N ha^{-1}	Three month growing period (August to November) in Switzerland	(Buchi et al. 2015).

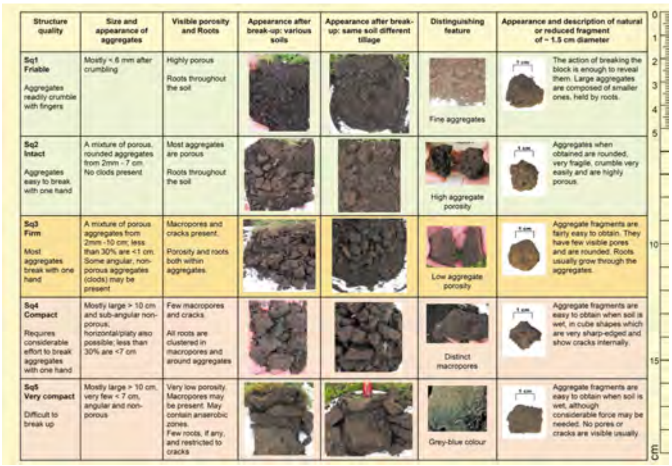
AHDB UK Research Review 90: A review of the benefits, optimal crop management practices and knowledge gaps associated with different cover crop species' (2016)

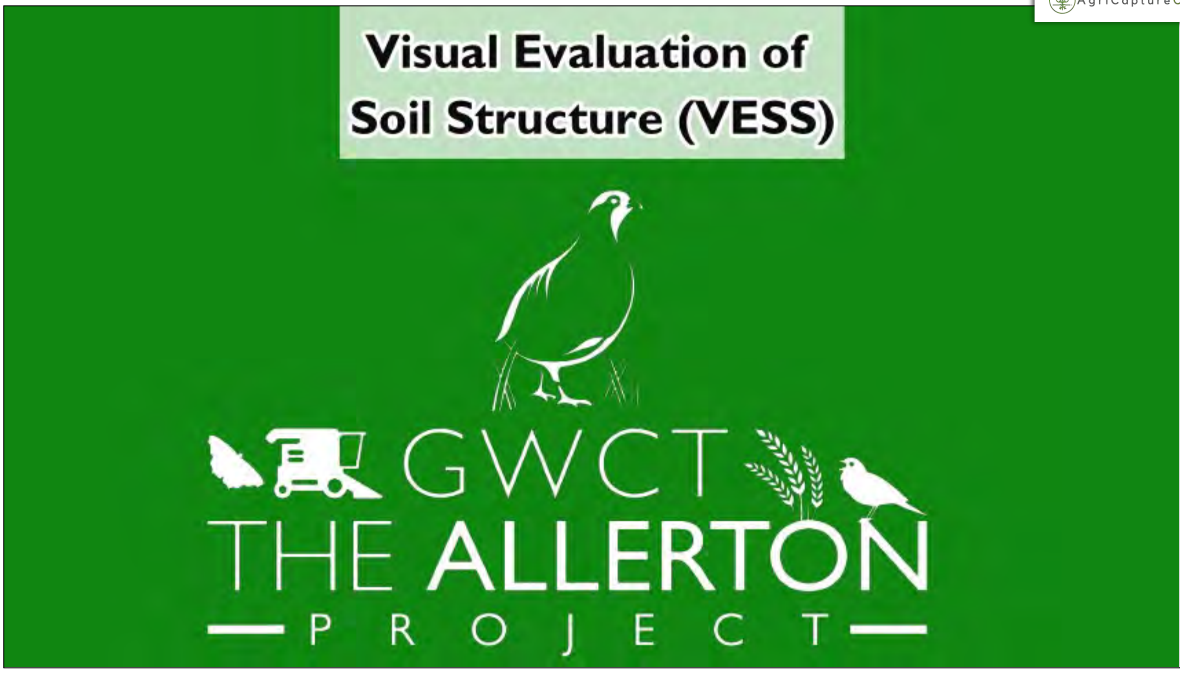
AgriCaptureCO_2

Benefits: Improve Soil Structure - 1

Soil Structure:

- Size, shape & arrangement of solids & air spaces
- Continuity of pores
- Ability to retain & transmit fluids
- Ability to support root growth
- Impacted by agricultural activity
- Scorable on VESS table





29

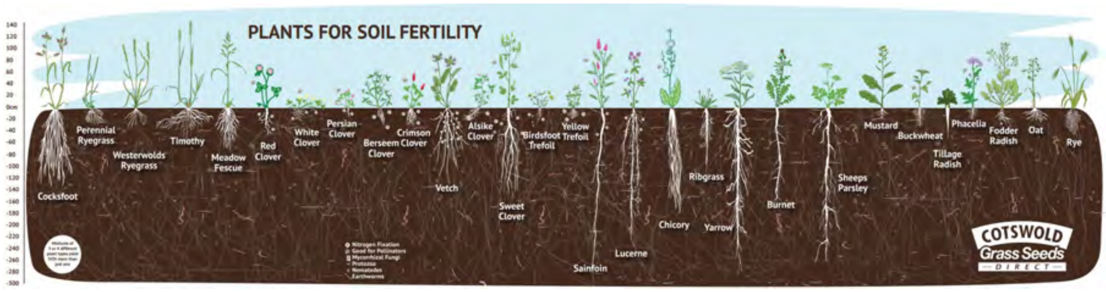
Benefits: Improve Soil Structure - 2

- Soil moisture retention dependent on particle & pore size distribution, bulk density & carbon (SOM) concentrations
- Carbon influences pore size distribution, moisture retention & aggregation
- Increased SOM/SOC from cover crops can improve physical, chemical and biological properties of soil

30

Benefits: Improve Soil Structure - 3

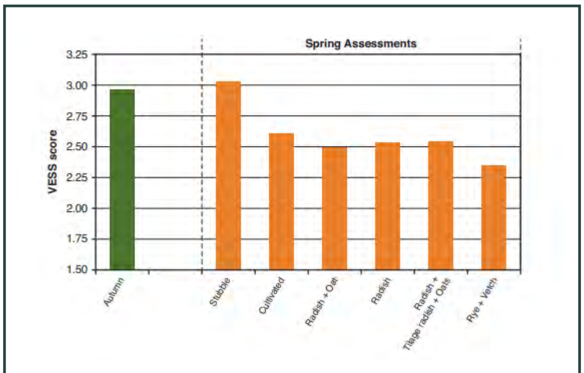
- Cover crops with a vigorous, active root system can help open up soil structure
- Impacts vary with species, soil type and cropping system
- Shallower rooting species with fibrous roots (such as rye or some clovers) can create a friable surface structure
- Deeper rooting plants (often brassicas/broadleaves) can reduce compaction at depth (>20cm) but may require full-season fallow; ill suited to catch crops.
- Finer roots of legumes can feed soil microbes while tap roots grow to depth



31

Benefits: Improve Soil Structure - 4

- Improvements in soil structure allow crop roots to grow more easily and locate nutrients not otherwise available, improve water infiltration and reduce need for cultivations
- Cover crops provide food for soil biota, especially burrowing earthworms, to produce virtuous circle of biological soil structuring

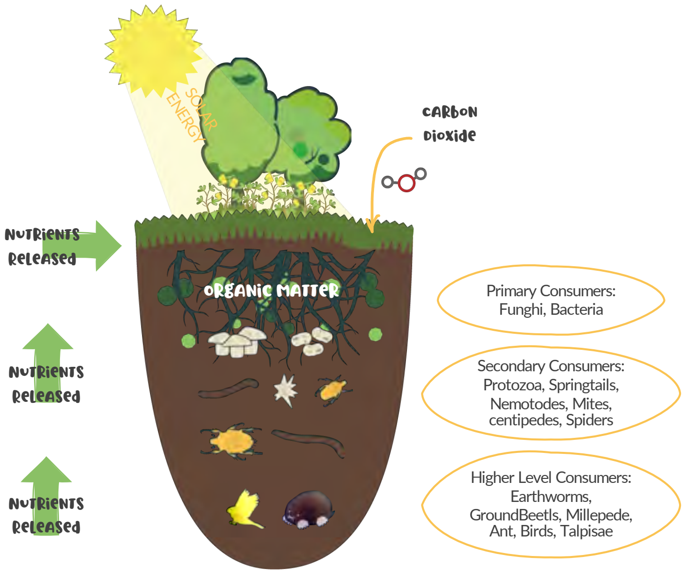


The impact of a range of cover crops compared to an autumn 'farm standard' cultivation of VESS (Visual Evaluation of Soil Structure) pre and post winter on a Kellogg's Origin™ site 2014/15 (a lower VESS score is indicative of a better soil structure)

32

Benefits: boost Soil biology - 1

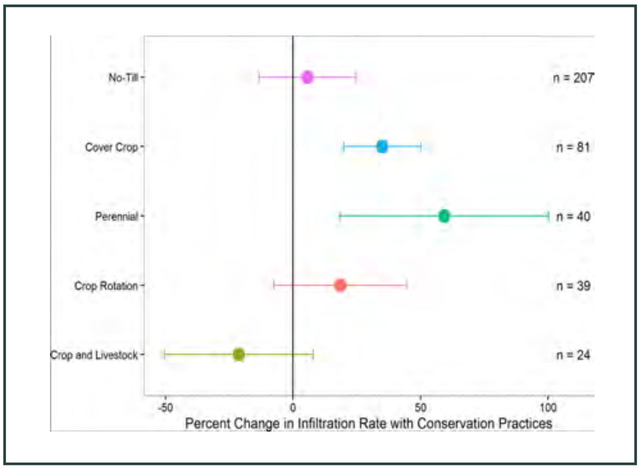
- The whole soil food web is vital in producing soil health & structure
- Cover crops can support microbial communities of bacteria and mycorrhizal networks via root exudates & addition of SOM
- Cover crops can support greater populations of earthworms, who mix soils and form channels in the soil profile, increasing aeration, infiltration and SOM (Stobart et al, 2015)



33

Benefits: Improve water infiltration/Reduce transpiration - 1

- Increasingly important as weather patterns become more extreme
- Reduces erosion & runoff
- Reduces catchment flood risk
- Improves soil water availability
- Improves crop resilience
- Cover crops can improve water infiltration rates by 35% (Basche/DeLonge 2019)



34

Benefits: Improve water infiltration/reduce transpiration - 2

35

Benefits - Managing weeds & pests - 1

- Cover & catch crops compete with weed species for space, light, water and nutrients
- They can alter the environmental conditions at the soil surface, preventing or delaying germination of some weed species and reducing seeding potential
- In this situation, cover & catch crops act as 'trap crops', inhibiting weed species until both are destroyed pre-seeding thereby reducing the soil seed bank
- Early emergence/rapid vigour/rapid growth/canopy closure important
- Mustard/phacelia produce rapid ground cover. Red/persian clovers can be mown frequently to aid weed control
- Undersowing of cash crops can also be an effective weed control method, reducing weeds by as much as 75% (Lorin et al, 2015)

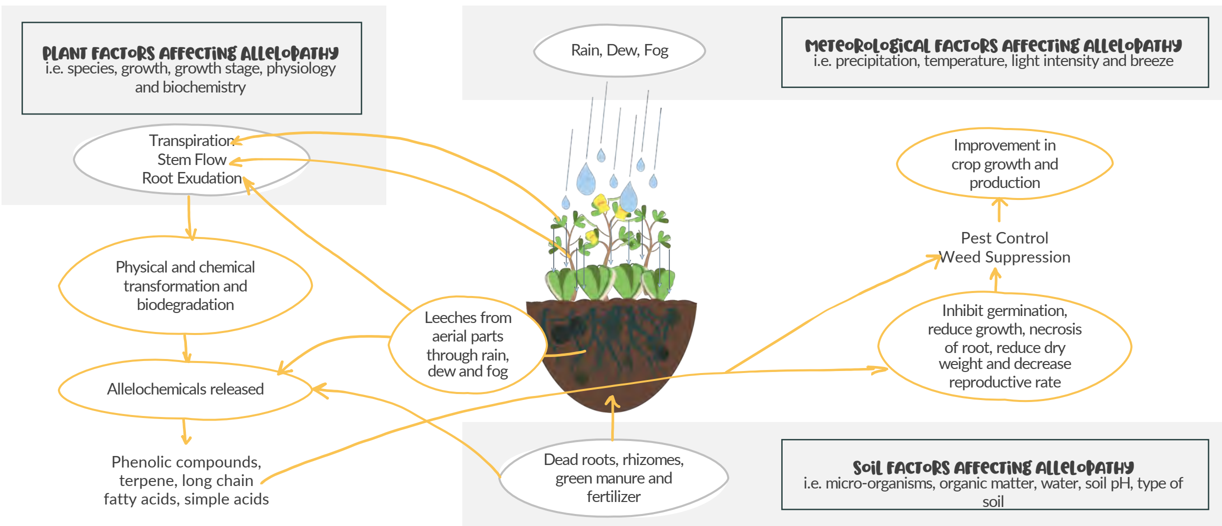
36

Benefits - Managing Weeds & Pests - 2

- Allelopathy – the stimulatory or inhibitory effect of chemical compounds produced by one plant on another
- Phytotoxic chemicals can enter the environment via volatilisation, foliar leaching, root exudation, residue decomposition or leaching from plant litter
- Allelochemicals can inhibit/retard germination, reduce plant growth & lower reproductive capacity
- Allelopathic effects can be inconsistent and narrow, but mustard/radish/rye often cited as effective species

37

Benefits - Managing Weeds & Pests - 2



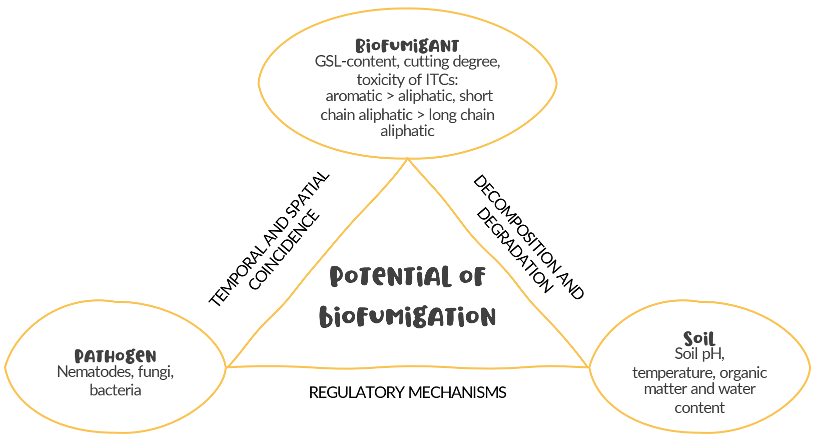
38

Benefits - Managing weeds & pests - 3

- Biofumigation vs soil-borne pests
- Brassicas (mustard/rapeseed/oilseed radish) potentially effective against plant parasitic nematodes such as beet/potato cyst
- Biofumigation occurs when cover crops are incorporated over winter, releasing compounds toxic to soil pests
- Effectiveness dependent on climate/soil conditions/method of CC destruction
- Some biofumigation requires sealing of soil with plastic for best results
- Potential issues for following cash crops: up to six week gap recommended between CC incorporation & planting

39

Benefits - Managing weeds & pests - 3



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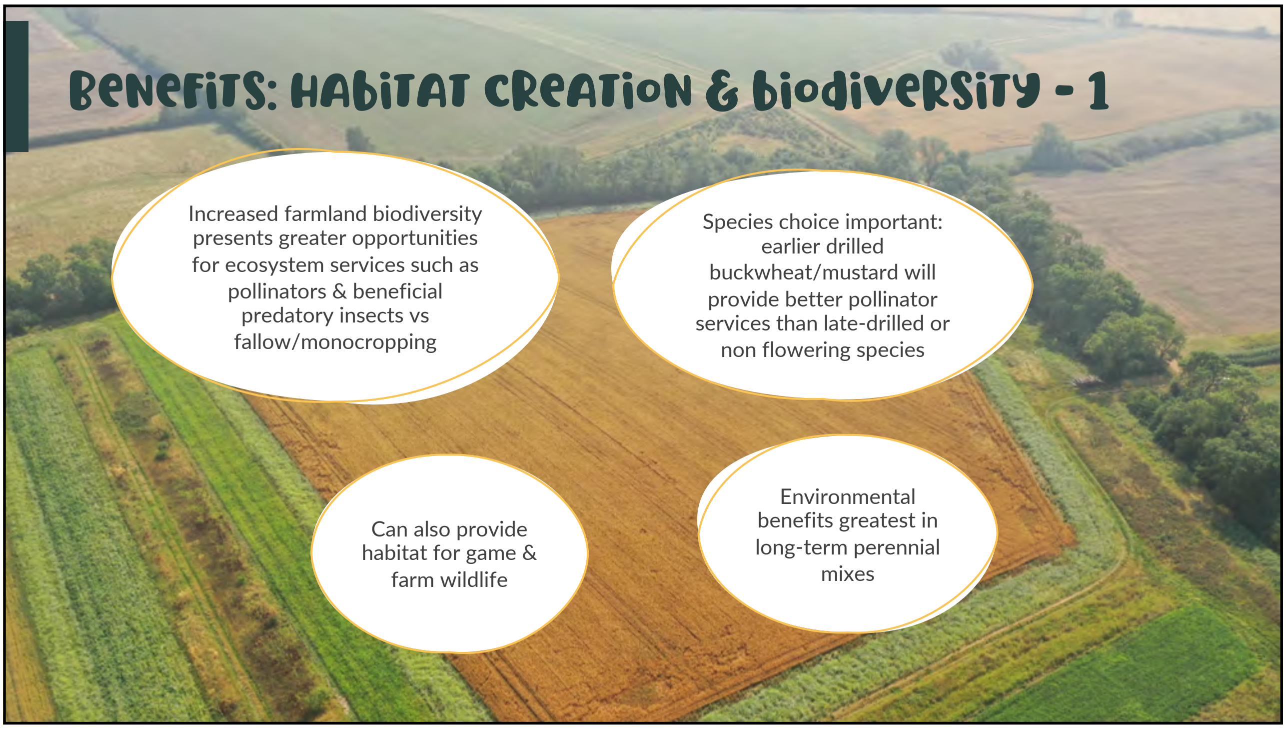
Benefits: Habitat creation & biodiversity - 1



41

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Benefits: Cover crops as forage - 1

- Some CCs can be utilised as forage to enable economically productive use of land between cash crops on arable/horticultural land
- Livestock may be used to terminate CCs instead of/in addition to mechanical/chemical methods
- Allows for increase in available forage area and may make some nutrients (N,P,K) more available to the following crop via manure vs mechanical incorporation
- Benefits of manure as OM & for invertebrate biodiversity

42

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Benefits: Cover crops as forage - 1

- Green manures such as white/red clover, lucerne and sanfoin provide high protein forage & micronutrients with minimal input requirements
- Some plants (e.g. chicory/sanfoin/trefoil) have anthelmintic properties to combat livestock parasites
- Legumes usually mixed with grasses to provide balanced sward
- Species selection vs livestock type important
- Potential issues of ground poaching & compaction in wet winter conditions
- Leguminous CCs removed as fodder will remove nutrients, but also stimulate additional root growth & N fixation

43

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Challenges of cover/catch crops - 1

- Seed mixtures can be expensive, and establishment costs high
- Depending on establishment system, some benefits may not be realised, i.e. intensive cultivation & impact on soil structure/SOM/SOC levels
- Fuel use in such intensive systems may also be disadvantageous to emissions reductions goals
- Growers may find it difficult to establish catch/cover crops in timely fashion to allow for biomass generation/root nodule development before destruction/winter, reducing their effectiveness
- Cover crops are of long-term benefit to soil health and productivity but it may be difficult to register short-term benefits or yield/profit increases, sapping enthusiasm

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Challenges of Cover/Catch Crops - 2

- Potential 'green bridge' issues with CCs acting as host to a range of aphid and fungal based diseases. Early destruction may be necessary to reduce risk, especially from aphids.
- CC species should be carefully selected to avoid rotational intensity, i.e. leguminous/cereal/brassica CCs should be considered in light of similar crops in the rotation to avoid disease carryover or build up of volunteers in following cash crop
- An increased incidence of slugs can be an issue following a cover crop, especially brassicas
- Residue management can be an issue in certain situations
- CC mixtures must be carefully selected to avoid competition

45

Challenges of Cover/Catch Crops - 3

- Termination of CCs should be effective to avoid contamination of following crop
- CCs must be carefully managed (cut/terminated) at appropriate times to ensure problem weeds do not reseed in the cover crop
- Timing of termination also important to manage N release from plant decomposition at point of requirement for following crop
- Care must be taken to avoid allelopathic impact of terminated cover crop on following cash crop
- Potential issue of CCs shading weed pests from herbicides
- Potential issue of late terminated CCs shading heavier soils and delaying spring field operations due to poor soil working conditions
- Transpiration of catch crops may reduce soil moisture for cash crop in dry conditions

46

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BEDANKT EFHARISTO POLI

HVALA VAM MERCI

DANKE DZIĘKUJĘ WAM

THANK YOU

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5 PRINCIPLES OF REGENERATIVE AGRICULTURE

HEALTHY SOIL · HEALTHY CROPS · HEALTHY BUSINESSES

BENEFITS OF COLLABORATIVE WORKING

MODULE: BIOLOGICAL DIVERSITY

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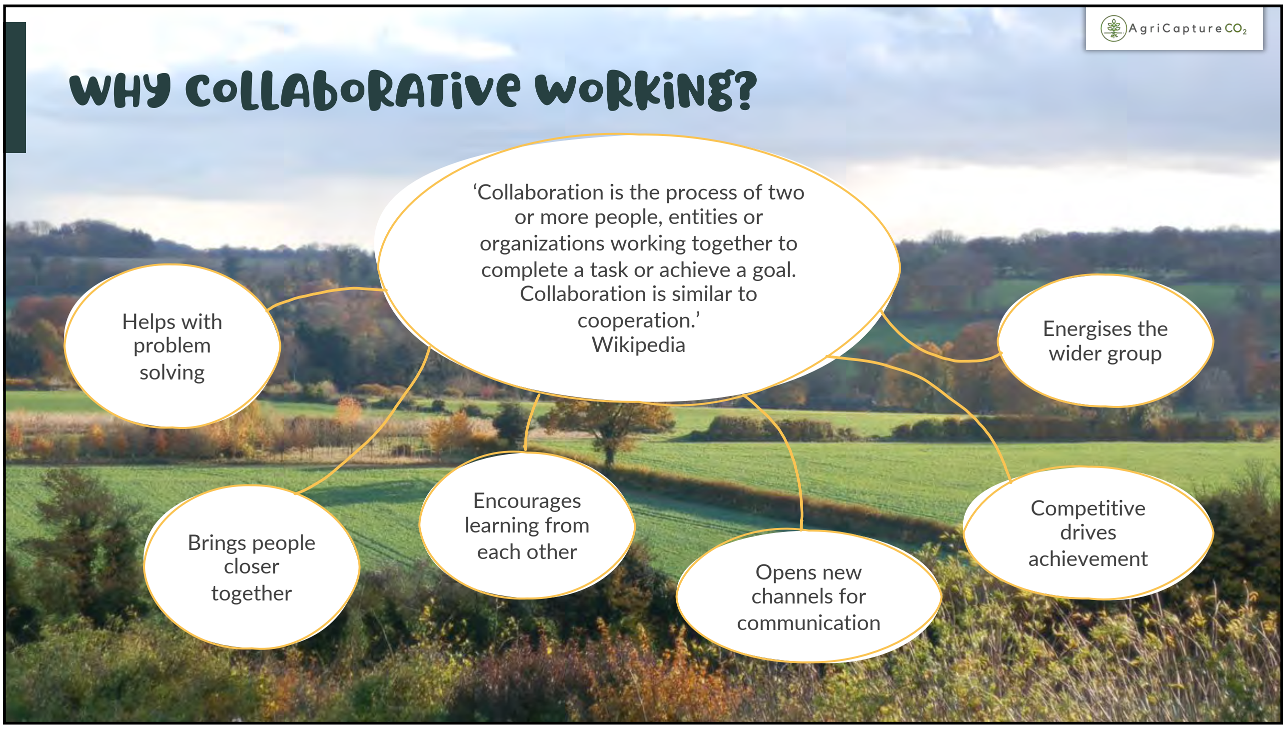
1

2

AGRI BENEFITS OF COLLABORATIVE WORKING



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WHY COLLABORATIVE WORKING?

- Major climate & environmental goals across the UK & EU this decade
  - Cleaner air & water
  - Increase natural biodiversity
  - Soil carbon sequestration
  - Mitigating climate change
  - Land use change
  - Flood mitigation
  - More sustainable food production
- Reg agri is 'part of the solution' but bigger gains can be made at 'landscape scale' than on individual holdings

4

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Farmer clusters: working together to achieve more

- Developed from 2012 by the Game & Wildlife Conservation Trust (GWCT) in association with Natural England in the UK
- 'A plan to help a number of farmers work more cohesively together in their locality, enabling them to collectively deliver greater benefits for soil, water and wildlife at a landscape scale'
- Bottom-up structure: farmer-led not government-led
- Voluntary grouping of local farms sets their own priorities & budget
- Set their own conservation plans helped by chosen conservation advisors
- No requirement to be part of UK environmental stewardship schemes

Game & Wildlife CONSERVATION TRUST

NATURAL ENGLAND

5

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Farmer clusters: working together to achieve more

- The GWCT approaches any prospective Farmer Cluster project with a single open question: "What wildlife do you want on your farm?"
- The first step in generating a farmer-led & outcome-oriented approach. Farmers:
  - appoint a lead farmer
  - choose their own advisor
  - set their own targets
  - record their own progress
- Cluster can centre of an important land feature (e.g. river valley) or just a contiguous area of land
- Now 100+ across UK

6

Farmer clusters: working together to achieve more

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Lead farmer drives the project & engages with peers

Facilitator is a local professional conservationist who can:

- advise on improvements
- offer training in monitoring techniques, law & other practicalities
- liaise with relevant government bodies
- bring in experts for assistance & training
- generally support the project

7

Farmer clusters: working together to achieve more

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- In UK, Natural England (NE) Countryside Stewardship Facilitation Fund available (from 2015)
- 3 year competitive agreements
- Minimum farmland area of 2,000ha
- Requires adhering to NE species priorities
- Significant reporting required to NE
- To retain more autonomy/creativity, some farmer clusters decide to forgo the Fund

8


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Farmer clusters:
working together to achieve more
Options for private funding of clusters include:
• Farmer contributions (e.g. an amount of money/ha of land enrolled
• Sponsorship by agricultural suppliers
• Water company ecosystem services funds
• Charitable trusts/individuals
• Corporate sponsorship
• Biodiversity offsetting & natural capital

9


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Farmer clusters:
working together to achieve more
It gives you the confidence that what you are doing to improve things is working
Important to create a baseline of monitoring at the start of the project:
Surveys need to be adapted and designed to collect data to detect improvements over time at the wider landscape level
It sets benchmarks of achievement within and between Clusters and with Rural and National datasets
It allows government bodies to be reassured that the money spent is being spent well and objectives are being achieved

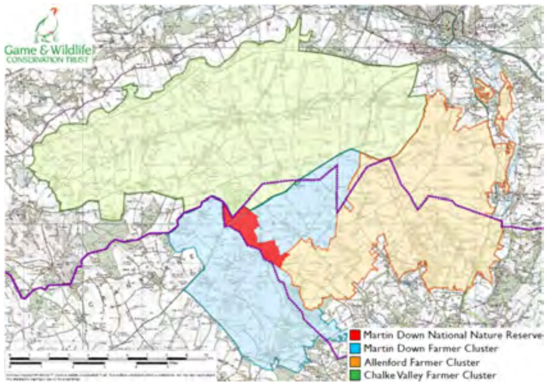
10

CASE STUDY: THE MARTIN DOWN SUPERCLUSTER

- Grouping of 3 farmer clusters surrounding the Martin Down National Nature Reserve (chalk geology)
- 5,500ha over 12 holdings
- Independently funded

Aims:

- To protect and enhance the iconic & threatened wildlife of Martin Down
- To protect, encourage & monitor the characteristic wildlife species of arable & mixed farmland
- To establish habitat links across & within the three clusters, to reconnect existing wildlife-rich features such as chalk downland



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CASE STUDY: THE MARTIN DOWN SUPERCLUSTER

Priority species & habitats include:

- Turtle Dove
- Hedgehogs
- Orchids
- Lapwing
- Barn Owl
- Harvest Mice
- Grey Partridge

A Turtle Dove caught on a trail camera

- Arable Flora
- Bumblebees
- Corn Bunting
- Small Blue / Duke Of Burgundy / Dark-green Fritillary Butterflies
- Soil Organic Matter
- Chalk Stream Water Quality

12

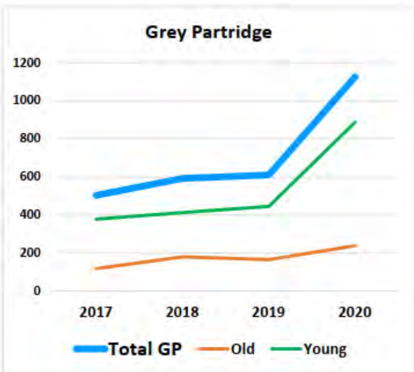
Case Study: The Martin Down Supercluster

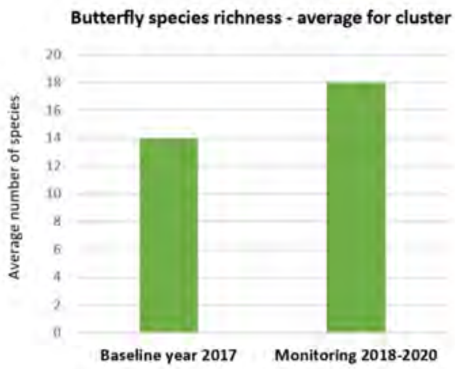
Since 2017:

- Created over 85 hectares of grass & flower margins, wild bird seed plots, cultivated margins for arable flora, arable reversions & pollen & nectar mixes
- Increased the amount of wild pollinator habitat on arable land by 50%
- Doubled the number of drinking ponds & puddles for turtle dove
- Improved hedgehog education in four villages
- Created grey partridge habitat on 600ha of the cluster area
- 9 out of 11 farmers now running Larsen traps to reduce magpie predation pressure on turtle doves
- Received a 2020 Defra Bees Needs award in the Farming Category

13

Case Study: The Martin Down Supercluster





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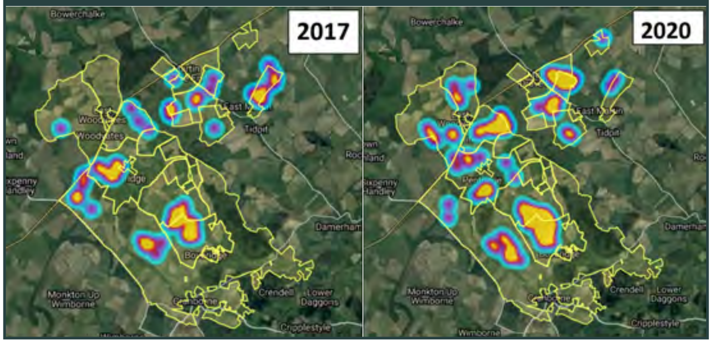
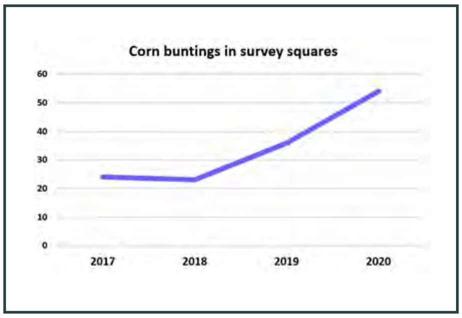
CASE STUDY: THE MARTIN DOWN SUPERCLUSTER

Corn bunting location map





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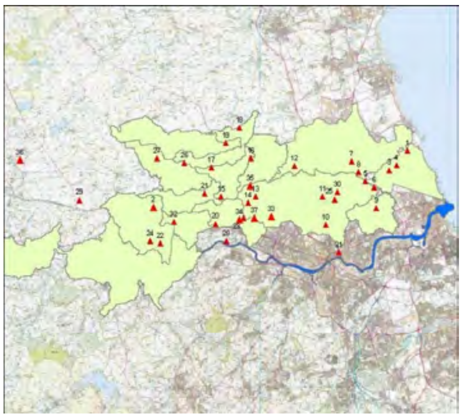
CASE STUDY: TYNE RIVERS TRUST

- 32 holdings over 7800ha in the Tyne River catchment (NE England)
- Priorities:
  - Increase riparian & wet woodland
  - Reduce agricultural diffuse pollution
  - Connect habitats through woodland & hedgerow planting
  - Reduce sediment movement into waterways
  - Improve water quality
  - Improve flood management through natural flood management techniques
- Primary focus on water management



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UK Environmental Land Management Scheme (ELM)

- Successor scheme to the CAP in England
- 'Public money for public goods' including clean water, air, biodiversity
- Moving away from area payments for agricultural production

Tier 1:	Sustainable Farming Incentive (SFI) to support sustainable farming at farm level
Tier 2:	Local Nature Recovery (LNR) supports action at local level to make space for nature alongside farming
Tier 3:	Landscape Recovery (LR) for landowners who want to take a more radical & large-scale approach to producing environmental & climate goods on a landscape scale

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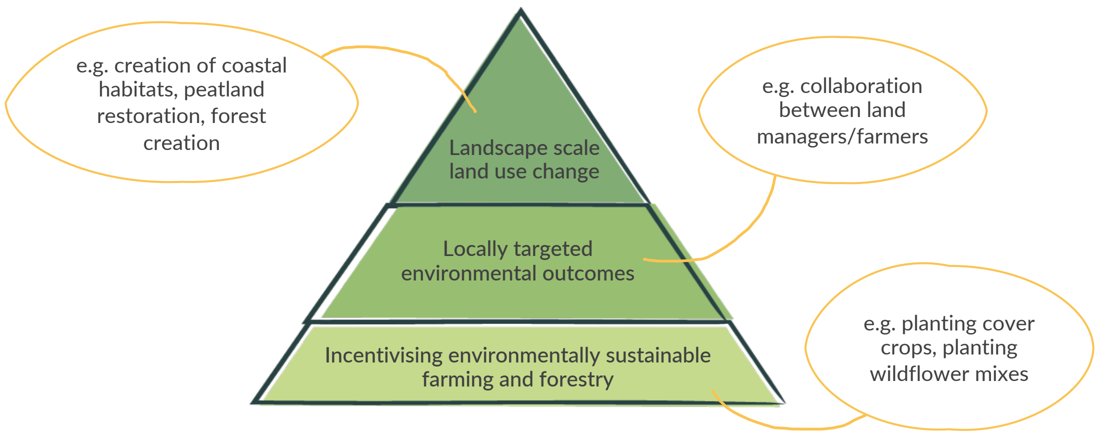
UK Environmental Land Management Scheme (ELM)



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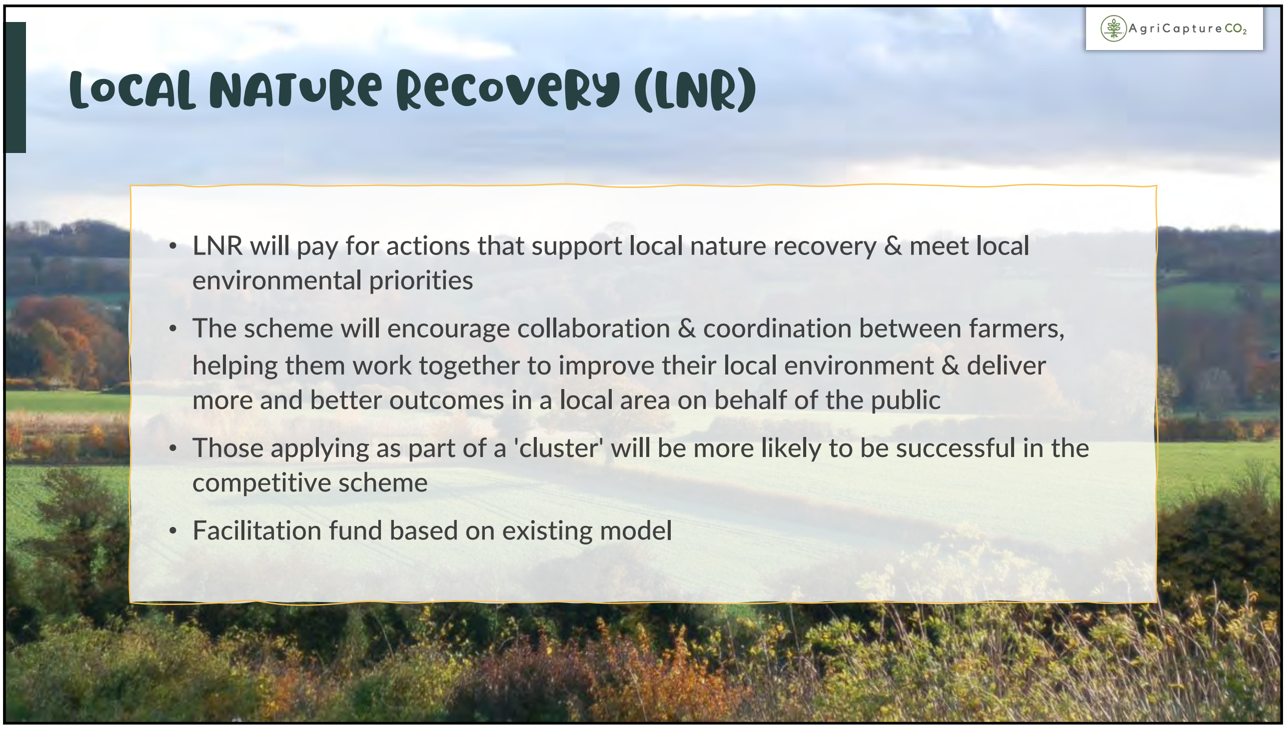
AgriCapture CO2
Local Nature Recovery (LNR)
• LNR will pay for actions that support local nature recovery & meet local environmental priorities
• The scheme will encourage collaboration & coordination between farmers, helping them work together to improve their local environment & deliver more and better outcomes in a local area on behalf of the public
• Those applying as part of a 'cluster' will be more likely to be successful in the competitive scheme
• Facilitation fund based on existing model

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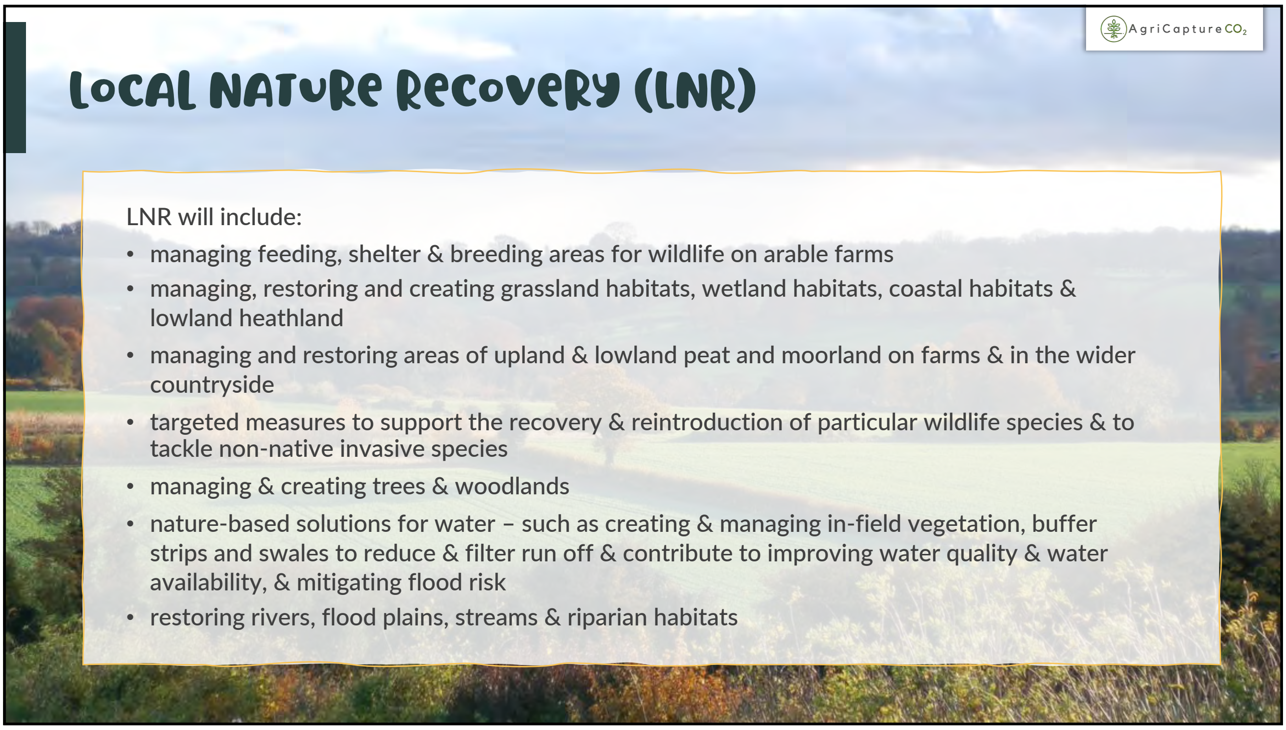
AgriCapture CO2
Local Nature Recovery (LNR)
LNR will include:
• managing feeding, shelter & breeding areas for wildlife on arable farms
• managing, restoring and creating grassland habitats, wetland habitats, coastal habitats & lowland heathland
• managing and restoring areas of upland & lowland peat and moorland on farms & in the wider countryside
• targeted measures to support the recovery & reintroduction of particular wildlife species & to tackle non-native invasive species
• managing & creating trees & woodlands
• nature-based solutions for water – such as creating & managing in-field vegetation, buffer strips and swales to reduce & filter run off & contribute to improving water quality & water availability, & mitigating flood risk
• restoring rivers, flood plains, streams & riparian habitats

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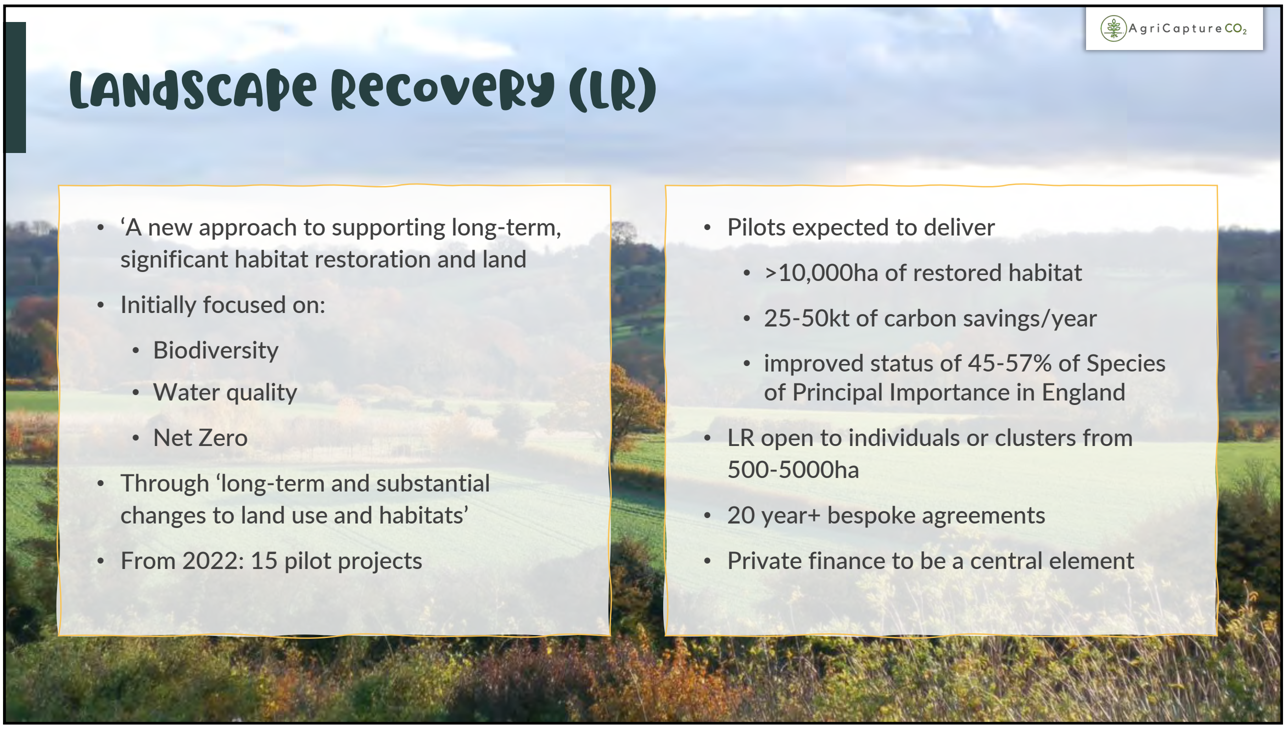
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Landscape Recovery (LR)
• 'A new approach to supporting long-term, significant habitat restoration and land
• Initially focused on:
• Biodiversity
• Water quality
• Net Zero
• Through 'long-term and substantial changes to land use and habitats'
• From 2022: 15 pilot projects
• Pilots expected to deliver
• >10,000ha of restored habitat
• 25-50kt of carbon savings/year
• improved status of 45-57% of Species of Principal Importance in England
• LR open to individuals or clusters from 500-5000ha
• 20 year+ bespoke agreements
• Private finance to be a central element

21


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Reflections
Collaborative working to achieve greater outcomes at landscape scale to meet scale of climate & environmental targets & challenges
Leverage collective wisdom, resources & enthusiasm
Priorities can be a mixture of biodiversity (flora & fauna), water & carbon
Private investors likely to look more favourably on large packets of land for carbon/biodiversity offsetting or net gain

22


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Bedankt
Efharisto poli
Hvala vam
Merci
Danke
Dziękuję wam
Thank you
gilab
SatAgro
One Carbon World
EEB
LEAF
GWCT
THE ALLERTON PROJECT
planet.
ELGO - DIMITRA
mellow yellow
EnvirometriX
Lancashire County Council
AGRICULTURAL UNIVERSITY OF ATHENS
ARTHUR'S LEGAL

23

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HEALTHY SOIL · HEALTHY CROPS · 5 PRINCIPLES OF REGENERATIVE AGRICULTURE · HEALTHY BUSINESSES

ENHANCED ROCK WEATHERING (ERW)

MODULES: INTEGRATION OF ORGANIC MATTER

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1

2

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WHAT IS ENHANCED ROCK WEATHERING (ERW)?

- Utilises the geologic carbonate-silicate cycle (or long carbon/inorganic carbon cycle)
- The long-term transformation of silicate rocks to carbonate rocks by weathering & sedimentation (& back again by volcanism)
- Carbon dioxide (CO_2) removed from the atmosphere by burial of weathered materials (& eventually returned via volcanism)
- Timescales of millions of years
- Regulates atmospheric CO_2 levels & global temperatures
- 1bnt/CO_2/year thought to be removed from atmosphere via weathering

3

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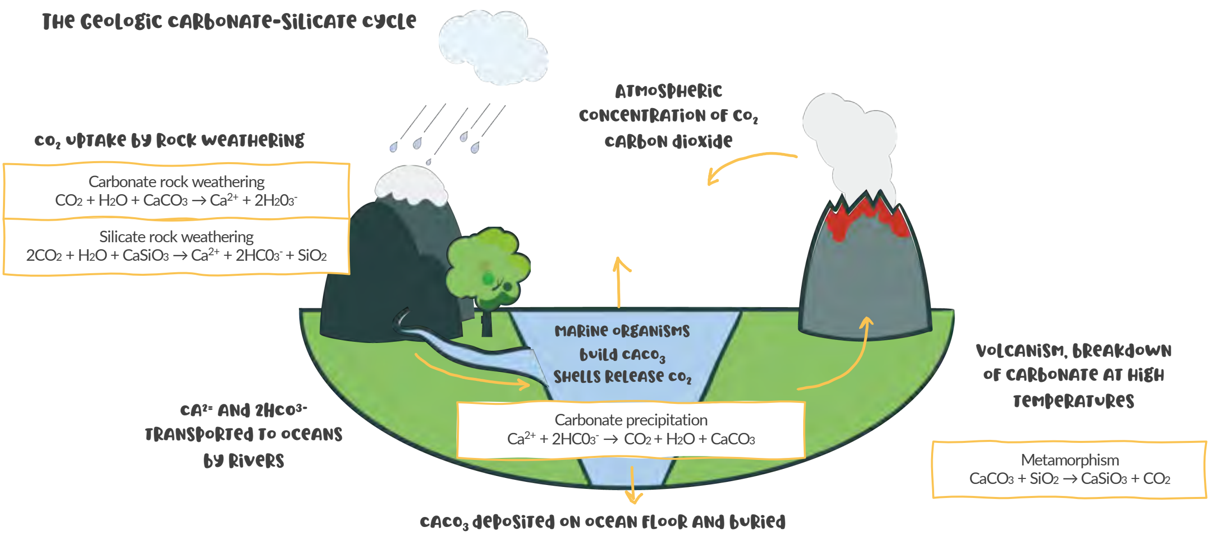
WHAT IS ENHANCED ROCK WEATHERING (ERW)?

- Rock weathering – mechanical/chemical/biological
- Carbonation affects carbonate & silicate minerals (e.g. basalt) which slowly dissolve when exposed to rainwater
- H_2O + CO_2 in the air forms carbonic acid (acid rain)
- In contact with carbonate/silicate rocks, triggers a chemical process which absorbs CO_2 from the air & combines with calcium/magnesium silicates to produce stable bicarbonate ions in soil
- Carbonate minerals created with stability for indefinite timescale.

4

WHAT IS ENHANCED ROCK WEATHERING (ERW)?



5

WHAT IS ENHANCED ROCK WEATHERING (ERW)?

- A biogeochemical method of carbon dioxide removal (CDR) from the air by speeding up the natural geologic weathering process
- Silicate rocks (e.g. basalt) mined & finely ground (<100 microns) to increase reactive surface area & catalyse rapid carbonation & dissolution
- Spread on agricultural land as an amendment
- Utilises CO2 produced in the soil biome from microbial respiration & root exudates to increase carbonic acid conc & rate of weathering
- Accelerates natural process by 100,000x
- Weathering most pronounced in wetter, w climates

6

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Benefits: ERW

Sequestration of inorganic carbon

- Croplands of China, India, USA, Brazil potential to sequester 0.5-2gt CO2/year via ERW at a cost of $80-$180/t CO2 (Beerling et al, 2020)
- 0.3t CO2 captured per tonne of basalt applied
- Suggested range of 10-30t basalt dust/ha/year
- Potential to contribute to global CDR goals & access carbon credits
- No conflict in land use between CDR & food production
- Utilises existing application machinery

7

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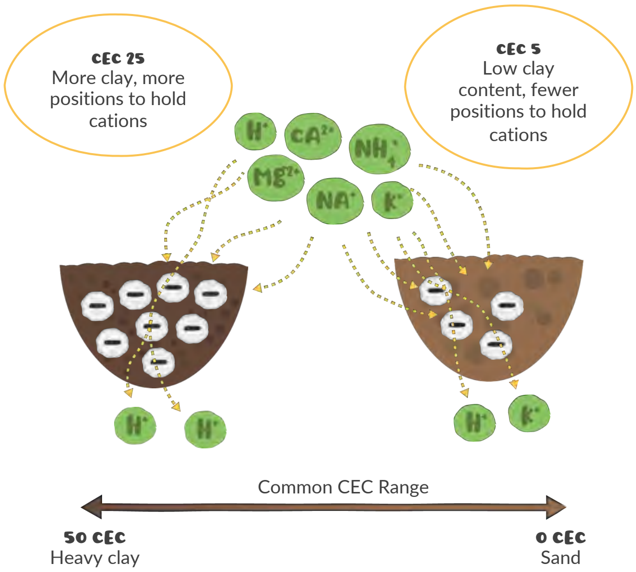
Benefits: ERW

Improves cation exchange capacity (CEC)

- Cation release from weathered basalt improves soil CEC
- Improves nutrient retention & availability (especially in coarse, sandy soils) & reduced leaching
- Increased formation of clay minerals from weathering of silicates may increase soil organic carbon retention
- Potential subsequent benefits for SOM, health & structure
- Reduction in fertiliser requirements
- Significant volumes of ERW applied may also compensate for some historic soil erosion



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Benefits: ERW

Soil nutrients

- Basalt a major source of some micronutrients: Ca, Mg, P, K, Fe in a slow-release form
- Also silica, absorbed by crops as silicic acid to reinforce cell walls, helps resist biotic (pests) & abiotic (drought/salinity/heat) stress & considered seriously depleted in many soils
- Potential for healthier, more resilient crops with lower pesticide use
- Silica also reduces plant uptake of heavy metals
- By generating alkaline leachate as they weather, silicate rocks reduce soil acidification (improve pH) helping with plant nutrient uptake & growth
- Alkaline properties also help immobilise toxic metals (e.g. aluminium)

9

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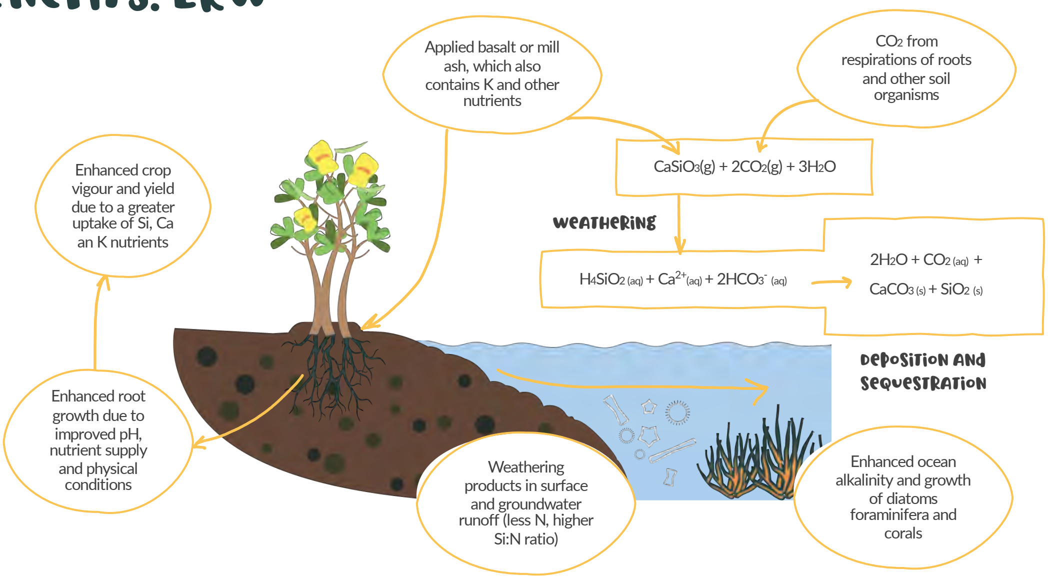
Benefits: ERW



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Benefits: ERW

Reduce Soil emissions

- Alkaline effects of silicates may also suppress soil nitrous oxide emissions by up to 50% (Beerling et al, 2018)
- May also avert liming-related CO_2 emissions: acidic (<ph6) soils can release CO_2 when treated with calcium carbonate
- Silicate weathering consumes CO_2 to produce bicarbonate & carbonate ions

11

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ERW & Regenerative Agriculture

- Verbruggen et al, 2021, suggests that mycorrhizal fungi have a significant role in enhanced weathering of basalt particles
- 'Weathering rates and hence carbon sequestration are likely to increase with agricultural activities that stimulate plant reliance on and investment in arbuscular mycorrhizal fungi' (MF)
- MF thrive in absence of artificial fertilisers vs slow-release ERW dust which suit its nutrient-cycling abilities
- Also a function of the greater levels of SOM (and therefore SOC) in healthy soils available for carbonation

12

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Case study: ERW & increased yields

- Kelland et al, 2020 demonstrated a 20% yield increase in a UK sorghum crop in a clay/loam soil
- 100t/ha basalt dust
- No additional P/K
- Single application of ERW achieved 2-4t/ha additional CO2 sequestration over 1-5 years

13

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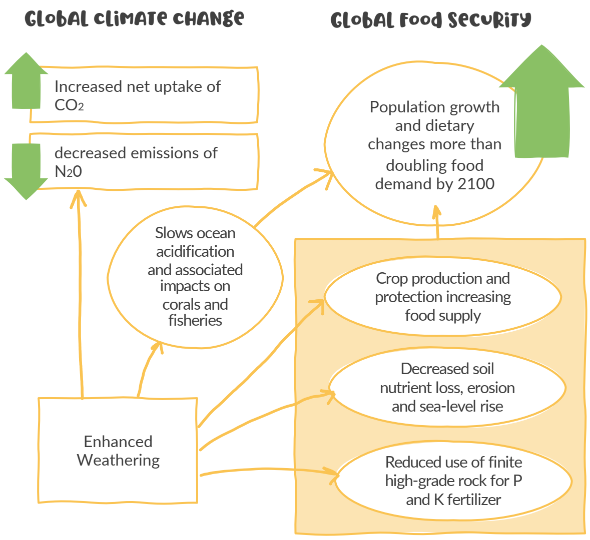
ERW: considerations

- Significant potential in widescale adoption of ERW, however:
- Important to avoid ‘carbon leakage’ in mining/crushing/transport of rock dust
- Important to use appropriate material: fast-weathering olivine is the most promising rock for ERW (at 0.9t CO_2 sequestered/t vs 0.3t for basalt) but also a source chromium & nickel, pollutants on farmed land
- Use of industrial bi-products (e.g. calcium rich iron & steel slags) also potentially problematic
- Effect of soil type/climate



Co-benefits to crops and soils

14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MERCI
DANKE
DZIĘKUJĘ WAM
THANK YOU

15

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5 Principles of Regenerative Agriculture

Healthy Soil · Healthy Crops · Healthy Businesses

Field Residue Retention

MODULES: INTEGRATION OF ORGANIC MATTER

AgriCapture CO2 · GWCT THE ALLERTON PROJECT

1

2


Field Residues
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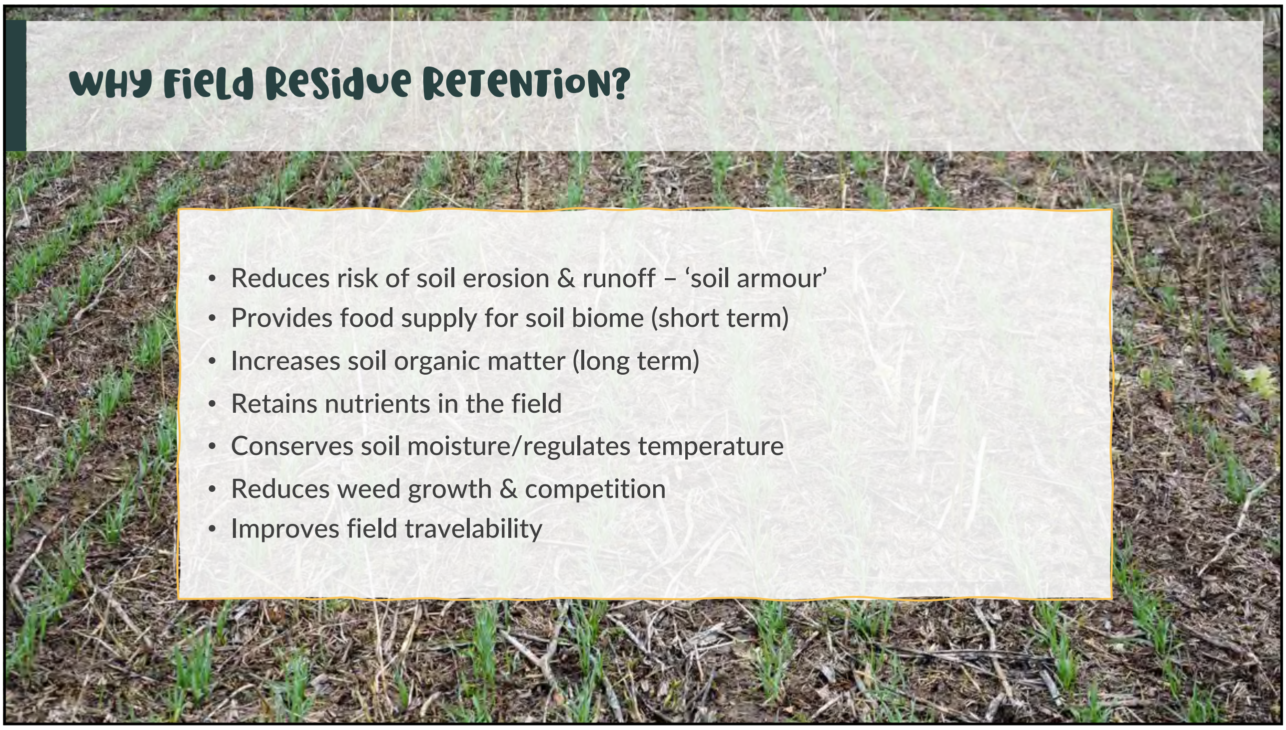
Aim to improve residue management, adopt soil mulching & utilise pruning waste
Biomass left in a field or orchard after a crop has been harvested
Stalks, stubble, leaves, seed pods
Often used as animal feed & bedding, for fuel/biofuel or burned

3


Why Field Residue Retention?
• Reduces risk of soil erosion & runoff – 'soil armour'
• Provides food supply for soil biome (short term)
• Increases soil organic matter (long term)
• Retains nutrients in the field
• Conserves soil moisture/regulates temperature
• Reduces weed growth & competition
• Improves field travelability

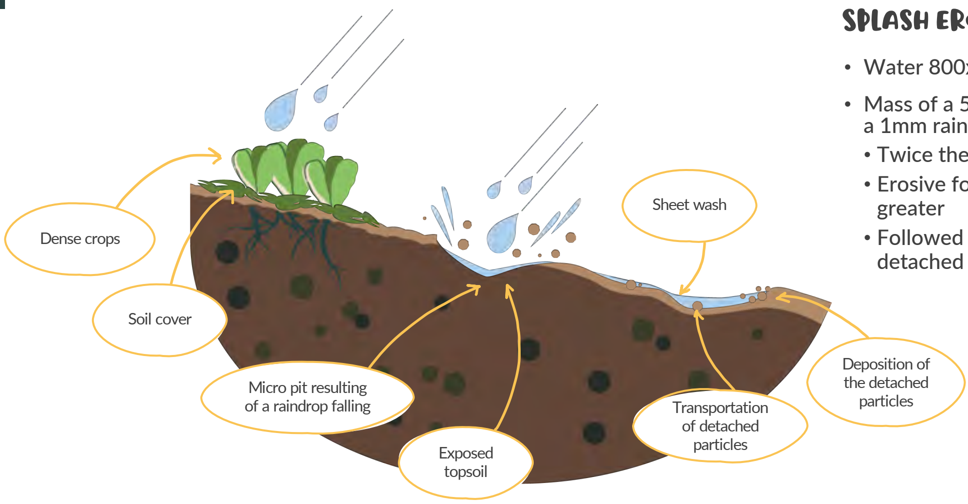
4

Soil erosion

- Cultivated soils with low residue covering most at risk of wind & water erosion
- Water erosion exacerbated by slope & intensity of rainfall
- Wind erosion exacerbated by soil type (coarse, light & peaty most at risk) field size, terrain
- Loss of valuable top soil; pollution of watercourses with sediment, nutrients & pesticides

5

Benefits: Reduce soil erosion



Splash erosion

- Water 800x heavier than air
- Mass of a 5mm raindrop 125x that of a 1mm raindrop
  - Twice the terminal speed
  - Erosive force on impact 500x greater
  - Followed by transportation of detached particles

6

Benefits: Reduce Soil Erosion

- Reduced tillage reduces soil disturbance & leaves significant quantities of residue on soil surface
- Residues intercept rainfall & reduce speed of surface flow, aiding infiltration
- 30% soil cover shown to reduce erosion by up to 70%
- 100% soil cover shown to virtually eliminate erosion – even on slopes
- Wind erosion also reduced via reduced tillage & surface residues, via direct protection & by increasing the 'roughness' of field surface

7

Benefits: Reduce Soil Erosion

Residue levels around 5% in plough-based systems…

…30% in min-till systems…

…and as high as 90-100% in no-till systems

8

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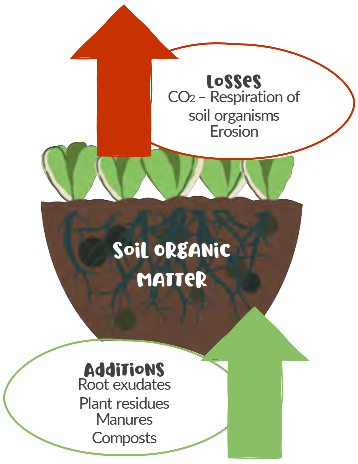
Benefits: increase soil organic matter (SOM)

- Levels of soil organic matter = equilibrium between inputs & decomposition of SOM by soil organisms. Inputs must exceed losses to build SOM.
- Levels of SOM present in soil can be affected by natural processes such as
  - Temperature
  - Rainfall
  - Soil type & texture
- But also human processes such as
  - Tillage
  - Removal of crops/crop residues
  - Application of artificial N
- Important to adapt management practices to reverse losses before increases can be gained



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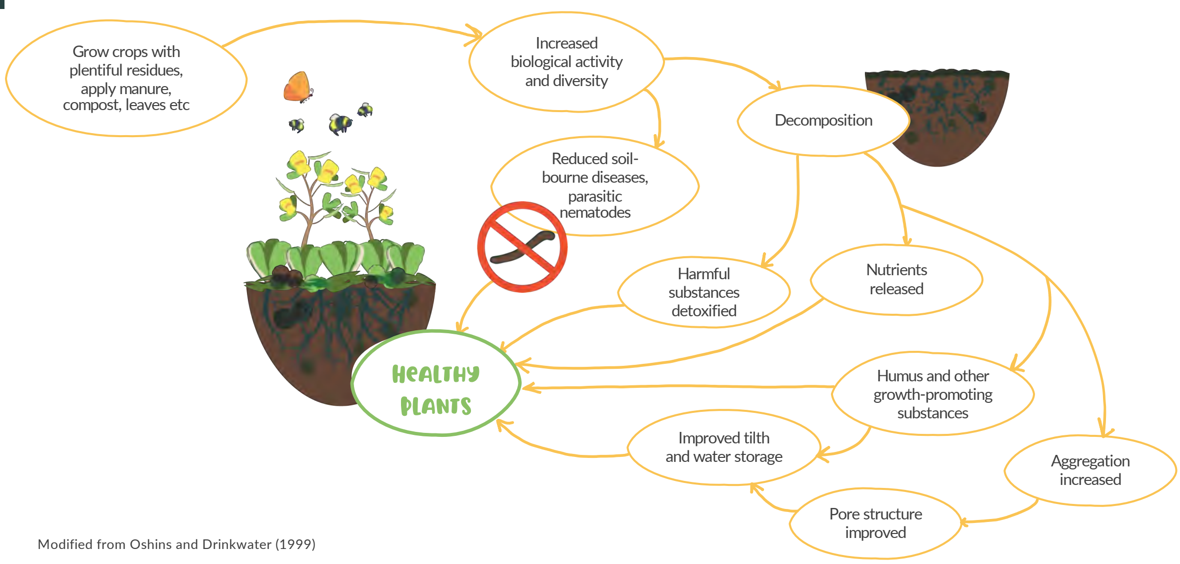
Benefits: increase soil organic matter (SOM)



Modified from Oshins and Drinkwater (1999)

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Benefits: increase soil organic matter (SOM)

- Crop residues provide food source for soil microorganisms: large, diverse populations are vital to a well-functioning soil
- OM in residues important even if only contributing to actively cycling, labile carbon stocks. C.10% of residue will be converted into stable carbon
- OM in residues contains vital macro- & micro-nutrients in complex organic molecules made available in simpler, inorganic (mineral) forms via mineralisation by soil microbes
- Also eaten & cycled by soil macrofauna, e.g earthworms, boosting their numbers
- Removal/incorporation/burning makes this vital food source unavailable

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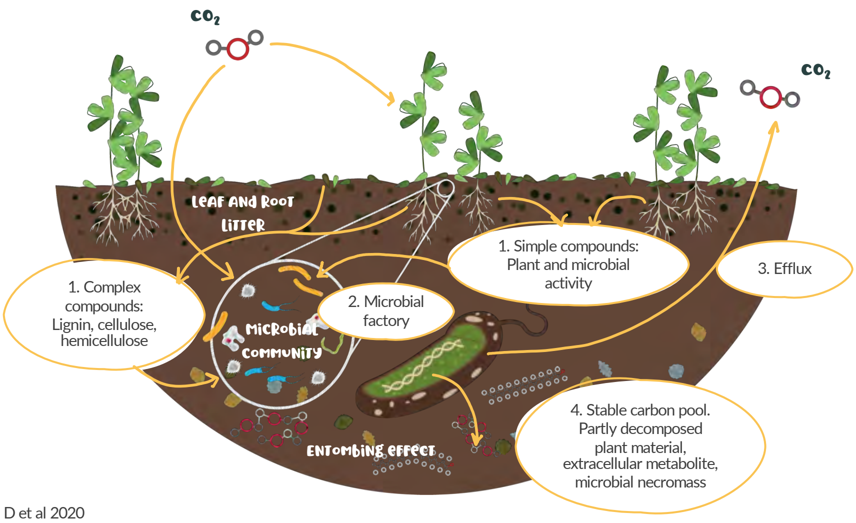
Benefits: increase soil organic matter (SOM)



Adapted from Naylor, D et al 2020
Annu. Rev. Environ. Resour. 45:25-59

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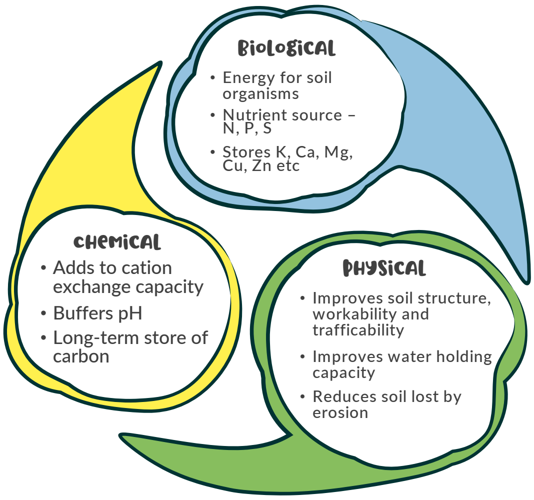
Benefits: Increase Soil Organic Matter (SOM)

- Wider biological, chemical & physical benefits of increasing SOM
- Reducing cultivations & residue removal an important first step in improving soil health
- SOM/SOC a vital element of improving soil structure, water holding capacity & building soil resilience



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Benefits: Retains Field Nutrients

- Removing crop residues removes nutrients which must be replaced
- Modern crop varieties already grown to maximise grain yield & removable biomass
- Also removes organic matter which may need to be replaced with off-field amendments
- Removing crop residues can also create compaction & damage soil structure

		Phosphate (P_2O_5)	Potash (K_2O)
		kg/t of fresh material	
Cereals	Grain only (all cereals)	7.8	5.6
	Grain and straw		
	Winter wheat/barley *	8.4	10.4
	Spring wheat/barley *	8.6	11.8
	Winter/spring oats *	8.8	16.7
Oilseed rape	Seed only	14.0	11.0

Source: AHDB RB209, UK

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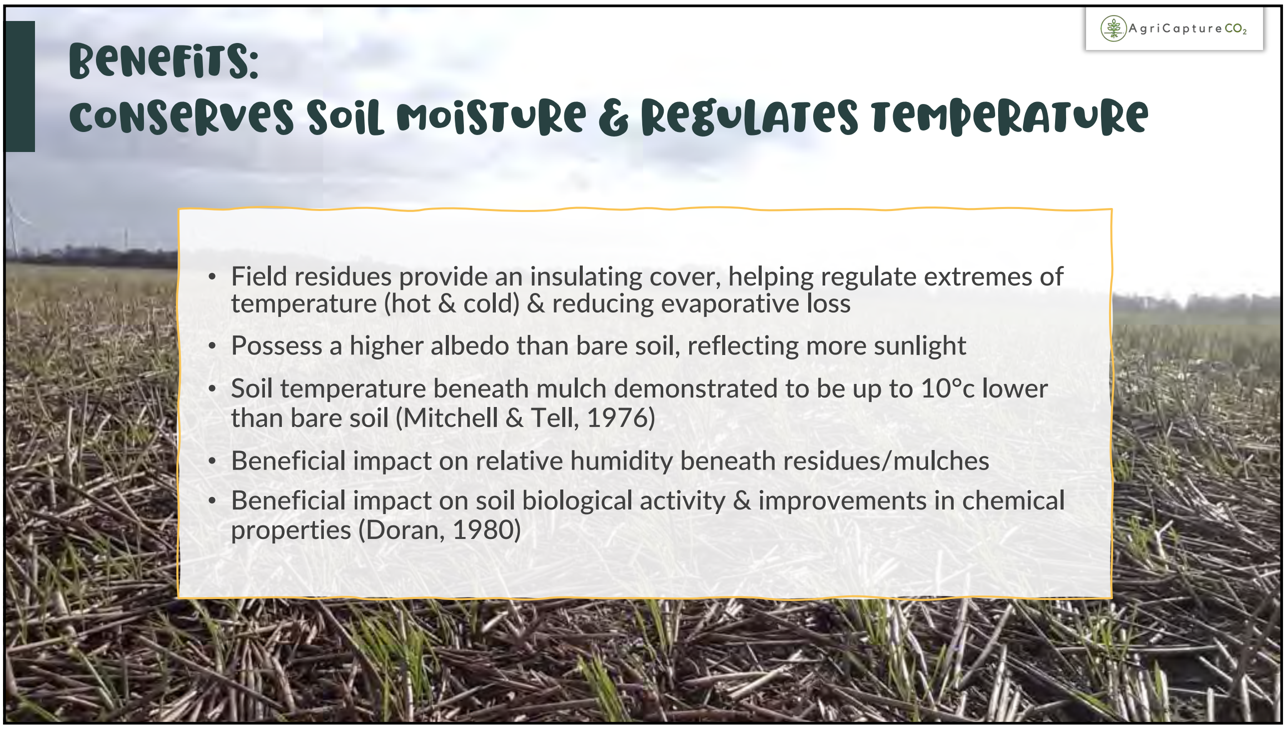
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Benefits:
Conserves Soil Moisture & Regulates Temperature
• Field residues provide an insulating cover, helping regulate extremes of temperature (hot & cold) & reducing evaporative loss
• Possess a higher albedo than bare soil, reflecting more sunlight
• Soil temperature beneath mulch demonstrated to be up to 10°c lower than bare soil (Mitchell & Tell, 1976)
• Beneficial impact on relative humidity beneath residues/mulches
• Beneficial impact on soil biological activity & improvements in chemical properties (Doran, 1980)

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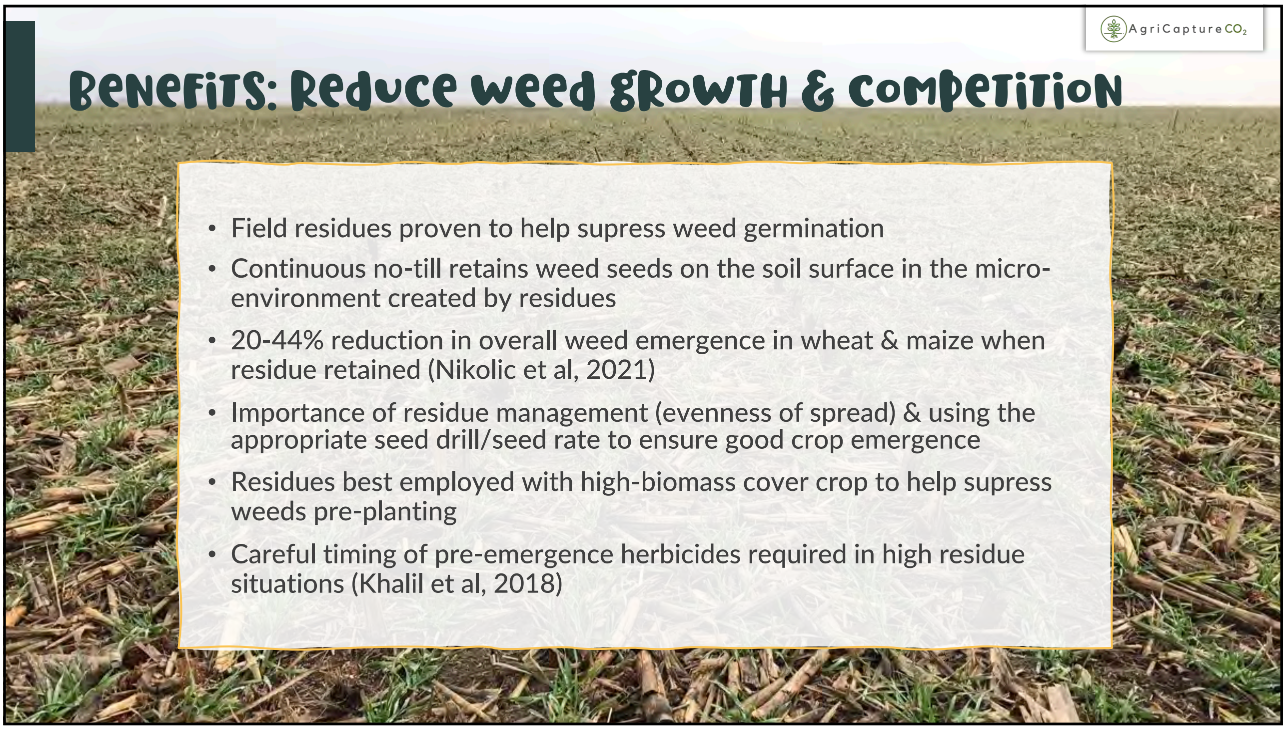
AgriCapture CO2
Benefits: Reduce Weed Growth & Competition
• Field residues proven to help supress weed germination
• Continuous no-till retains weed seeds on the soil surface in the micro-environment created by residues
• 20-44% reduction in overall weed emergence in wheat & maize when residue retained (Nikolic et al, 2021)
• Importance of residue management (evenness of spread) & using the appropriate seed drill/seed rate to ensure good crop emergence
• Residues best employed with high-biomass cover crop to help supress weeds pre-planting
• Careful timing of pre-emergence herbicides required in high residue situations (Khalil et al, 2018)

16

Mulch as residue

- Primarily used in smaller-scale agriculture & horticulture
- Uses the principles of residue retention but using larger quantities of off-field materials such as straw, grass, compost, leaf litter, wood chip, sawdust, pruning waste
- A valuable means of increasing SOM in small-scale horticultural production with significant soil movement
- Also non-organic 'mulches' such as plastics, rock/gravel
- Mulches can reduce the amount of plant protection product (PPP) infiltrating soil – though in drought conditions may also allow them to remain on soil surface for longer (Ng et al, 2014)

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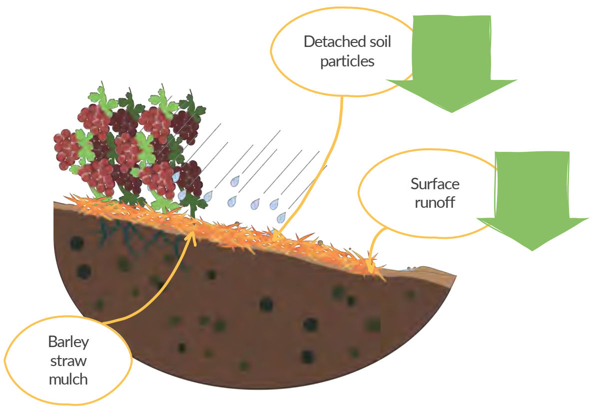
Case study: Straw mulch in Mediterranean vineyards

- Study into the impact of barley straw mulch on soil erosion & surface runoff in vineyards in eastern Spain (Prosdocimi et al, 2016)
- 75g/m2 straw mulch reduced water loss from 52% to 39% of simulated rainfall
- Sediment loss reduced from 10 to 3g/l runoff
- Erosion rate reduced from 2.8 to 0.6 Mg/ha/hour
- By increasing infiltration, mulching also increases soil water holding capacity



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Challenges of Field Residue Retention

- Some residues are also a valuable crop, e.g. straw
- Residues can impede drilling/establishment of following crop & require careful management, e.g. straw rake
- Carbon:Nitrogen (C:N) ratio of some residues may cause short-term nutrient immobility
- Residues can act as a vector for pests, e.g. slugs
- Potential impact on residual pre-emergence herbicides

ORGANIC ADDITION	C:N RATIO
Micro-organism's composition	8:1
Microorganism's preferred diet	24:1
Livestock slurries	4 -10:1
Vetches	11:1
Biosolids	14:1
Farmyard manure	17-20:1
Pea straw	29:1
Green wastes and composts	30:1
Oat straw	70:1
Wheat straw	80:1
Paper waste	150-200:1

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DANKE DZIĘKUJĘ WAM
THANK YOU

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5 PRINCIPLES OF REGENERATIVE AGRICULTURE
HEALTHY SOIL · HEALTHY CROPS · HEALTHY BUSINESSES

INCREASE BIODIVERSITY FOR FARM BENEFIT

MODULES: SOIL PROTECTION, BIOLOGICAL DIVERSITY, MAINTAIN LIVING ROOTS

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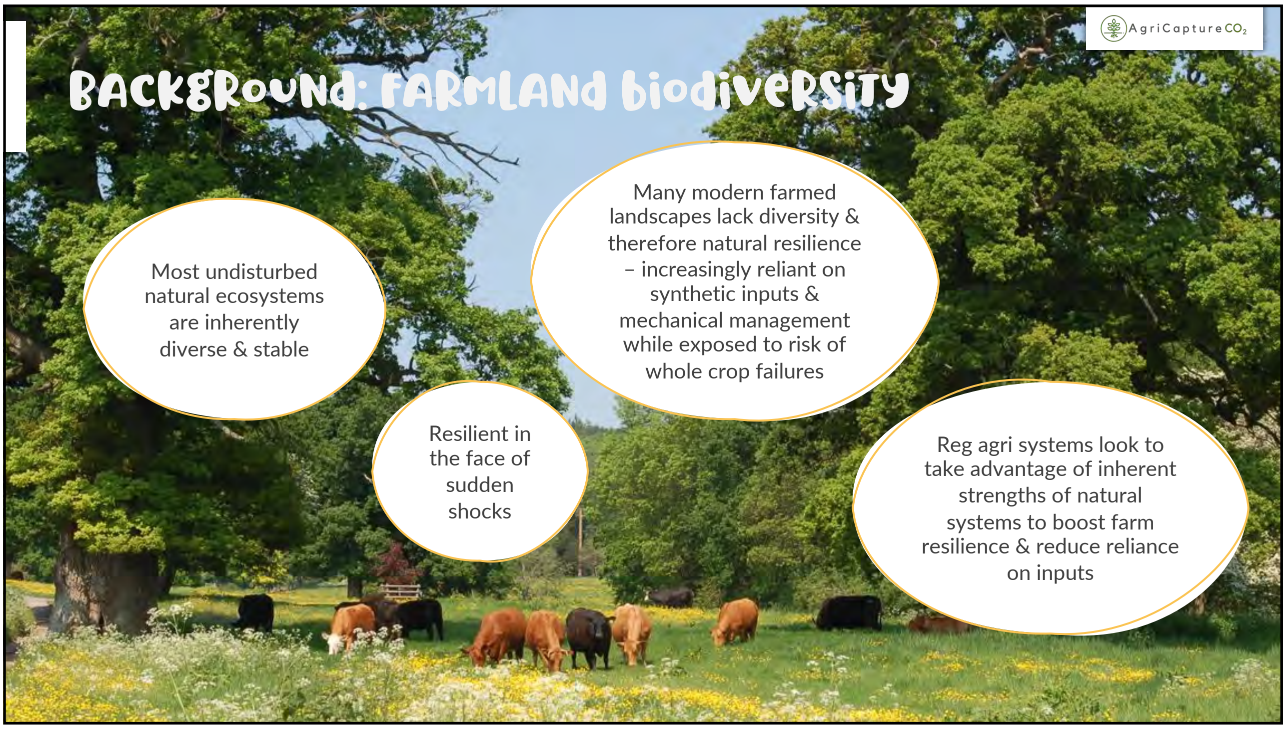

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Background: Farmland biodiversity

- Biodiversity: the number, variety & variability of living organisms
- The basis of many natural benefits provided by ecosystems – ‘ecosystems services’
- ‘Agriculture is the largest contributor to biodiversity loss’ (European Court of Auditors, Biodiversity in Farming, 2019)
- ‘Biodiversity generally decreases when the intensity of farming increases’ (European Environment Agency, 2015)

4

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Ecosystem Services

- The direct & indirect contributions ecosystems (known as natural capital) provide for human wellbeing & quality of life
  - Provisioning services
  - Regulating services
  - Cultural services
  - Supporting services
- Different ecosystem services supply combinations of these services either directly or indirectly
- Increasingly important in EU agricultural policies – e.g. post-CAP UK 'Public Money for Public Goods'
- All services underpinned by biodiversity

Source: NatureScot

5

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Background

- Habitat loss, climate change & modern farming practices all contributary factors in biodiversity decline across EU
- Increase in PPP use – especially herbicides & insecticides – a significant factor in decline of farmland biodiversity, including wild plant species & invertebrates
- Impact on non-target species & entire food web & ecosystem services
- Intensification of modern cropping systems has led to a decrease in aboveground & belowground biodiversity
- Increased intensity of farmland tillage leading to deteriorating soil health & biome diversity, as well as soil erosion & carbon loss
- Increasing plant diversity enhances soil biodiversity (McDaniel et al, 2014) leading to increased soil health & resilience

6

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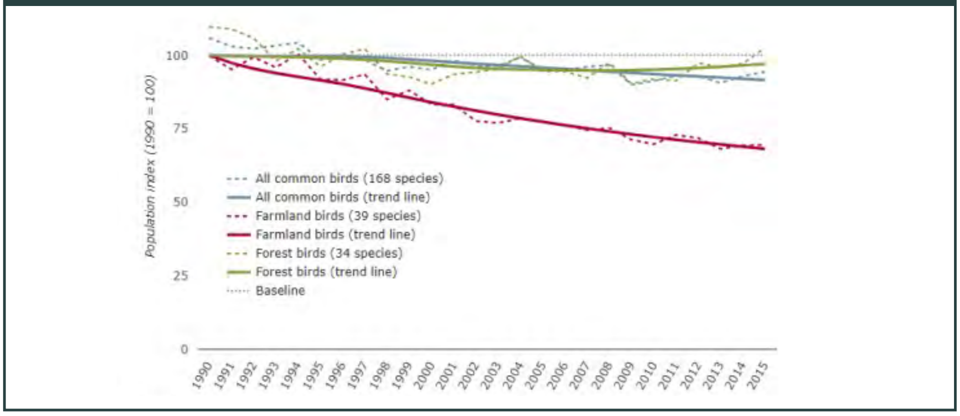
Background: impact on farmland biodiversity

EU Common Birds Index



Source: European Environment Agency

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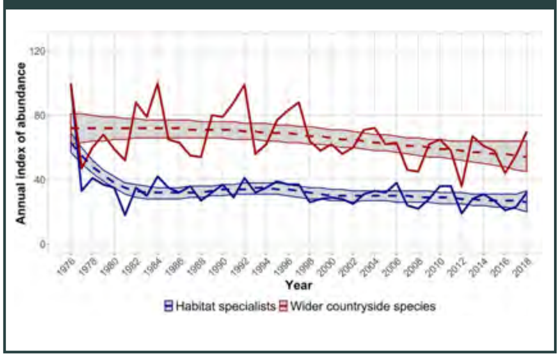
Background: impact on farmland biodiversity

UK butterfly index, 1976-2018



EU Grassland Butterfly Indicator, 1990-2017

Source, Warren et al, 2020

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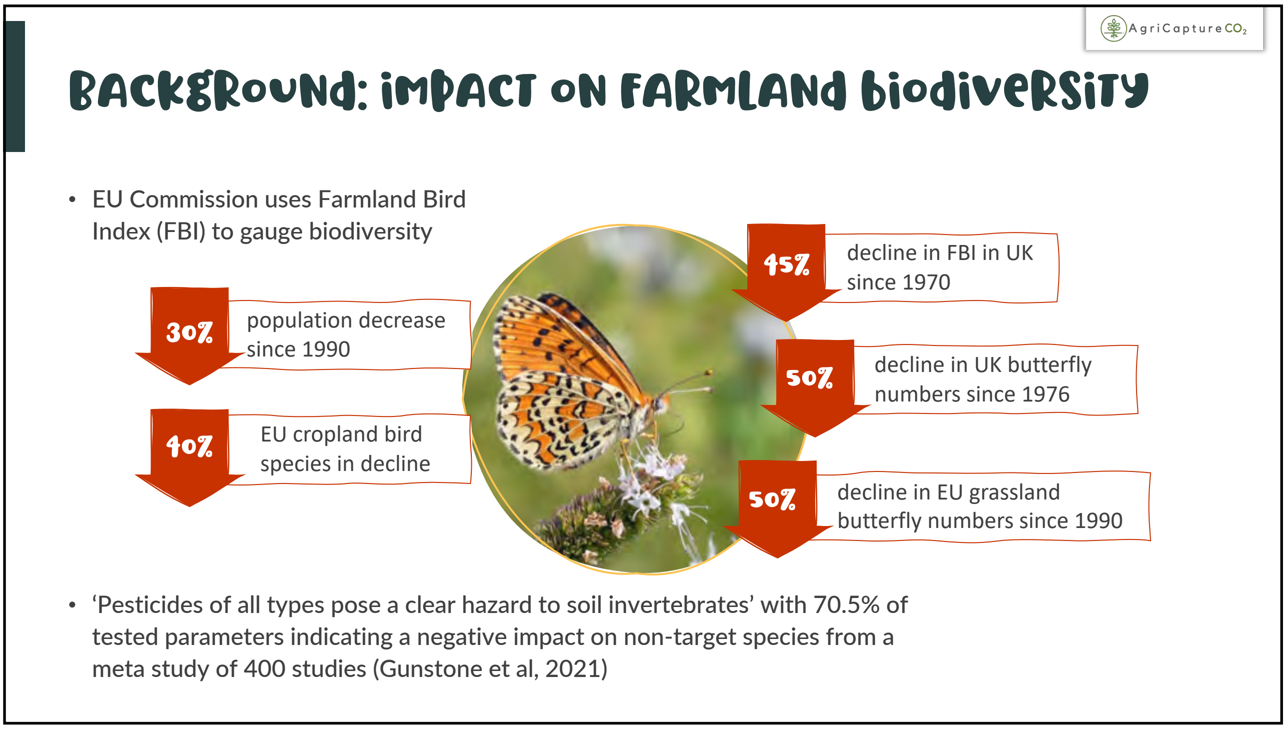
AgriCapture CO2
Background: impact on farmland biodiversity
• EU Commission uses Farmland Bird Index (FBI) to gauge biodiversity
30% population decrease since 1990
40% EU cropland bird species in decline
45% decline in FBI in UK since 1970
50% decline in UK butterfly numbers since 1976
50% decline in EU grassland butterfly numbers since 1990
• 'Pesticides of all types pose a clear hazard to soil invertebrates' with 70.5% of tested parameters indicating a negative impact on non-target species from a meta study of 400 studies (Gunstone et al, 2021)

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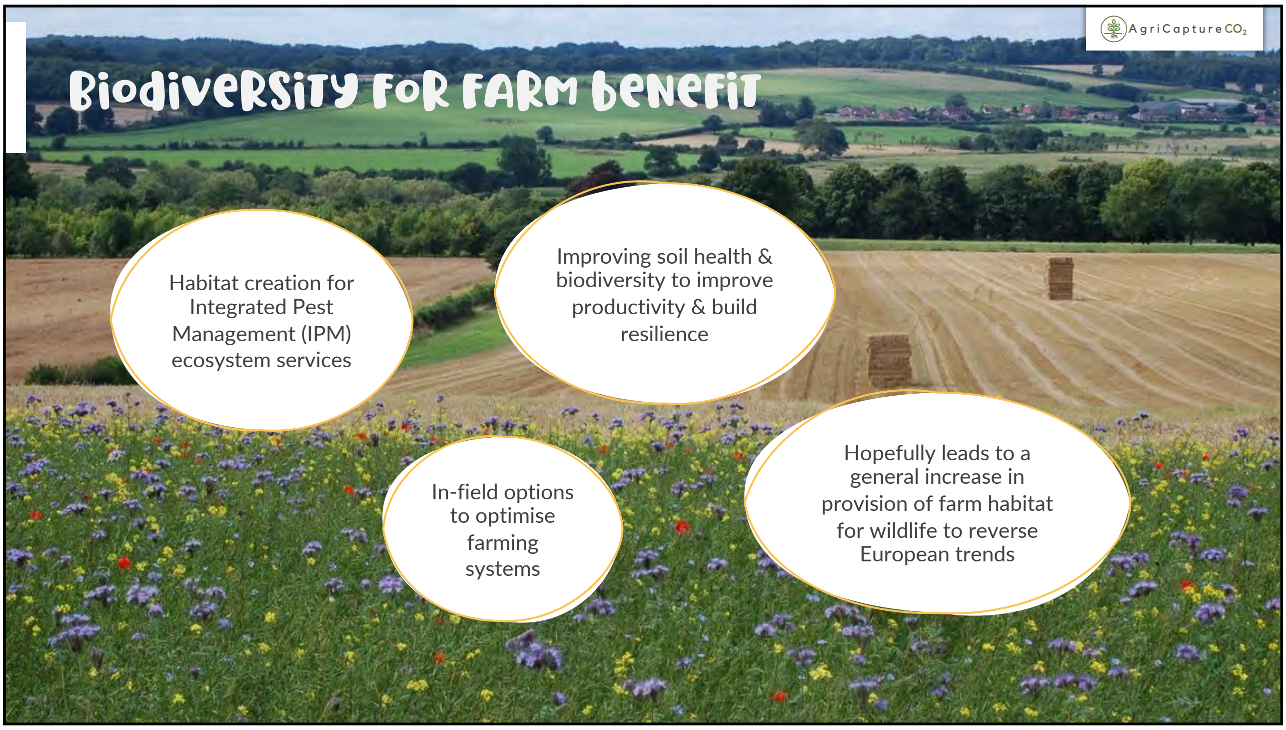
AgriCapture CO2
Biodiversity for farm benefit
Habitat creation for Integrated Pest Management (IPM) ecosystem services
Improving soil health & biodiversity to improve productivity & build resilience
In-field options to optimise farming systems
Hopefully leads to a general increase in provision of farm habitat for wildlife to reverse European trends

10

Integrated Pest Management (IPM)

- 'Integrated Pest Management' is the careful consideration of all available plant protection methods and subsequent integration of appropriate measures that discourage the development of populations of harmful organisms and keep the use of plant protection products and other forms of intervention to levels that are economically and ecologically justified and reduce or minimise risks to human health and the environment.
- (Sustainable Use Directive, 2009)

LEAF Integrated Farm Management wheel

11

Integrated Pest Management (IPM)

- EU Directive 2009/128/EC 'aims to achieve a sustainable use of pesticides in the EU by reducing the risks and impacts of pesticide use on human health and the environment and promoting the use of Integrated Pest Management (IPM) and of alternative approaches or techniques, such as non-chemical alternatives to pesticides'
- Many of the actions taken by member states under the Directive also relevant to the Biodiversity Strategy 2030 & the Farm to Fork Strategy
- EU countries required to adopt National Action Plans (NAPs) to implement the Directive
- Adopted into UK law post-Brexit

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Integrated Pest Management (IPM)

- Aerial spraying is banned and exceptions are only granted under strict conditions
- 900,000 sprayers have ben tested for accurate and safe application
- Pesticide use us prohibited or minimised in public parks, sports grounds, hospitals and schools
- Farmers must implement Integrated Pest Management and give preference to non-chemical methods if they provide satisfactory pest control
- Four million farmers have been trained to use pesticide safely
- The number of EU approved low risk and/or non-chemical pesticide substances has doubled since 2009
- Rivers, lakes, ground water and drinking water must be protected against pesticides
- Organic farming crops now cover 6.7% of the EU Agricultural Area and organic production has increased by 18.7% from 2012 to 2016according to Eurostat

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Integrated Pest Management (IPM)

- IPM can play a significant role in making farming more environmentally, economically & socially sustainable
- It allows producers to make informed decisions to manage crops & minimise reliance on pesticides
- IPM can help maintain biodiversity, decrease pollution & lower the build-up of pesticide resistance as well as potentially reduce costs/increase margins
- The diversity of solutions available in IPM helps ensure the long-term sustainability of control measures
- Targeted use of PPPs as a final resort
- Making ecosystem services work for you!

IPM Hierarchy

1. Achieving prevention and suppression of harmful organisms
2. Monitoring of harmful organisms
3. Decisions made based on monitoring and thresholds
4. Non-chemical methods
5. Pesticide Selection
6. Reduced Use
7. Anti-resistance strategies
8. Evaluation
9. PREVENT – DETECT – CONTROL

14

Integrated Pest Management (IPM)

- Select low-risk locations
- Healthy rotations (including cover & break cropping)
- Cultivation techniques
- Crop varieties & varietal mixtures
- Seed rates & plant densities
- Sowing date & conditions
- Machinery hygiene
- Effective field nutrition
- Effective field drainage
- Protection & enhancement of beneficial field organisms
- Physical/manual weed control
- Mulching & green covers
- Biopesticides/stimulants
- Monitoring & application of pest thresholds
- Polycultures
- Trap crops, allelopathy & biofumigation
- Organic amendments
- Improve soil health
- Use clean & tested seeds/saplings
- Spot treatment of injurious species, e.g. weed wiping
- Reduced rate applications of PPPs
- Precision/variable rate application
- Preventative action based on risk factors, e.g. weather, variety

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Benefits of Habitat Creation

6 key elements to aiding farmland wildlife:

Existing habitat	Field boundaries	Wet features
often most wildlife rich – should be the priority when providing space for wildlife	When well managed, can support a range of wildlife & provide habitat connectivity	with appropriate management can be focus for range of farm wildlife
Flower rich habitats	**Seed-rich habitats**	**Farmed area**
many native flowering plants are impacted by farming practices, including rare arable specialists & species rich grasslands	Traditional farming systems provided seed-rich habitats that farmland wildlife developed to exploit	Small management changes to benefit farm wildlife

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Benefits of Habitat Creation

- IPM more difficult in a homogenous landscape with pests establishing significant populations in the ecosystem
- Heterogenous landscapes offer greater potential for biological control of plant pests & diseases
- Offer safe havens for beneficial organisms beyond the productive area
- Combine temporal & spatial diversification, e.g:
    - Rotational diversity breaks pest lifecycles
    - Polycropping can reduce problem weed populations
- Diversity = resilience

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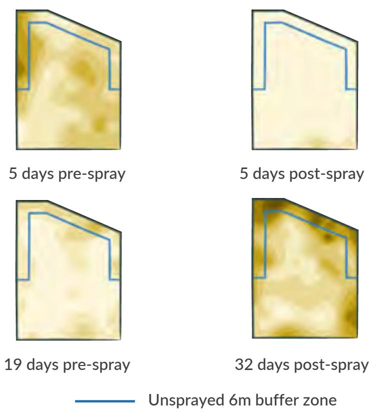
Benefits: Encouraging Beneficials

- GWCT IPM research measured the abundance & distribution of natural pest predators from the field to landscape scales
- Primarily located <60m from margins & in-field habitats
- Due to diversity of plants & habitat outside monocropped area
- An application of dimethoate insecticide severely reduced most species.
- Recovery was slow, with beneficial predator species recovering most slowly

Impact of the insecticide dimethoate on the distribution of beetles



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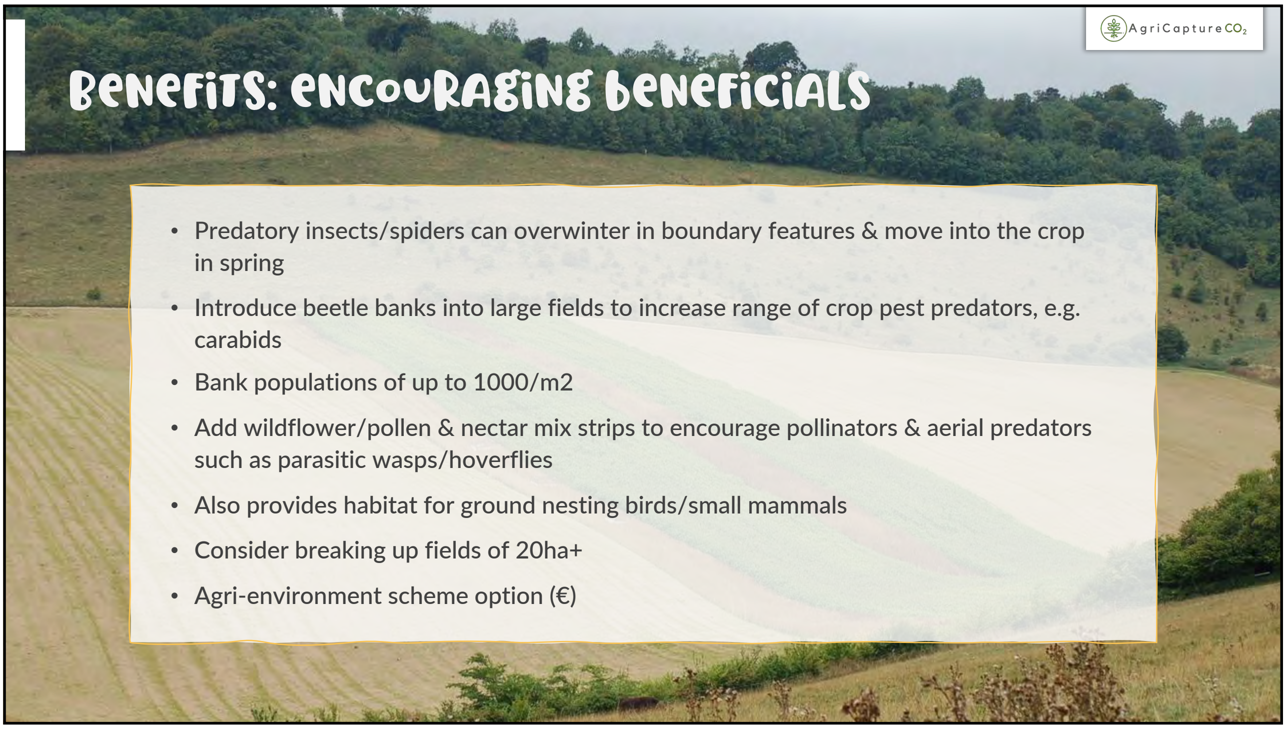
AgriCapture CO2
Benefits: encouraging beneficials
• Predatory insects/spiders can overwinter in boundary features & move into the crop in spring
• Introduce beetle banks into large fields to increase range of crop pest predators, e.g. carabids
• Bank populations of up to 1000/m2
• Add wildflower/pollen & nectar mix strips to encourage pollinators & aerial predators such as parasitic wasps/hoverflies
• Also provides habitat for ground nesting birds/small mammals
• Consider breaking up fields of 20ha+
• Agri-environment scheme option (€)

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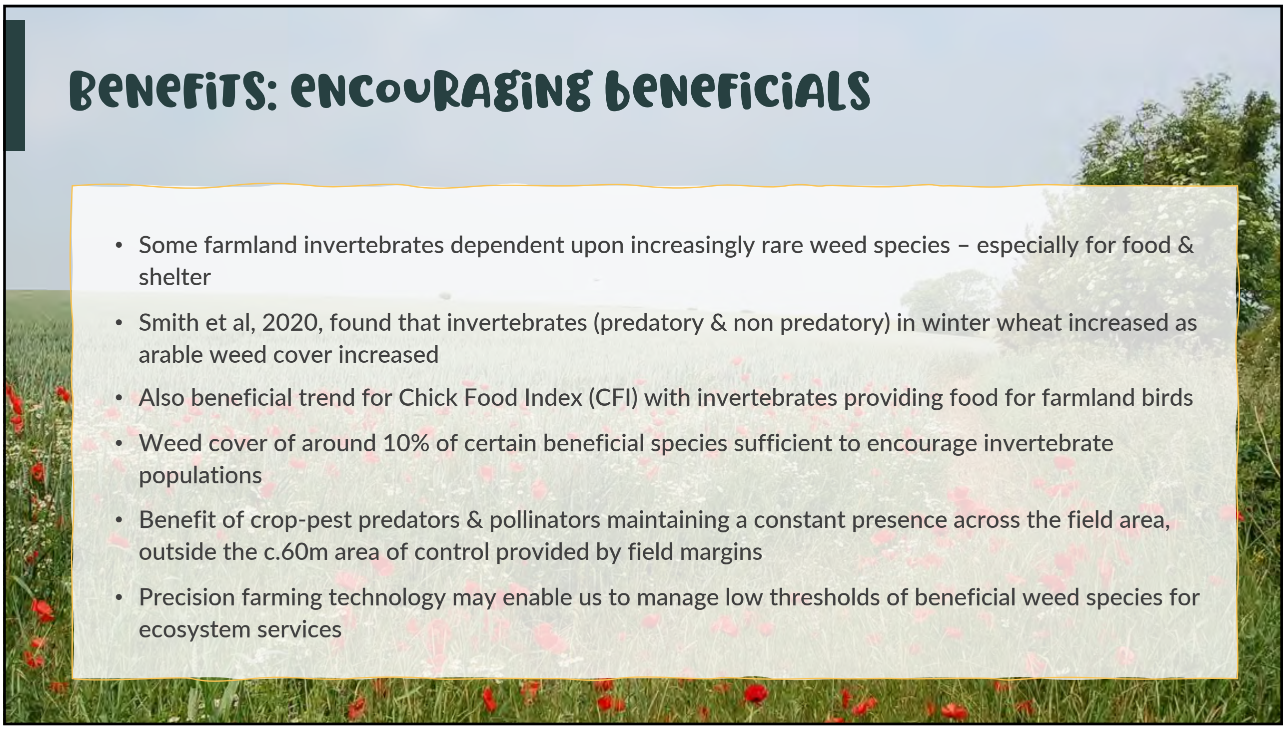
Benefits: encouraging beneficials
• Some farmland invertebrates dependent upon increasingly rare weed species – especially for food & shelter
• Smith et al, 2020, found that invertebrates (predatory & non predatory) in winter wheat increased as arable weed cover increased
• Also beneficial trend for Chick Food Index (CFI) with invertebrates providing food for farmland birds
• Weed cover of around 10% of certain beneficial species sufficient to encourage invertebrate populations
• Benefit of crop-pest predators & pollinators maintaining a constant presence across the field area, outside the c.60m area of control provided by field margins
• Precision farming technology may enable us to manage low thresholds of beneficial weed species for ecosystem services

20

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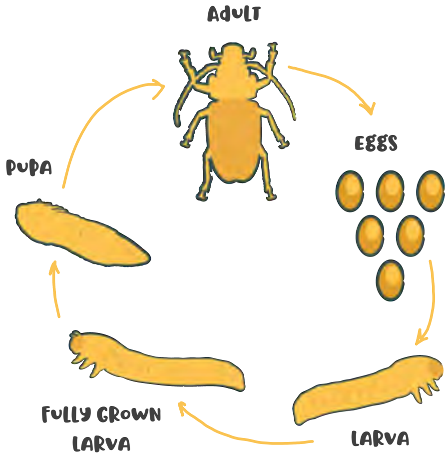
Benefits: encouraging beneficials

- Ground (carabid) beetles (carabidae)
- 350+ species with many different characteristics beneficial in farming systems
- Live in & on the surface of soil including arable fields, dead wood & vegetative ground cover
- Generalist predators; feed on aphids, fly eggs & larvae, moth/butterfly eggs & larvae, slugs & weed seeds
- Breeding can occur in summer/autumn, over wintering as larvae or breeding in the spring & over-wintering as adults
- Techniques to benefit:
  - Reduce cultivations
  - Reduce insecticide use via IPM
  - Provide habitat on field margins & beetle banks
  - Encourage beneficial weed species



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Benefits: encouraging beneficials

- Annual EU output attributed to insect pollination = €15 billion
- But significant decline in pollinator numbers in Europe due to habitat degradation
- Pollinators can be encouraged through the provision of the appropriate flowering plants in sufficient quantities & with appropriate nesting sites
- Provision of 2.2% flower-rich habitat per farm, more than doubled density of UK bumblebee colonies
- BEESPOKE - Benefiting Ecosystems through Evaluation of food Supplies for Pollination to Open up Knowledge for End users (2019-2023)
- Pilot farms will test out crop specific seed mixes & management methods for 14 crop types across 72 demonstration sites in Northern Europe

Interreg North Sea Region BEESPOKE
EUROPEAN UNION

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Benefits: Encouraging Beneficials

- Pollinators require both pollen & nectar-rich flowers to provide food
- Nectar is Fuel: Nectar from flowers is high in sugar, used by pollinators as fuel. The sugar attracts pollinators to the plant
- Pollen is Food: Pollen provides protein & nutrients, used by pollinators to feed their young. Pollen also used by the plant for fertilisation to produce seed
- By protecting, encouraging or planting a variety of spring, summer and autumn flowering plants farmers can provide excellent pollinator food sources
- Pollinators also require habitat to nest & overwinter – typically undisturbed tussocky grassland or earth banks
- Multiple agri-environment scheme options (€)

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Case Study: Encouraging Beneficials

- Plumford apple farm (Kent, UK)
- Grower of Traditional Heritage Apples & core varieties for retailer Marks & Spencer (M&S)
- New orchard established 2020-21 with intention to investigate relationship between wildflower density & populations of crop pest predators & pollinators as part of M&S Farming with Nature initiative
- King's 'IPM Flower Mix' - a perennial mix of native wild flowers and agricultural legumes
- 3 key flower families; Umbellifers, Rosaceae & Asteraceae, which support key predatory insect species such a hover flies, ladybirds, lacewings, solitary bees & spiders

M&S FOOD NIAB kings

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Case Study: Encouraging Beneficials

- 6ha orchard
- Trial treatments to include control of only fine leaved grasses - most typical of the seed mix likely to be established in orchard alleys
- Treatments then start with a 20% flower component increasing to 70%
- Cost of highly diverse IPM mix taken into account: some treatments only every other alley but ensures that every row of trees is next to a flower rich strip

Different treatments within wildflower trial

1. Fine leaved grasses only
2. 20%fl:80%gr
3. 30%fl:70%gr
4. 30%fl:70%gr every other row
5. 50%fl:50%gr every other row
6. 70%fl:30%gr every other row

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Benefits: Agroforestry

- A land management approach combining trees & shrubs with crops & livestock
  - Silvopastoral (trees + livestock)
  - Silvoarable (trees + crops)
  - Hedgerows & buffer strips
  - Forest farming
- Lampkin et al, 2015, found that pest problems were reduced in agroforestry systems due to the greater diversity of habitat vs monocultures. (Greater & more even distribution of, e.g. carabids in silvoarable systems)
- Higher abundance & species richness of invertebrates & other farmland species
- Improved nutrient capture
- Improved soil water infiltration

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Benefits: Soil biome

- Soil organisms are hugely diverse & play a range of critical roles in delivering ecosystem services
  - Retention & cycling of nutrient
  - Decomposition & recycling of organic matter
  - Maintaining soil structure
  - Improving water infiltration & retention
  - Degrade environmental pollutants

- Recent reviews have highlighted the largely negative impacts of modern agriculture on soil biota & their function, e.g:
  - Intensive cultivations
  - Excessive synthetic inputs
  - Low-diversity monocultures
  - Low levels of organic matter input
- Reductions in diversity & species richness of soil biota; simplified food webs & breakdown of beneficial symbiosis – e.g. plants & mycorrhizal fungi

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Benefits: Soil biome

- UK Natural England report 'Managing soil biota to deliver ecosystem services' 2012
- Practices likely to support & enhance soil biota are 'systems oriented approaches' which require management changes across the whole farm system and are based on reg agri principles:
  - Manage amount & quality of organic matter inputs
  - Reduce intensity of tillage
  - Diversify cropping systems
  - (Plus some 'point interventions' to target narrow elements of soil health)

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Benefits: Soil biome

Direct impacts of OM inputs:

- OM inputs provide a direct source of energy/food for many soil biota. OM inputs generally lead to an increase in the biomass of soil biota in all groups
- Variation in the decomposability of the OM inputs (indicated by the C:N ratio) may increase species richness

Indirect impacts of OM inputs:

- Decomposition of OM inputs stimulates structure development and improves structural stability in soils
- Soils with regular inputs of OM have improved structural characteristics with positive benefits for aeration (in clay soils) & water holding capacity (in sandy soils) giving a wider range of niche habitats
- Decomposition of OM inputs increases cycling of nutrients, stimulating plant growth, further stimulating C inputs to the soil biota through roots, root exudates & residues
- OM inputs therefore may reduce the indirect (fertiliser) and direct (cultivation) energy demands of agricultural systems and also reduce runoff & associated sediment loss

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Benefits: Soil biome

Direct impact of Reduced tillage:

- Tillage has direct negative impacts on macrofauna so reduced numbers of tillage operations and/or increased duration of no-till periods likely to lead to increased biomass of macrofauna

Indirect impact of Reduced tillage:

- Tillage disrupts connectivity of pores & water films. Reducing the occurrence or frequency of this disruption is likely to increase soil mesofauna biomass
- Reducing tillage associated with increased fungal biomass especially of mycorrhizal fungi. Reduced tillage also stimulates soil biota more generally via increased OM inputs & increased stabilisation of niche habitats
- Changes in tillage lead to reduced soil erosion & nutrient loss, as well as above-ground biodiversity. Reductions of fuel use/reduced loss of soil carbon also beneficial for farm carbon budget

30

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Benefits: Soil biome

Direct impact of diversified cropping on soil biota

- Reduced monocropping encourages beneficial crop/soil biological associations, e.g. mycorrhizal fungi
- Increases in plant diversity (temporal & spatial) likely to lead to increase in species richness of soil biota through more diverse litter, exudates, rooting patterns, & plant associations
- Diverse & well managed margins also important to colonise field spaces & act as niche habitats in own right

Indirect impacts of diversified cropping on soil biota

- Also beneficial for above-ground species diversity (e.g. wildlife habitat)
- This may deliver additional ecosystem services, e.g. crop pollination
- Diverse cropping reduces exposure to potential disease outbreaks of monocropped systems & reliance on synthetic PPPs (which may impact soil biome)

31

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Benefits: In-field options to optimise farming systems

Potential for multifunctional nature-based features to aid productivity in modern farmed landscape

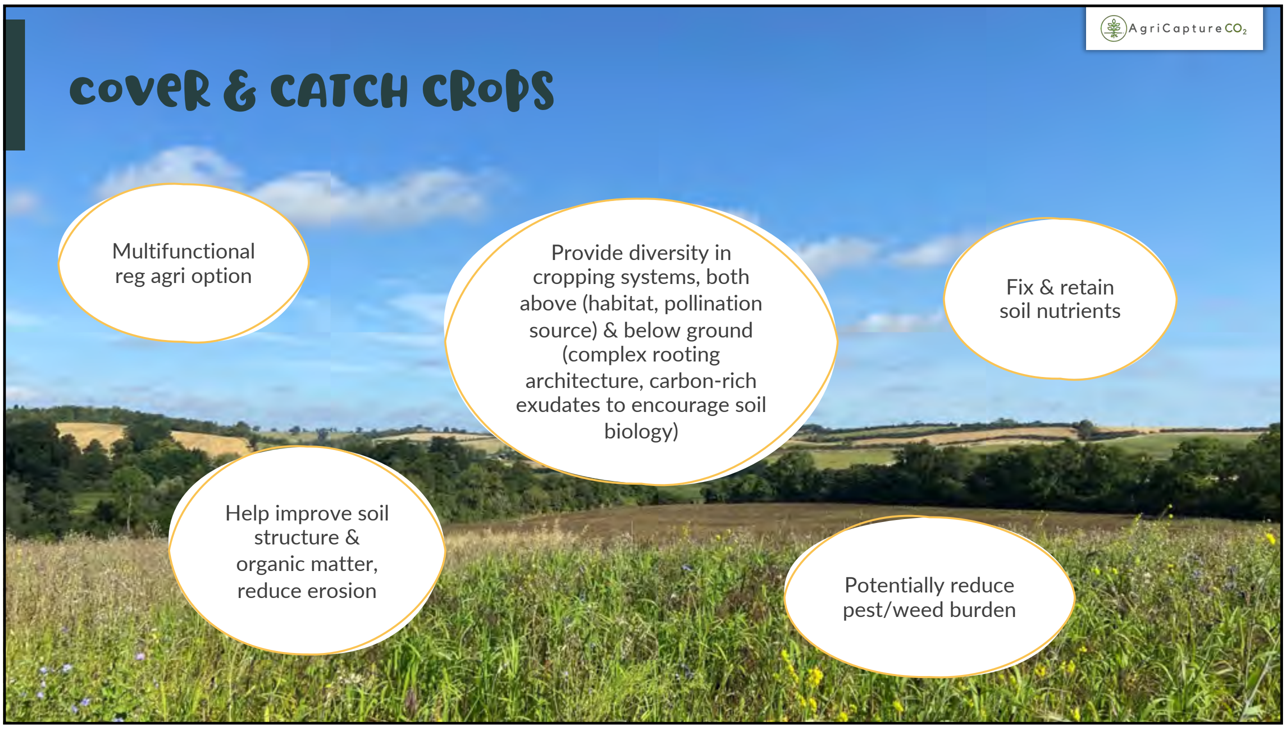
Beetle banks/grass margins can be used to break up slopes & reduce soil erosion & runoff while also providing ecosystem services, e.g. habitat for crop pest predators/pollinators

Remove less productive areas from cropping with in-field options (especially field edge) to improve productivity & reduce inputs

Buffer strips along watercourses to reduce pesticide drift & soil/nutrient runoff

Multiple agri-environment scheme options (€)

32


AgriCapture CO_2
COVER & CATCH CROPS
Multifunctional reg agri option
Provide diversity in cropping systems, both above (habitat, pollination source) & below ground (complex rooting architecture, carbon-rich exudates to encourage soil biology)
Fix & retain soil nutrients
Help improve soil structure & organic matter, reduce erosion
Potentially reduce pest/weed burden

33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BEDANKT
EFHARISTO POLI
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THANK YOU
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GWCT
THE ALLERTON
planet.
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EnvirometriX
Lancashire County Council

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5 PRINCIPLES OF REGENERATIVE AGRICULTURE

HEALTHY SOIL · HEALTHY CROPS · HEALTHY BUSINESSES

INTEGRATION OF GRAZING LIVESTOCK

MODULES: SOIL PROTECTION, INTEGRATION OF ORGANIC MATTER, MAINTAIN LIVING ROOTS, BIOLOGICAL DIVERSITY

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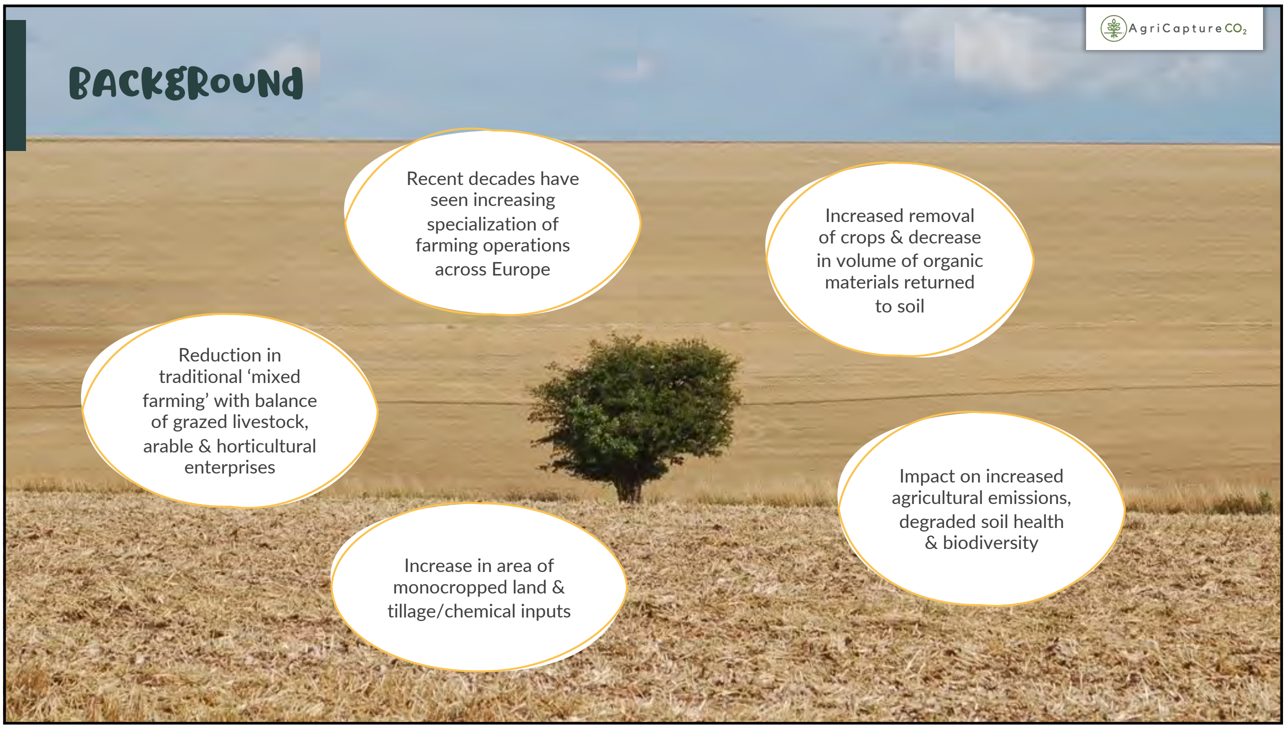
AgriCapture CO2
Background
Recent decades have seen increasing specialization of farming operations across Europe
Increased removal of crops & decrease in volume of organic materials returned to soil
Reduction in traditional 'mixed farming' with balance of grazed livestock, arable & horticultural enterprises
Impact on increased agricultural emissions, degraded soil health & biodiversity
Increase in area of monocropped land & tillage/chemical inputs

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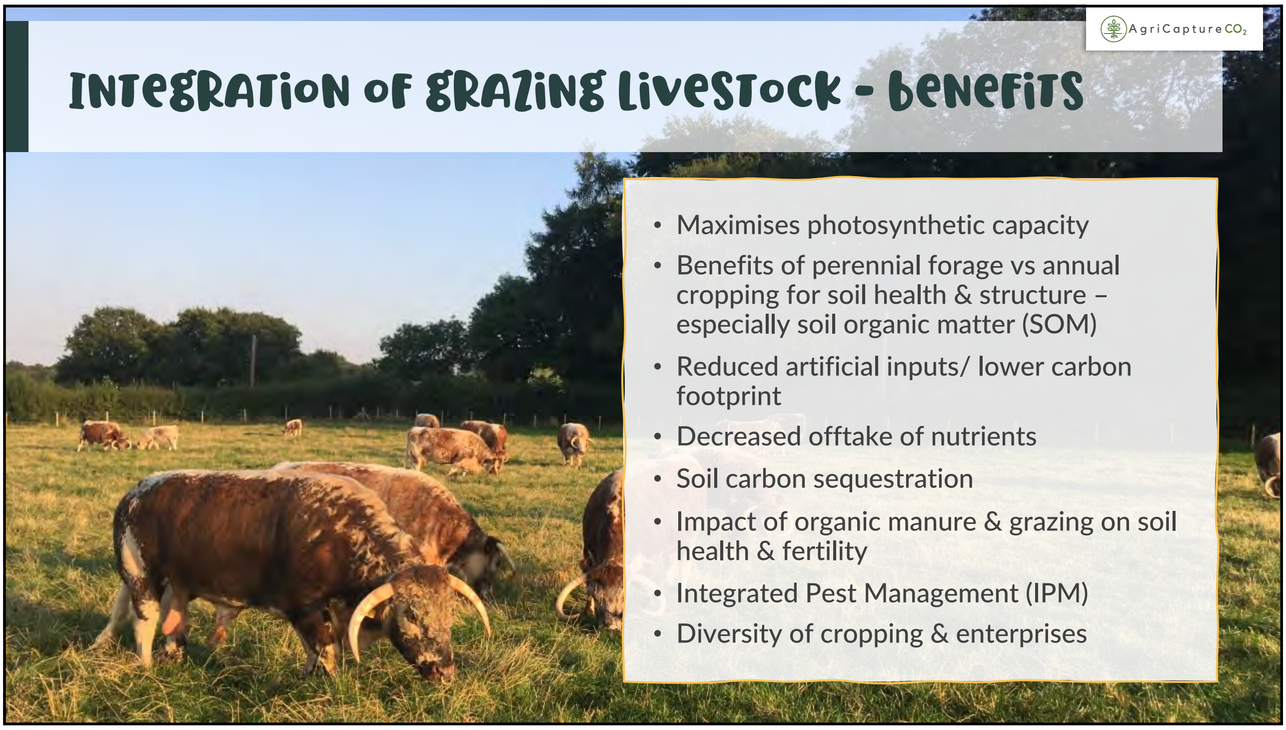
AgriCapture CO2
Integration of grazing livestock - benefits
• Maximises photosynthetic capacity
• Benefits of perennial forage vs annual cropping for soil health & structure – especially soil organic matter (SOM)
• Reduced artificial inputs/ lower carbon footprint
• Decreased offtake of nutrients
• Soil carbon sequestration
• Impact of organic manure & grazing on soil health & fertility
• Integrated Pest Management (IPM)
• Diversity of cropping & enterprises

4

Options to integrate leys & livestock

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- Selling standing crops of grass, clover etc to make silage or hay
- Renting out grazing for the duration of the ley
- 'Flying livestock' - short term grazing visits, such as over-winter grazing of leys by sheep
- Taking responsibility for others stock whilst grazing your ley on a liveweight gain contract
- Contract grown crops i.e. lucerne, sainfoin or silage for local farmers
- Stockless leys - can provide benefits if establishment costs are minimal and the ley is left long enough

5

Benefits: Soil health & structure

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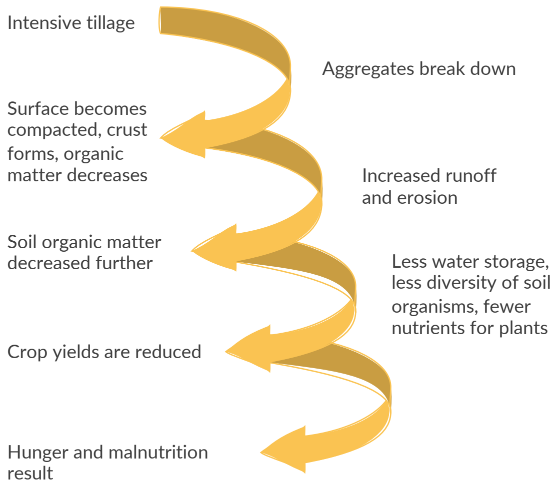
Tillage for cropping is major driver of soil degradation:

- Oxidises (SOM) - the foundation of healthy soil – and releases CO2
- Destroys aggregates, the building blocks of soil structure
- Creates compaction, decreasing aeration & infiltration
- Disrupts soil biome, impacting micro- & macro-organisms
- Creates conditions for soil erosion, nutrient leaching & runoff
- Reduces soil residue cover
- Direct tillage erosion

6

Tillage & Soil Health/Structure



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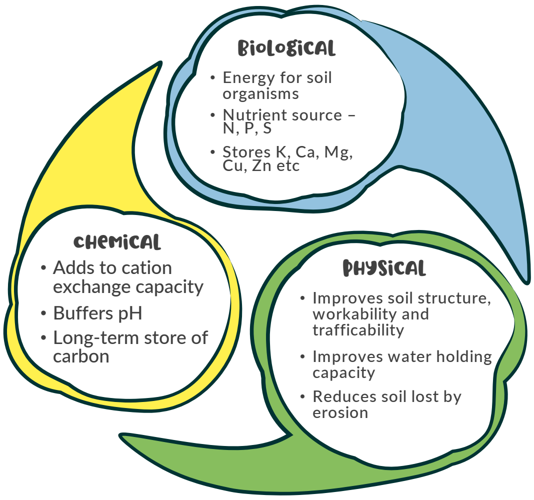
What is Soil Organic Matter (SOM)?

- All living or once living materials within & added to soil
- Includes roots, crop residues, manures & composts
- Contains carbon, nitrogen, phosphorous, sulphur, potassium, magnesium, calcium & other micronutrients
- Composed of c.58% carbon
- The interaction of OM with parent geology is a key process in soil formation
- Agricultural soils typically from 1-6% SOM
- +1% SOM can increase yield by as much as 10%

8

Soil organic matter (SOM)

- Essential for soil biological, physical & chemical processes
- The living, the 'dead' & decomposing (detritus) & the 'very dead' (humus) – actively cycling vs stable, long-term soil organic carbon (SOC)
- Provides nutrients & energy for soil biome
- Keystone of healthy soil structure & aggregation
- Boosts water holding capacity (WHC)
- Buffers pH & aids cation exchange capacity (CEC)



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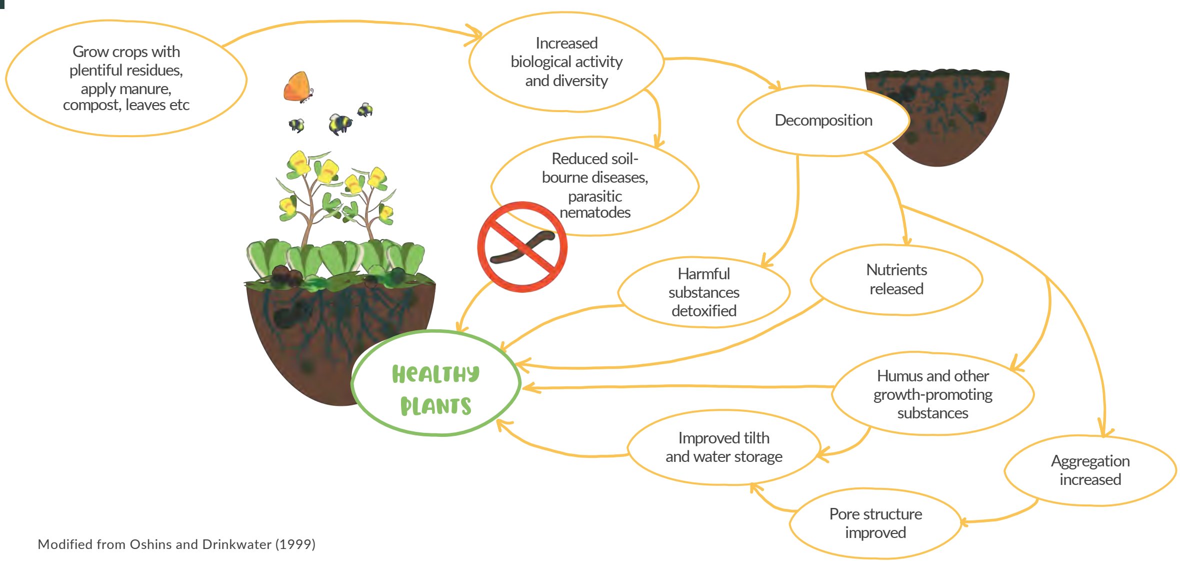
Why is soil organic matter important?



Modified from Oshins and Drinkwater (1999)

10

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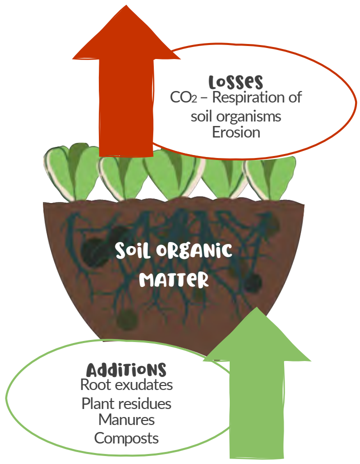
Building Soil Organic Matter

- Levels of soil organic matter = equilibrium between inputs & decomposition of SOM by soil organisms. Inputs must exceed losses to build SOM.
- Levels of SOM present in soil can be affected by natural processes such as
  - Temperature
  - Rainfall
  - Soil type & texture
- But also human processes such as
  - Tillage
  - Removal of crops/crop residues
  - Application of artificial N
  - Important to adapt management practices to reverse losses before increases can be gained



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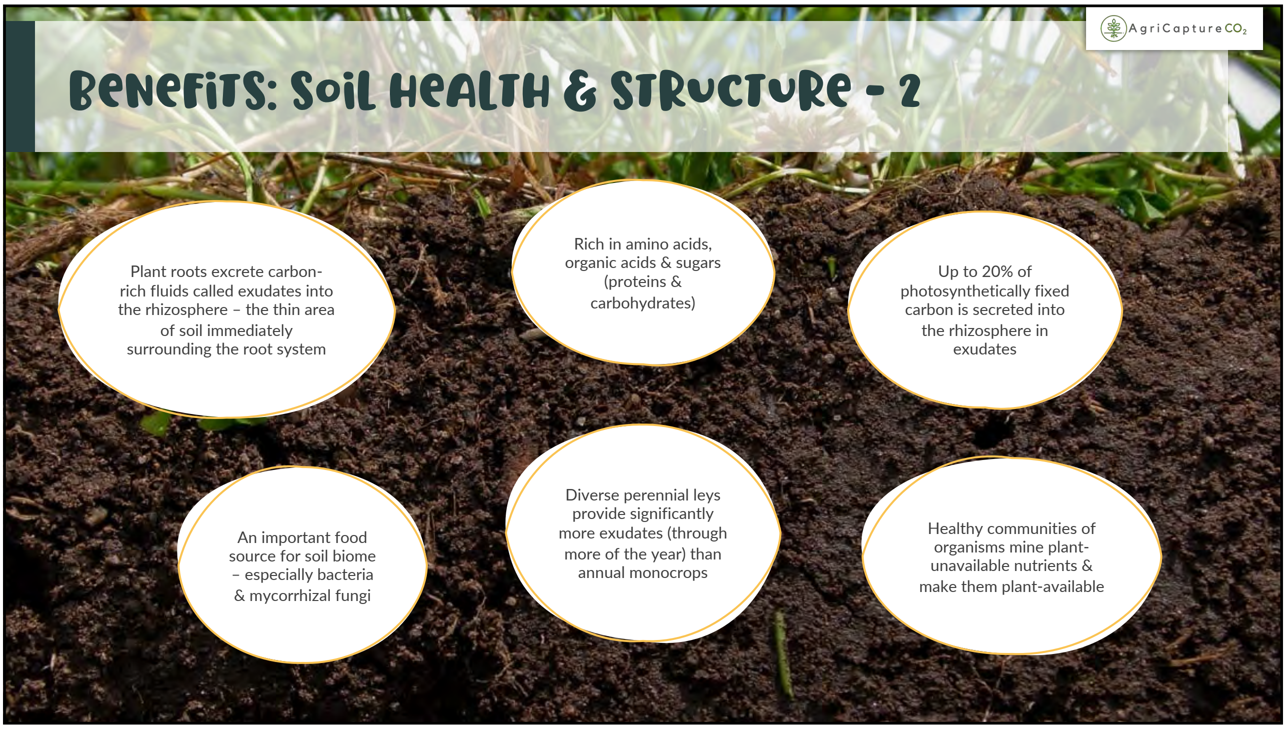
Benefits: Soil Health & Structure

- Cropping with perennial grass/diverse swards reduces tillage & high-carbon inputs associated with annual arable & horticultural monocrops
- Stabilises existing SOM level
- Reduced compaction & erosion associated with intensive cultivations
- Permanent soil cover & living roots
- Allows development of deeper & more complex root architecture which benefit soil structure & biome
- Managed grazing can stimulate additional root growth & exudation, while applying organic manure
- Increase in SOM & associated benefits
- All 5 principles of Regen Agri!

12


AgriCapture CO_2
Benefits: Soil Health & Structure - 2
Plant roots excrete carbon-rich fluids called exudates into the rhizosphere – the thin area of soil immediately surrounding the root system
Rich in amino acids, organic acids & sugars (proteins & carbohydrates)
Up to 20% of photosynthetically fixed carbon is secreted into the rhizosphere in exudates
An important food source for soil biome – especially bacteria & mycorrhizal fungi
Diverse perennial leys provide significantly more exudates (through more of the year) than annual monocrops
Healthy communities of organisms mine plant-unavailable nutrients & make them plant-available

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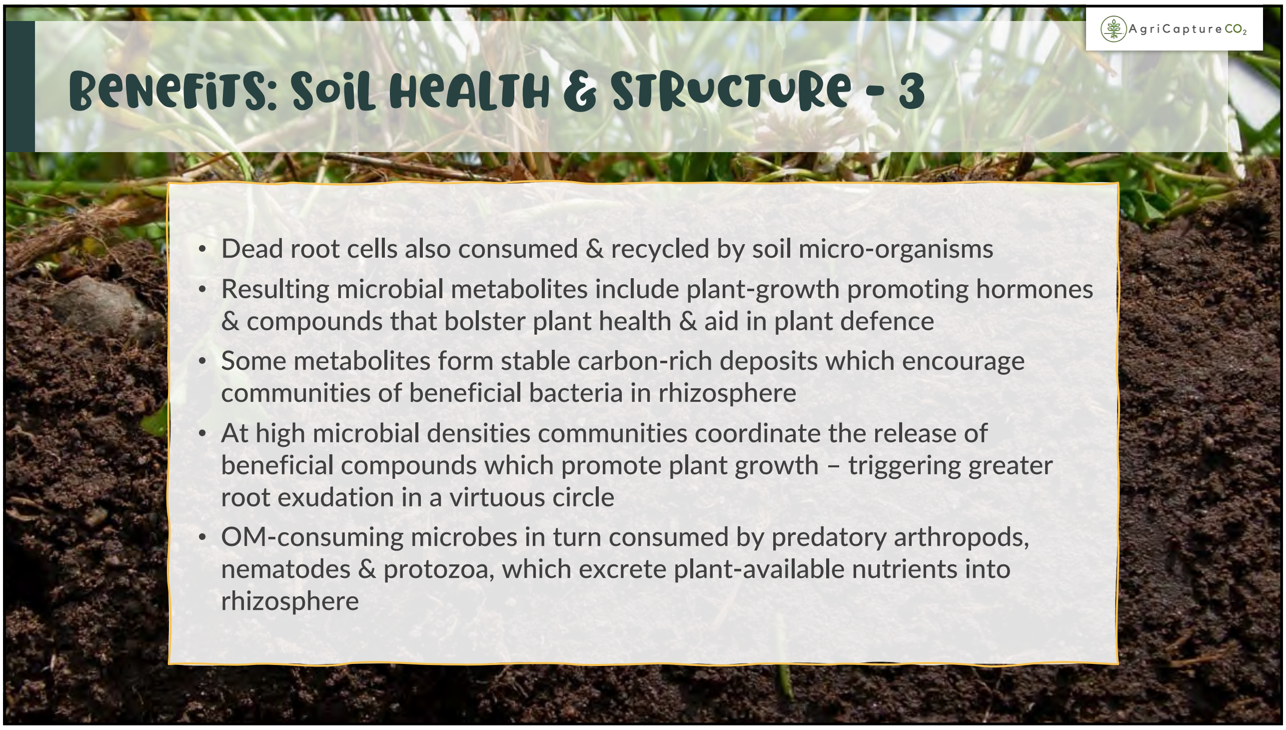
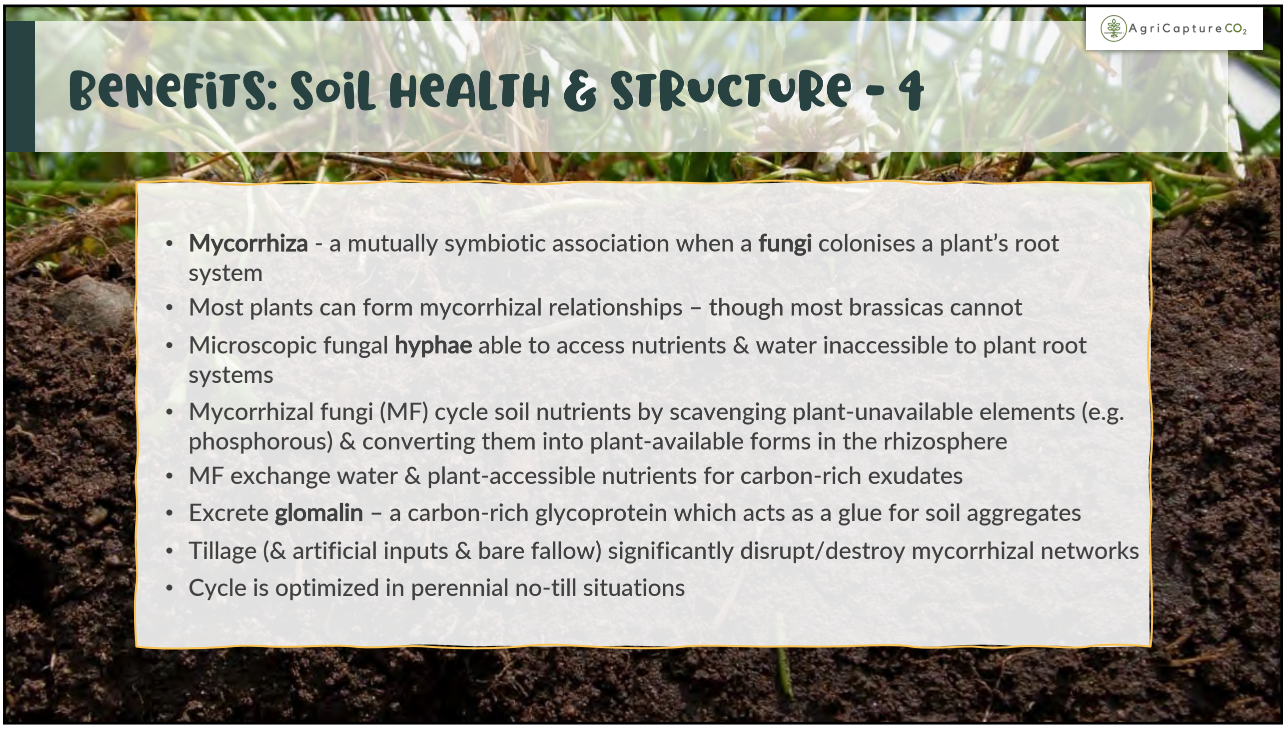

AgriCapture CO_2
Benefits: Soil Health & Structure - 3
• Dead root cells also consumed & recycled by soil micro-organisms
• Resulting microbial metabolites include plant-growth promoting hormones & compounds that bolster plant health & aid in plant defence
• Some metabolites form stable carbon-rich deposits which encourage communities of beneficial bacteria in rhizosphere
• At high microbial densities communities coordinate the release of beneficial compounds which promote plant growth – triggering greater root exudation in a virtuous circle
• OM-consuming microbes in turn consumed by predatory arthropods, nematodes & protozoa, which excrete plant-available nutrients into rhizosphere

14


AgriCapture CO_2
Benefits: Soil Health & Structure - 4
• **Mycorrhiza** - a mutually symbiotic association when a **fungi** colonises a plant's root system
• Most plants can form mycorrhizal relationships – though most brassicas cannot
• Microscopic fungal **hyphae** able to access nutrients & water inaccessible to plant root systems
• Mycorrhizal fungi (MF) cycle soil nutrients by scavenging plant-unavailable elements (e.g. phosphorous) & converting them into plant-available forms in the rhizosphere
• MF exchange water & plant-accessible nutrients for carbon-rich exudates
• Excrete **glomalin** – a carbon-rich glycoprotein which acts as a glue for soil aggregates
• Tillage (& artificial inputs & bare fallow) significantly disrupt/destroy mycorrhizal networks
• Cycle is optimized in perennial no-till situations

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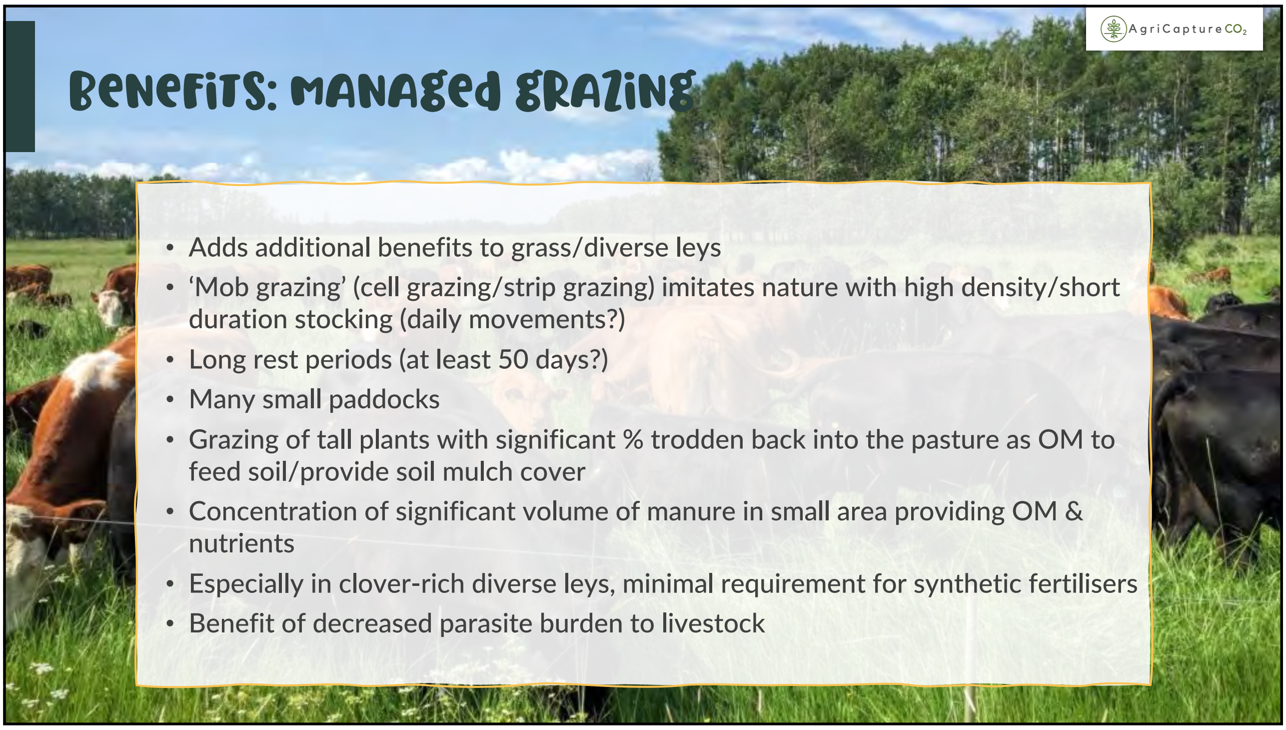
AgriCapture CO_2
Benefits: Managed Grazing
• Adds additional benefits to grass/diverse leys
• 'Mob grazing' (cell grazing/strip grazing) imitates nature with high density/short duration stocking (daily movements?)
• Long rest periods (at least 50 days?)
• Many small paddocks
• Grazing of tall plants with significant % trodden back into the pasture as OM to feed soil/provide soil mulch cover
• Concentration of significant volume of manure in small area providing OM & nutrients
• Especially in clover-rich diverse leys, minimal requirement for synthetic fertilisers
• Benefit of decreased parasite burden to livestock

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Benefits: Managed grazing

- Traditional grazing systems (e.g set stocking) can lead to overgrazing as livestock continually graze fresh regrowth depriving plant of ability to recover
- Plants cease root growth & exudation as all energy reserves redirected to leaf growth to boost photosynthesis
- In mob grazing systems, >50% of plant generally left ungrazed – encourages continued root growth & exudation (Graze 1/3, leave 1/3, trample 1/3)
- Plant's physiological response to grazing action (wounding) is to increase nutrient demands from rhizosphere via increased exudate production
- Virtuous circle of organic carbon feeding the soil & nutrient cycling back to the plant
- Increases pasture resilience by encouraging deeper root growth & boosting SOM

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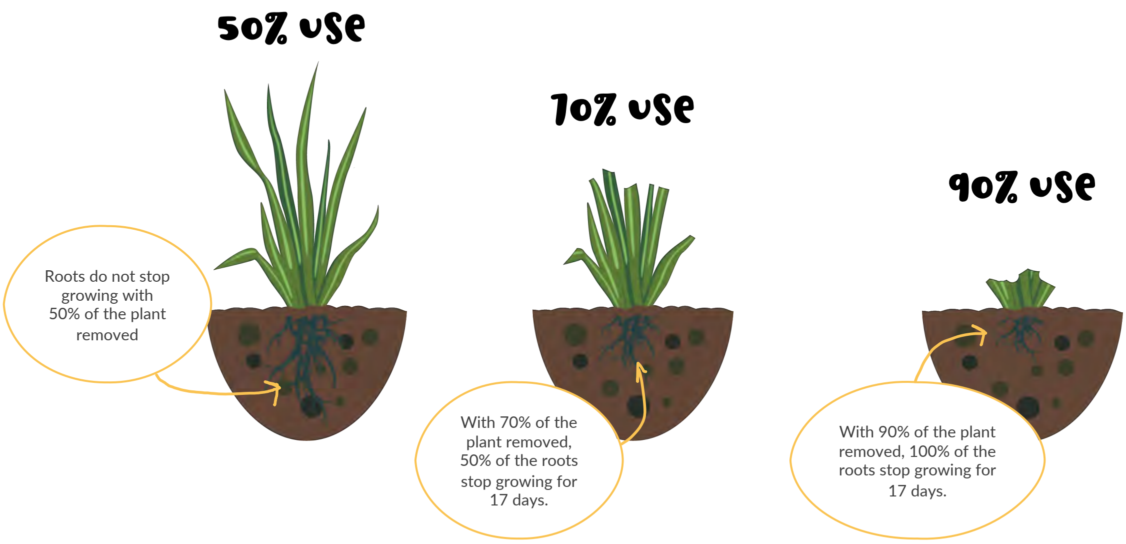
Benefits: Managed grazing



18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Benefits: diverse herbal leys
Ideally suited to mob grazing systems – ryegrass leys do not have the physical structure for mob grazing
Diverse swards have increased above-ground biomass & provide greater stability of biomass production vs grass monocultures
Legumes & herbs can provide considerably higher amounts of minerals and protein per kg DM of grazed forage vs grass monocultures
Short-intensity grazing forces livestock to graze whole sward rather than graze selectively
Livestock benefit from full range of sward properties: some species higher in protein; minerals; anthelmintics
Deep rooting species & legumes increase nutrient availability & reduce need for synthetic inputs

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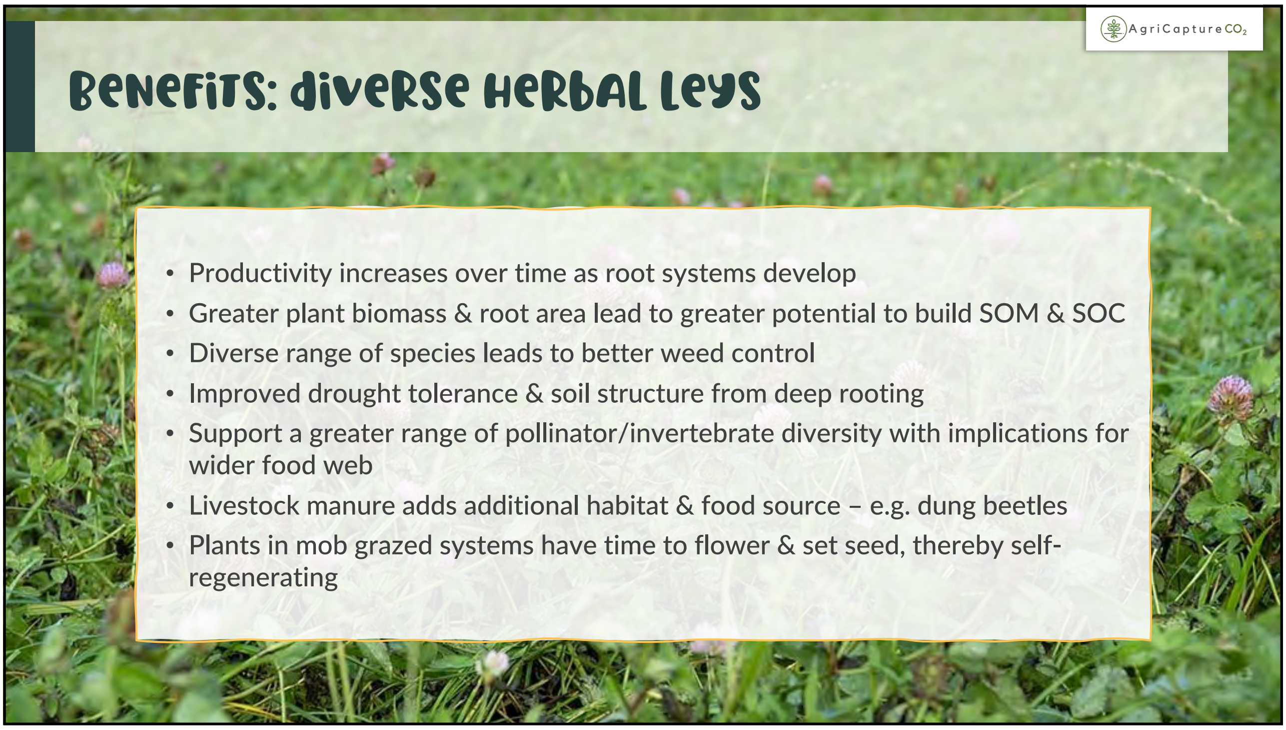
AgriCaptureCO_2
Benefits: diverse herbal leys
• Productivity increases over time as root systems develop
• Greater plant biomass & root area lead to greater potential to build SOM & SOC
• Diverse range of species leads to better weed control
• Improved drought tolerance & soil structure from deep rooting
• Support a greater range of pollinator/invertebrate diversity with implications for wider food web
• Livestock manure adds additional habitat & food source – e.g. dung beetles
• Plants in mob grazed systems have time to flower & set seed, thereby self-regenerating

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Benefits: diverse herbal leys

Example forage grasses:

- Ryegrasses
- Timothy
- Cocksfoot
- Festuloliums

Example forage legumes:

- Red & white clover
- Lucerne
- Sanfoin
- Winter vetch

Example forage herbs:

- Burnet
- Chicory
- Ribgrass
- Sheep's parsley

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Choosing the right ley (AHDB UK)

	Specialist silage leys (1–3 years)	Medium-term cutting and grazing leys (2–4 years)	Long-term cutting and grazing leys (5+ years)
Perennial ryegrass (diploid)	✗	✓	✓
Perennial ryegrass (tetraploid)	✓	✓	✗
Italian ryegrass	✓	✗	✗
Hybrid ryegrass	✓	✓	✗
Timothy	✗	✓	✓
Cocksfoot	✗	✓	✗
White clover (small leaf)	✗	✓	✓
White clover (medium leaf)	✓	✓	✓
White clover (large leaf)	✓	✓	✗
Red clover	✓	✓	✗

Source: 'Livestock and the Arable Rotation, AHDB (2018)

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Benefits: Nutrients in organic manure

Contains macro- & micro-nutrients needed for crop production

Inorganic (readily plant accessible) & organic (slow release) forms

Nitrogen (N)
• Ammonium N (NH4) is the predominant form of inorganic manure N • Nitrate N (NO3) an inorganic form of N present in much smaller quantities • Urea, organic N which converts rapidly to inorganic ammonium • Organic N (Org-N) contributes to long-term soil nitrogen supply

Phosphorous (P) & Potassium (K)
• Primarily plant-available in organic forms

Primary micronutrients
• Calcium (Ca) magnesium (Mg) sulphur (S) Iron (Fe)

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Benefits: Nutrients in Organic Manure

- In mob/strip grazing regimes, manure deposited evenly across the field
- Organic manure provides rapidly-accessible food source for soil biome to boost biological activity
- May help increase soil organic matter
- Grazing livestock cycle & retain greater degree of nutrients in-field versus arable/horticultural/forage production
- Removal of oilseed rape + straw removes 15kg of phosphate/t of fresh material, 17.5kg/t potassium & 2.5kg/t magnesium (AHDB)
- Diverse leguminous swards fix/cycle their own N, P, K & other nutrients, reducing need for inputs

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Benefits: Nutrients in Organic Manure

Livestock type	Total N produced by 1 livestock type (kg/year)[1]	Total P_2O_5 produced by 1 livestock type (kg/year)	Total K_2O produced by 1 livestock type (kg/year)
1 Dairy cow (over 9000 litre milk yield)	115	52	92
1 Dairy cow (6000 to 9000 litre milk yield)	101	44	77
1 Dairy cow (up to 6000 litre milk yield)	77	34	61
1 Dairy heifer replacement, 13 months to first calf	61	25	58
1 Dairy heifer replacement, 3 to 13 months	29	10.3	24
1 Beef suckler cow[2] (over 500 kg)	83	31	66
1 Beef suckler cow[2] (up to 500 kg)	61	24	47
1 Steer / Heifer for slaughter, over 25 months	50	22	47
1 Steer / Heifer, 13 to 25 months	50	15.7	38
1 Steer / Heifer, 3 to 13 months	28	10	24
1 Bull beef, 3 months and over	54	8.8	38
1 Bull for breeding, over 25 months	48	22	38
1 Bull for breeding, 3 to 25 months	50	15.7	38
1 Calf, up to 3 months	1.4	0.77	2.6
1 Lamb (from 6 months up to 9 months)	0.5	0.07	1.3
1 Sheep (from 9 months old to first lambing, tupping or slaughter)[3]	0.7	0.38	2.6
1 Sheep up to 60 kg (inc. lamb to 6 months)	7.6	3.2	9.6
1 Sheep over 60 kg (inc. lamb to 6 months)	11.9	3.7	14.4
1 Goat	15	6.9	10.2
1 Breeding deer	15.2	6.4	12.4
1 Deer (other)	12	4.3	9.1
1 Horse	21	20	54

[1] Includes an allowance for N losses from livestock housing and manure storage
[2] Suckler cow; includes calf up to weaning age
[3] Assumes 6 months in this category

Source: SRUC TN650 'Optimising the application of bulky organic manures (2013)

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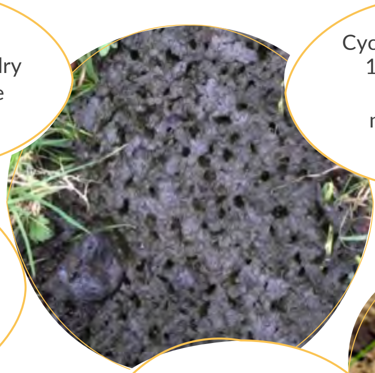
Benefits: Nutrients in organic manure…dung beetles

A cow can produce 4-6kg dry matter manure each day



Cycle nutrients up to 1m into the soil, boosting soil microbiology & earthworms

Also help aerate soil & boost water infiltration

Fungi, bacteria & weathering all degrade manure – but dung beetles are key. Poor populations can lead to slow decomposition & poor pasture performance

Help control livestock parasites & fly larvae which live in dung

Rollers, burrowers & dwellers

Dung beetles also important part of food web & farm biodiversity

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Benefits: Integrated Pest Management (IPM)

'Integrated Pest Management' is the careful consideration of all available plant protection methods and subsequent integration of appropriate measures that discourage the development of populations of harmful organisms and keep the use of plant protection products and other forms of intervention to levels that are economically and ecologically justified and reduce or minimise risks to human health and the environment.

(Sustainable Use Directive, 2009)

LEAF Integrated Farm Management wheel

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Benefits: Integrated Pest Management (IPM)

- IPM can play a significant role in making farming more **environmentally, economically & socially sustainable**
- It allows producers to make informed decisions to manage crops & **minimise reliance on pesticides**
- IPM can help **maintain biodiversity, decrease pollution & lower the build-up of pesticide resistance**
- The diversity of solutions available in IPM helps ensure the long-term **sustainability** of control measures

IPM Hierarchy

1. Achieving prevention and suppression of harmful organisms
2. Monitoring of harmful organisms
3. Decisions made based on monitoring and thresholds
4. Non-chemical methods
5. Pesticide Selection
6. Reduced Use
7. Anti-resistance strategies
8. Evaluation
9. PREVENT – DETECT – CONTROL

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Case Study: Integrated Pest Management (IPM) & Black-grass

- Black-grass: native annual grass most common in cultivated winter arable cropping
- Costs UK arable farmers c800,000t lost production & c.£400m per year
- High seed return (up to 1000 per plant) & widespread resistance to selective herbicides
- Introducing temporary leys (2-5 years) into arable rotations as cultural control method
- 70% soil seedbank decline per year – but initial seedbank numbers can be very high & 98% control needed to stabilise weed population

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CASE STUDY: INTEGRATED PEST MANAGEMENT & BLACK-GRASS

- Establish a grass/diverse ley in the autumn/spring - ideally into a stale seed bed
- Control black-grass by either cutting or grazing before the black-grass seeds (& repeat)
- Minimum two-year ley required to reduce soil black-grass burden to acceptable levels
- Grass/clover leys can be sold as forage, diverse leys more beneficial for grazing & soil conditioning/SOM accumulation
- Additional benefit of income & organic manure from grazing
- Use of agri-environment scheme options – e.g. GS4 legume & herb-rich swards

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CHALLENGES OF INTEGRATING LIVESTOCK

- Lack of skills within business
- Livestock do not need to be owned or managed by the business
- Requirement for fencing/water
- Modern quick-fencing is highly flexible
- Potential for soil damage from poaching
- Good practice should always be followed
- Pest carryover from forage leys to cereals (e.g. leatherjackets, wireworm)
- Appropriate rotations/seed rates can manage this risk

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Bedankt
Efharisto poli
Hvala vam
Merci
Danke
Dziękuję wam
Thank you
gilab
SatAgro
One Carbon World
EEB
European Environmental Bureau
GWCT
THE ALLERTON PROJECT
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HEALTHY SOIL · HEALTHY CROPS · HEALTHY BUSINESSES

5 PRINCIPLES OF REGENERATIVE AGRICULTURE

INTEGRATION OF ORGANIC MATTER

MODULE: INTEGRATION OF ORGANIC MATTER

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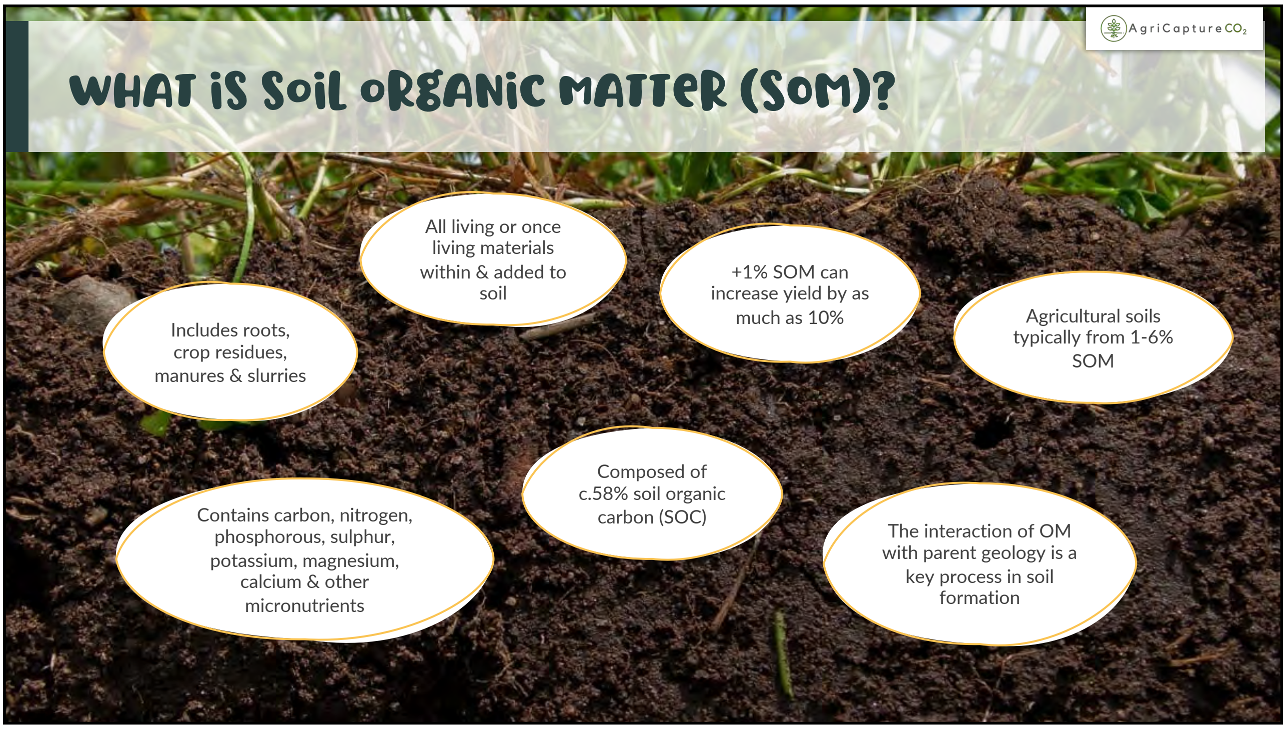
AgriCapture CO2
WHAT IS SOIL ORGANIC MATTER (SOM)?
All living or once living materials within & added to soil
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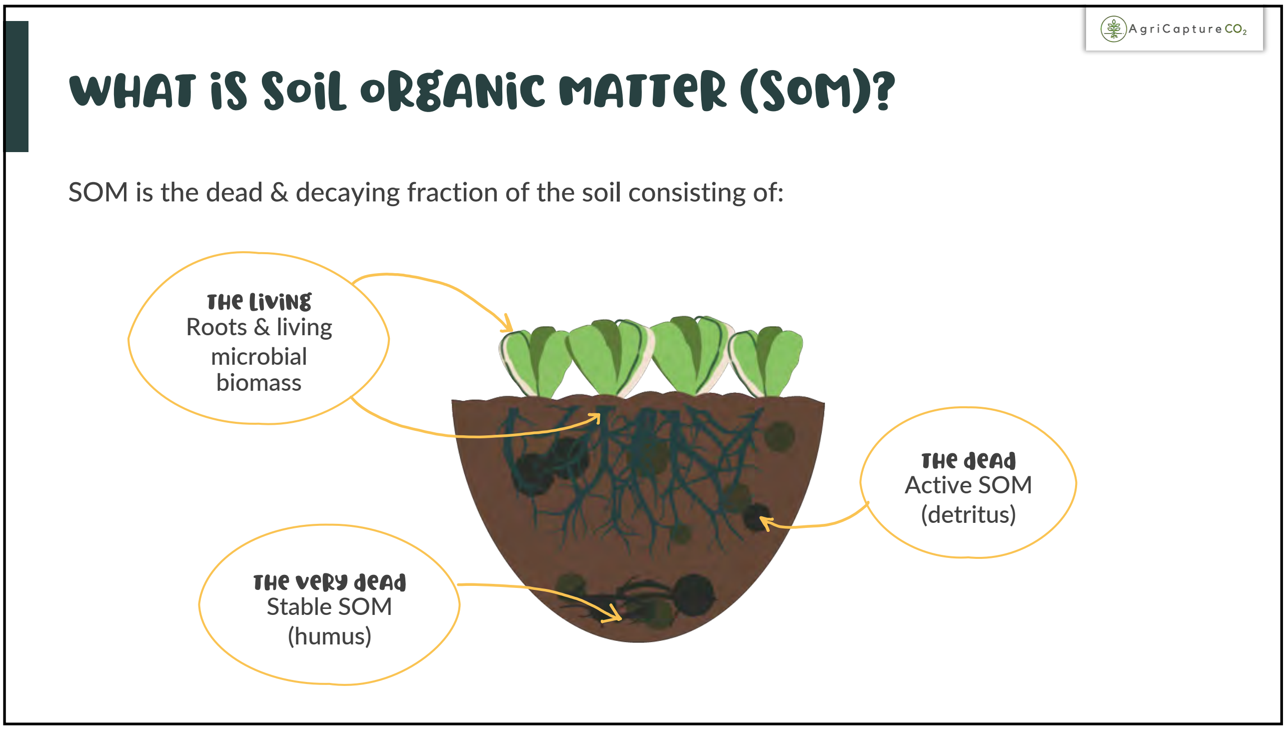
Includes roots, crop residues, manures & slurries
Agricultural soils typically from 1-6% SOM
Composed of c.58% soil organic carbon (SOC)
Contains carbon, nitrogen, phosphorous, sulphur, potassium, magnesium, calcium & other micronutrients
The interaction of OM with parent geology is a key process in soil formation

3


AgriCapture CO2
WHAT IS SOIL ORGANIC MATTER (SOM)?
SOM is the dead & decaying fraction of the soil consisting of:
THE LIVING
Roots & living microbial biomass
THE DEAD
Active SOM (detritus)
THE VERY DEAD
Stable SOM (humus)

4

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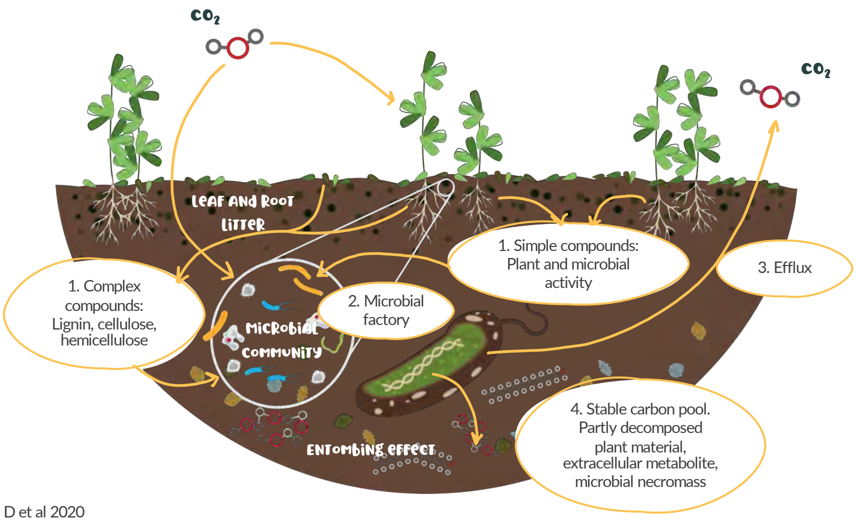
WHAT IS SOIL ORGANIC MATTER (SOM)?



Adapted from Naylor, D et al 2020
Annu. Rev. Environ. Resour. 45:25-59

5

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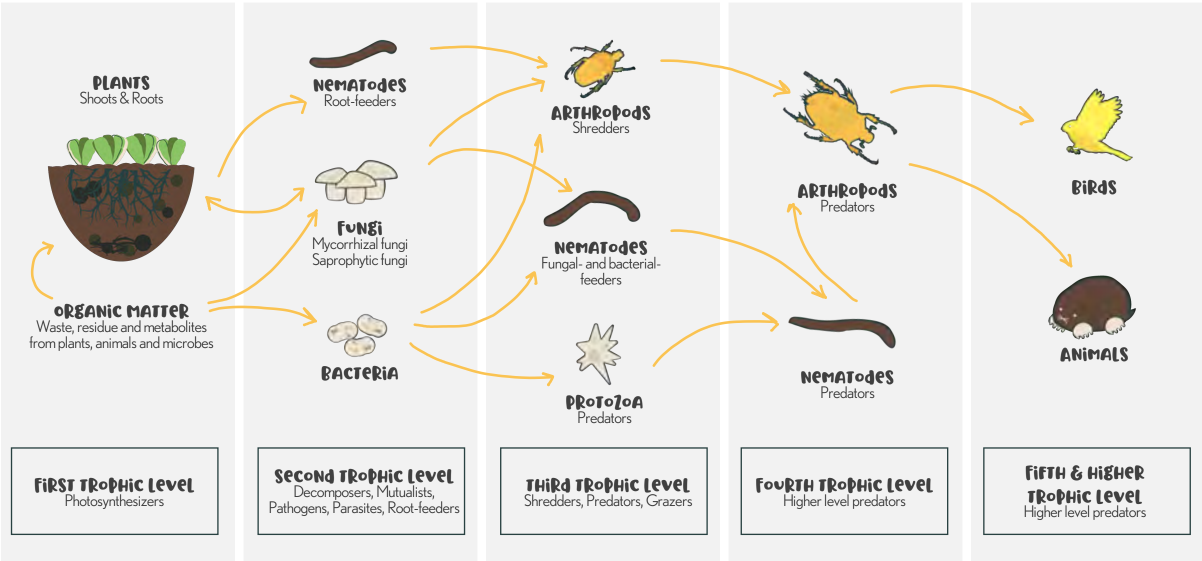
WHAT IS SOIL ORGANIC MATTER (SOM)?

The living:

- Includes plant roots, bacteria, viruses, fungi, protozoa, algae, earthworms & insects
- A result of the energy captured in photosynthesis
- Microorganisms, earthworms & insects feed on plant residues & manures for energy & nutrition
- They mix OM into soil & recycle plant nutrients, as well as produce exudates alongside mycorrhizal networks which promote soil aggregate formation

6

SOM & The Soil Food Web



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What is Soil Organic Matter (SOM)?

Detritus (the dead)

- 'Labile' carbon
- Recently deceased plant residues, roots, soil fauna & recently added manures
- Active & easily decomposed fraction; provides short-term fertility (N,P,K) needed by plants
- Decomposition produces organic compounds which help in aggregate formation & soil structure
- The main supply of food for microorganisms, insects & earthworms

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WHAT IS SOIL ORGANIC MATTER (SOM)?

9

WHAT IS SOIL ORGANIC MATTER (SOM)?

HUMUS (THE VERY DEAD)

- 'Recalcitrant' carbon
- The relatively stable portion of SOM which resists decomposition – gives high OM soils their dark colour
- Consists of molecules bound tightly to clay particles, particles inside micro-aggregates & inert compounds
- Stores essential nutrients for slow release
- Can be made more accessible to microorganism through natural soil processes such as freezing/thawing, but also via tillage
- Can hold 80-90% of its weight in moisture, increasing soil water holding capacity
- Charcoal/biochar a very stable form of carbon which helps maintain a high cation exchange capacity & supports biological activity by providing suitable habitat

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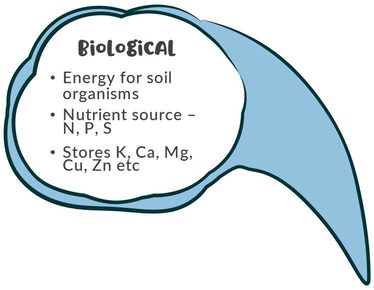
WHY IS SOIL ORGANIC MATTER IMPORTANT?

Biological

- Provides food source for soil microorganisms: large, diverse populations are vital to a well-functioning soil
- Regular OM additions therefore important even if only contributing to active C stocks
- SOM contains vital macro- & micro-nutrients in complex organic molecules made available in simpler, inorganic (mineral) forms via mineralisation by soil microbes
- Chelates can fix and retain certain soil nutrients, and are organic molecules resulting from the decomposition of SOM (or can be secreted from plant roots)



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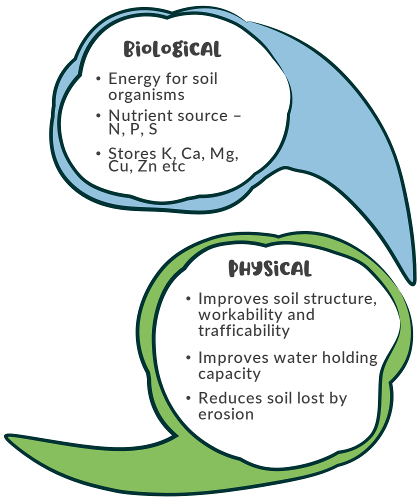
WHY IS SOIL ORGANIC MATTER IMPORTANT?

Physical

- SOM improves soil aggregation, structure & aeration
- Improves rooting & plant growth
- Increases water infiltration & water holding capacity
- Decreases risk of waterlogging, runoff & erosion
- Increases number of field working days
- SOM difficult to build in coarse, sandy soils due to low aggregation (which protects OM from microbial exploitation) & limited protective bonds with fine materials



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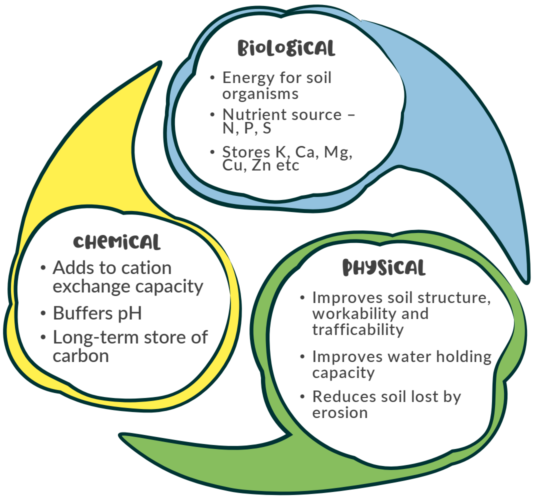
WHY IS SOIL ORGANIC MATTER IMPORTANT?

CHEMICAL

- Humus has a high cation exchange capacity (CEC) and keeps many nutrients from leaching by binding them tightly to the soil
- SOM buffers changes in pH by taking free hydrogen out of solution as acids are produced or releasing it as bases are produced
- SOM binds harmful soil minerals (such as aluminium at low pH) & reduces harm to plants, but also some pesticide residues, reducing leaching & pollution



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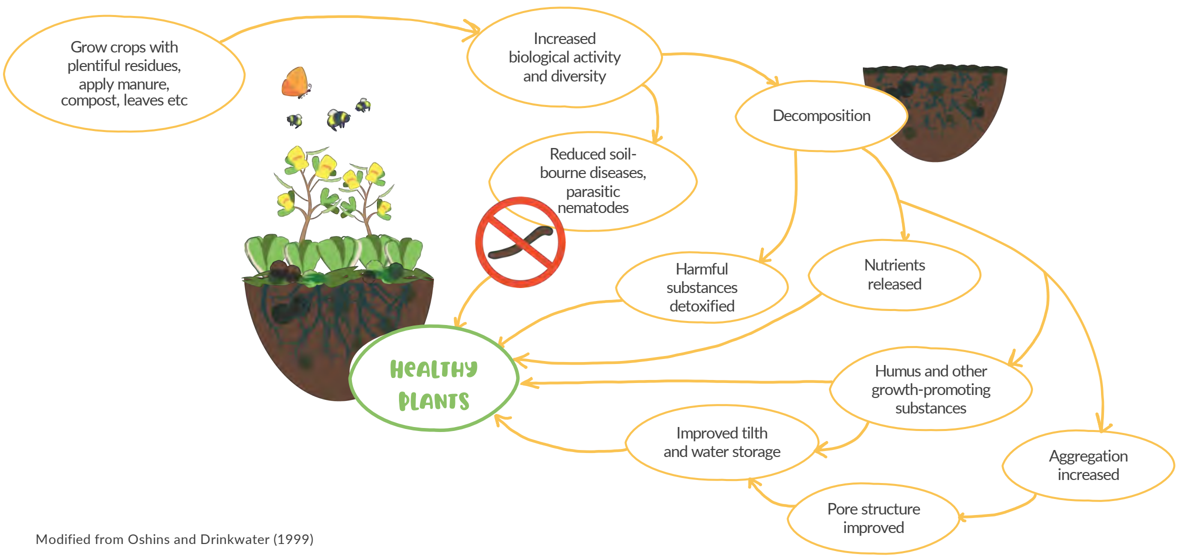
WHY IS SOIL ORGANIC MATTER IMPORTANT?



Modified from Oshins and Drinkwater (1999)

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Why is Soil Organic Matter Important?

SOM is protected by:

- Formation of strong chemical bonds with fine soil particles
- Physical protection inside small aggregates
- Conversion to highly stable humus
- Anaerobic, wet soil conditions
- Stable biochar/charcoal binding SOM

Actively cycling OM/that not protected by the mechanisms above are more available for soil organisms to utilise

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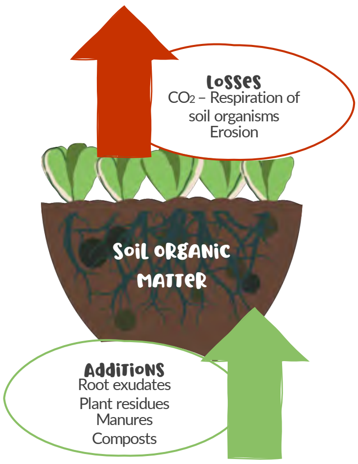
Organic Matter Additions - 1

- Levels of soil organic matter = equilibrium between inputs & decomposition of SOM by soil organisms. Inputs must exceed losses to build SOM.
- Levels of SOM present in soil can be affected by natural processes such as
  - Temperature
  - Rainfall
  - Soil type & texture
- But also human processes such as
  - Tillage
  - Removal of crops/crop residues
  - Application of artificial N
- Important to adapt management practices to reverse losses before increases can be gained



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ORGANIC MATTER ADDITIONS - 2

CARBON:NITROGEN (C:N) RATIO

- Dictates how fast soil microbes break down biomass & release nitrogen
- Microbes use carbon for energy & nitrogen for protein
- C:N of 24:1 'ideal' diet for soil microbes
- To decompose high C:N microbes utilise soil N, resulting in a temporary N deficit (immobilisation)
- Manures with a lower C:N will be consumed with excess N remaining in the soil (mineralisation) - though they may also scavenge soil carbon to achieve this
- Higher C:N manures more likely to contribute to stable SOM
- Choice of manure = important

ORGANIC ADDITION	C:N RATIO
Micro-organism's composition	8:1
Microorganism's preferred diet	24:1
Livestock slurries	4 -10:1
Vetches	11:1
Biosolids	14:1
Farmyard manure	17-20:1
Pea straw	29:1
Green wastes and composts	30:1
Oat straw	70:1
Wheat straw	80:1
Paper waste	150-200:1

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ORGANIC MATTER ADDITIONS - 3

Impact of organic matter additions also related to:

- Loading rate: rate & frequency of application. Benefits often only seen after significant applications over many years
- Dry weight: organic materials can range in water content from 10% to 90%. Carbon is closely related to dry matter
- Economics: AHDB (UK) research indicates OM applications become uneconomic above £30/t (€35) dry matter/hectare/year (including costs of application)

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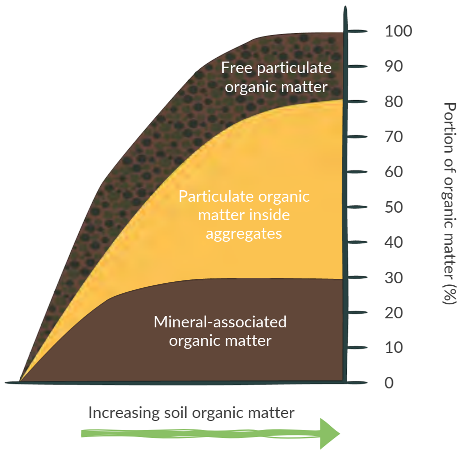
ORGANIC MATTER ADDITIONS – 4

- Easier to increase SOM in degraded soils vs additional improvements to high SOM soil
- But difficult to raise SOM levels in coarse, sandy soils (where 2% SOM might be a good level) vs fine textured clay soils (where 6% might be good)
- Degraded soils will initially see free mineral surfaces bound with OM particles
- Small aggregates will form around OM particles, in turn forming larger aggregates
- Once mineral sites & micro-aggregates are saturated, OM accumulates as free particles within larger aggregates or unaffiliated with minerals
- This unprotected free particulate OM is actively cycling
- This process goes into reverse under soil degradation



Organic matter changes in soil as practices favouring buildup are implemented.
Redrawn and modified from Angers (1992)

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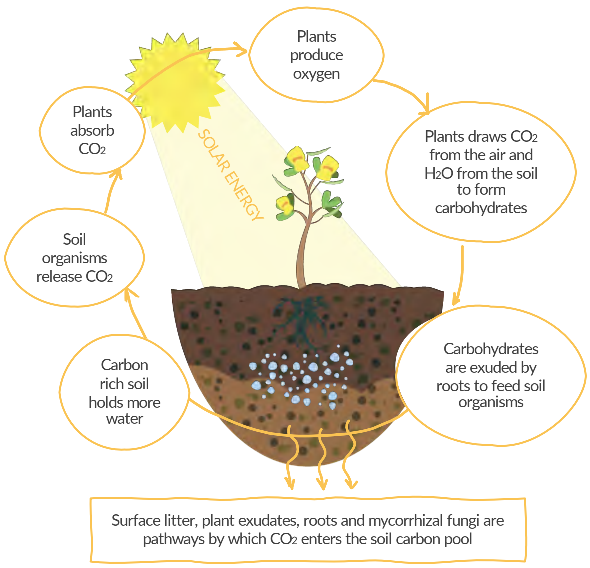
ORGANIC MATTER ADDITIONS – 5

IN FIELD – COVER CROPS

- Cover crops produce biomass at large volumes above & below ground
- Stimulates & feeds soil biological activity
- Benefits dependent on varieties used – grains & grasses contribute more stable OM than legumes due to higher degree of lignification. Also perennial legumes vs annual
- Long-term incorporation in a low-tillage rotation essential to increasing SOM
- Destruction (herbicide/crimping/topping) accelerates carbon cycling
- Can be grazed, adding organic livestock manure



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ORGANIC MATTER ADDITIONS - 6

IN FIELD - COVER CROPS

- Living root exudates act as rich carbon source for rhizosphere, the thin area of soil immediately surrounding the plant roots rich in microorganisms & mycorrhizal fungi
- Encourage nutrient cycling from the soil via these organisms to the plant
- Exudates: fluids containing sugars, amino acids and other carbon-based compounds
- 5-21% of all photosynthetically fixed carbon is transferred from plants to the soil via exudates (Walker et al, 2003)
- Annual crops generally a poor source of exudates vs diverse cover crops
- Ready availability of nutrients (e.g. from fertiliser) reduces root exudation as nutrients are readily available – impacts rhizosphere community

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ORGANIC MATTER ADDITIONS - 7

OFF-FIELD

- Farmyard manure
- Chicken litter
- Paper crumble
- Slurries
- Digestates
- Biosolids
- Composts
- Wood chip
- Mulch
- Biochar

IN-FIELD

- Crop residues
- Cover crops
- Grazed livestock

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ORGANIC MATTER ADDITIONS - 8

- Different characteristics of different manures
- Consider:
  - Availability
  - Cost
  - C:N ratios
  - Nutrient content
  - Timing of application & type of incorporation to avoid soil structure damage

Organic Material	Examples	Soil biology	Soil structure*
Solid: 'stable'	Compost	Moderate improvement	Moderate improvement
	Biosolids	Some improvement	Moderate improvement
Solid: 'active'	FYM	Large improvement	Large improvement
	Poultry manures	Moderate improvement	Little or no improvement
Liquid	Slurries & Digestates	Little or no improvement	Little or no improvement

Source:
'Measuring & Managing Soil Organic Matter' AHDB/BBRO 2018

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CASE STUDY: AHDB/BBRO GREAT SOILS PROJECT (UK)

- Long term experiment (from 1991) investigating impact of OM additions on soil/crop quality in an arable rotation (cereals/potatoes)
- Sandy loam soil (Wick series)
- Annual applications vs artificial nutrients on control
- Measurements of topsoil chemical/physical/biological properties in October 2017
- AHDB/BBRO Soil Health Scorecard
- Results demonstrate value of bulky OM inputs (especially FYM/compost) in increasing soil OM & structure

Treatment	Applications to autumn 2017	Organic matter loading (t/ha)
Control	None	0
Cattle FYM	23 years	129
Cattle slurry	23 years	53
Green compost	13 years	62
Green/food compost	7 years	27
Food-based digestate	9 years	7

*balanced with manufactured fertiliser nitrogen to ensure N supply does not limit crop growth

Figure 2. VESS assessment of the long-term FYM (left) and control (right) treatments

Source: 'Testing the effect of organic material additions on soil health' AHDB & BBRO, 2019

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Case Study: AHDB/BBRO Great Soils Project (UK)

Attribute*	Control	FYM (23 yrs)	Slurry (23 yrs)	Green compost (13 yrs)	Green/food compost (6 yrs)	Food-based digestate (9 yrs)
SOM (%)**	3.0	4.1	3.6	4.0	3.7	3.4
pH **	6.4	7.0	6.4	7.0	6.2	6.5
Ext. P (mg/l)**	56	73	53	60	59	65
Ext. K (mg/l)**	80	311	194	187	140	167
Ext. Mg (mg/l)**	44	87	75	63	66	48
VESS score	2	2	2	1	2	2
Earthworms (Number/pit)	11	13	9	11	9	13

Investigate

Monitor

No action needed

*SOM: Soil Organic Matter – comparison to 'typical' levels for the soil type and climate; Partnership project 2 **ahdb.org.uk/greatsoils**
Ext. P, K & Mg: Extractable Phosphorus, Potassium and Magnesium; See '*The Nutrient Management Guide - RB209*' for specific crop advice, **ahdb.org.uk/nutrient-management-guide-rb209**
VESS: Visual Evaluation of Soil Structure – limiting layer score; **www.sruc.ac.uk/info/120625/visual_evaluation_of_soil_structure**
Earthworms: total number of adults and juveniles; >8/pit = 'active' population for arable or ley/arable soils; Partnership project 2 **ahdb.org.uk/greatsoils**
**Attributes that showed a statistically significant difference between treatments ($P<0.05$)

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Application of Organic Matter - Summary

- Important to increase stable SOM stocks on depleted soils
- Apply actively cycling OM to healthy soils to feed soil biome & replace naturally cycling carbon
- Minimise SOM losses via management practices, e.g. reduced tillage
- Keep soil surface covered with living crops or plant residues
- Utilise rotations that increase biodiversity & add OM
- Apply additional sources of OM where possible, e.g. manures

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AGRI INTEGRATION OF OM

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5 Principles of Regenerative Agriculture
Healthy Soil · Healthy Crops · Healthy Businesses

Green Manure/Stockless Grass

MODULES: BIOLOGICAL DIVERSITY, INTEGRATION OF ORGANIC MATTER, MAINTAIN LIVING ROOTS, SOIL PROTECTION

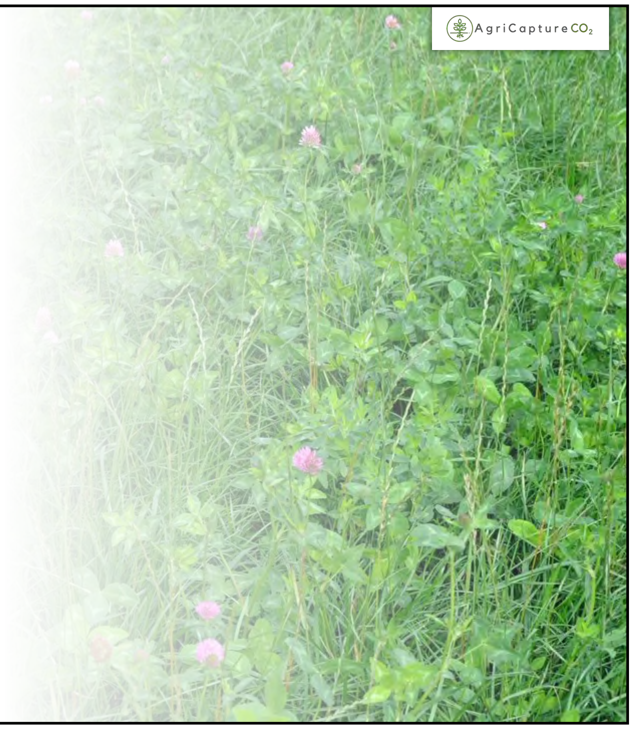
AgriCapture CO_2 · GWCT THE ALLERTON PROJECT

1

2

WHAT IS A GREEN MANURE?

- A crop grown to improve & protect the soil & increase on-farm nutrient security & stability
- Primarily to benefit following crops
- Vital for fertility in organic systems, but increasingly popular in conventional to improve sustainability, soil organic matter & reduce costly inputs
- From short-term catch crops to long-term perennial leys
- Grasses, legumes, brassicas, medicks: mixes are effective to achieve multiple outcomes
- Soil type, climate, latitude & farm system important factors



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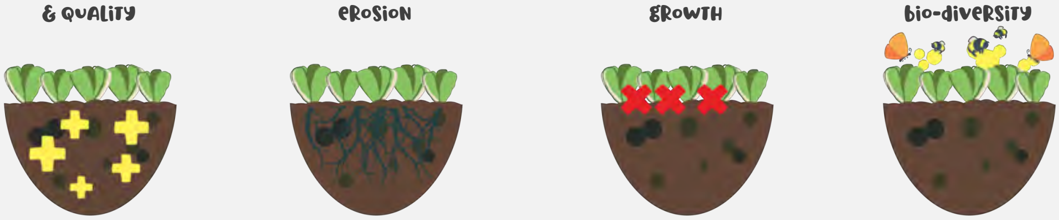
WHAT IS A GREEN MANURE?

SIMILAR TO A COVER CROP WITH FOUR MAIN MODES OF ACTION:

- Improving soil fertility
- Improving soil structure
- Managing weeds & pests
- Environmental management

Build Soil Health & Quality	Retain Soil From Erosion	Supress Weed Growth	Improves Bio-Diversity



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Types of green manure

Long term	Winter	Summer	Undersown
• Often 2-3 years • Legume-rich mix builds fertility in organic rotations. • In stockless systems, cut often to provide N-rich mulch	• Cover crop • Established as an alternative to bare fallow primarily to reduce leaching & soil erosion	• Provide a boost of N mid-rotation between two catch crops	• legumes broadcast into established crops in spring to provide nutrition & competition for weeds & pests, especially in organic systems

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Benefits of green manures

- Benefits of perennial leys vs annual cropping for soil health & structure – especially soil organic matter (SOM)
- Maximise photosynthetic capacity through the year
- Reduce/eliminate artificial inputs & lower carbon footprint
- Decreased offtake of nutrients & increased nutrient cycling
- Soil carbon sequestration
- Integrated Pest Management (IPM)
- Diversity of cropping & habitat

6

Benefits: green manures

- Nitrogen management
- Fast-growing green manures such as Persian/crimson clover can be grown as catch-crops to fix N between annual cash crops, usually in the summer
- Slower growing perennial legumes such as red/white clover/sanfoin/lucerne grown as part of a ley to build soil N over a longer period – a central element of organic rotations
- Green manures can be effective at reducing leaching, especially if fast growing & deep rooting, e.g. grazing rye/mustard.
- Over winter, this can be more significant than any legume N fixing which requires temperature >7°c
- Inter-row establishment in orchard/vineyard systems

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Benefits: build soil fertility - 1

- Legume cover crops provide N via biological nitrogen fixation (BNF) from the atmosphere
- Converts atmospheric N (N2) to ammonia (NH3) then ammonium (NH4)
- Early establishment (late summer/early autumn) is key, as fixation can take up to 6 weeks to commence
- N fixation most effective above 7°c (limited in winter in N Europe)
- Available to following crops and other soil biology after incorporation & mineralisation (short term) or increasing soil mineralizable nitrogen SMN (longer term)
- Leys containing >30% legumes can eliminate need for synthetic N

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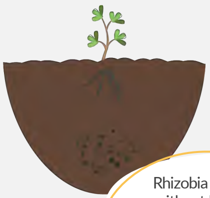
Benefits: build Soil fertility - 2

Pre-symbiosis

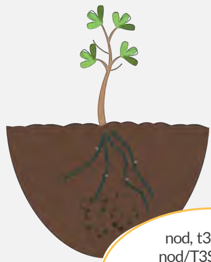
- Rhizobia thrive in soil
- Host seedlings must acquire symbionts in each generation



Rhizobia persist in soil without legume hosts and are attracted to host roots

I: Nodule formation & invasion

- Rhizobia instigate nodule formation through at least three different mechanisms
- A suite of other rhizobial functions promote nodule infection and modulate host range
- Hosts select for rhizobial compatibility



nod, t3SS & non-nod/T3SS rhizobial mechanisms have evolved to instigate nodule formation

II: Symbiotic nitrogen-fixation

- Nitrogen fixation requires the nitrogenase enzyme and microaerobic conditions in the nodule
- Hosts sanction ineffective rhizobia, selecting for nitrogen fixation

nod+ fix+ rhizobia are favoured by the host over mutants and are released back into the soil in higher numbers

9

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Benefits: build Soil fertility - 3

Many factors determine leguminous N fixation:

- Species & biomass
- Established legumes fix more N than newly established plants
- Establishment of effective root nodules via Rhizobia bacteria
- Existing levels of soil N – legumes may also scavenge available soil N before fixing it themselves (though this too will eventually be released)
- Volume of plant biomass
- Soil type
- Climate
- Carbon to nitrogen (C:N) ratio

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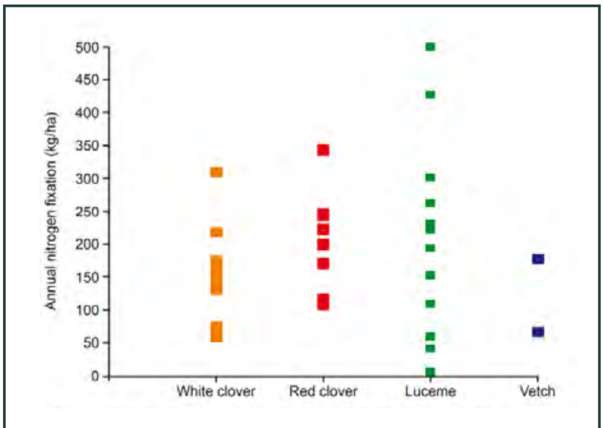
Benefits: builds Soil Fertility - 4

- Significant variability in N fixation depending on species, location, climate
- Specific bacterial species interact with specific legumes
- Repeated growing of certain legumes will usually ensure good populations of complimentary bacteria
- Seed inoculants available
- N fixation broadly related to biomass production & soil N availability: poor growth/high residual N will impede fixation
- General soil macro/micro nutrient status also important – green manures are still a crop!



Nitrogen fixation by different leguminous green manures showing the range of measurements that have been made (data from DEFRA Project OF0316

11

Benefits: build Soil Fertility - 5

- Carbon:Nitrogen (C:N) ratio = amount of C in biomass divided by amount of N
- Predicts how fast soil microbes break down biomass and release N to soil
- Microbes use carbon for energy and N for protein
- C:N of 24:1 considered 'ideal' for soil microbes
- To decompose high C:N microbes utilise soil N, resulting in a temporary N deficit (immobilisation)
- Crops with a lower C:N will be consumed with excess N remaining in the soil (mineralisation)
- Cover crop mineralisation must be balanced with following crop need to reduce nutrient loss

Species	C:N ratio	Above Ground N Content (%)	
Hairy Vetch	11:1	4.3	Maitland and Christie, 1989
Red Clover	14:1	3.1	Maitland and Christie, 1989
Crimson Clover	16:1	2.8	Wagger, 1987; Samson et aL,
White Mustard:late	26:1	1.5	Crowther and Mirchandani, 1931
Winter Rye: early	32:1	-	Wagger, 1987
late	38:1	-	Wagger, 1987
Annual Ryegrass	34:1	1.3	Wivstad, 1990

How Much Nitrogen Does My Cover Crop Take Up and When Do I Get It Back?
University of Nebraska, Institute of Agriculture and Natural Resources, Crop Watch, August 2020.

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Benefits: build Soil Fertility - 6

- Non legume/legume mixes observed to have higher biological N fixation due to competition for soil nitrogen leading to more rapid conversion of N2 (Li et al, 2015)
- Green manures have their biggest impact on soil mineral N in year 1 after incorporation
- Plan cropping regimes for N demand to coincide with incorporation, or risk leaching
- Availability of N not just related to C:N – carbon can be in different forms, e.g. lignin is more resistant to decomposition than cellulose
- Some plants contain chemicals (e.g. polyphenols) which can impede microbial activity

Species	Range of N fixed	Other information	Reference
Red clover *(Trifolium pretense)*	8 – 177 kg N ha^{-1}	In the sowing year (between spring and winter crops in the same year) of several studies in Northern Temperate regions.	(Li et al. 2015; Carlsson and Huss-Danell 2003)
Crimson clover *(Trifolium incornatum)*	77 - 111 kg N ha^{-1}	Growing period July/August to November in Denmark, the study was conducted over two years	(Mueller and Thorup-Kristensen 2001).
Persian clover *(T. resupinatum)*	100 kg N ha^{-1}		
Egyptian or Berseem clover *(T. alexandrinum)*	32 – 69 kg N ha^{-11}		
Common vetch *(Vicia sativia)*	40 – 90 kg N ha^{-1}		
Hairy or winter vetch *(Vicia villosa)*	149 kg N ha^{-1}		
	75 – 80 kg N ha^{-1}	When an autumn sown winter cover crop was killed in the spring, grown in Georgia, USA	(Nesmith and McCracken 1994).
Lucerne or alfalfa *(Medicago sativa)*	36 kg N ha^{-1}	After 12 weeks growth, sown in the spring in Canada.	(Townley-Smith et al. 1993).
Field or broad bean *(V. faba)*	150 kg N ha^{-1}	Three month growing period (August to November) in Switzerland	(Buchi et al. 2015).

AHDB UK Research Review 90: A review of the benefits, optimal crop management practices and knowledge gaps associated with different cover crop species' (2016)

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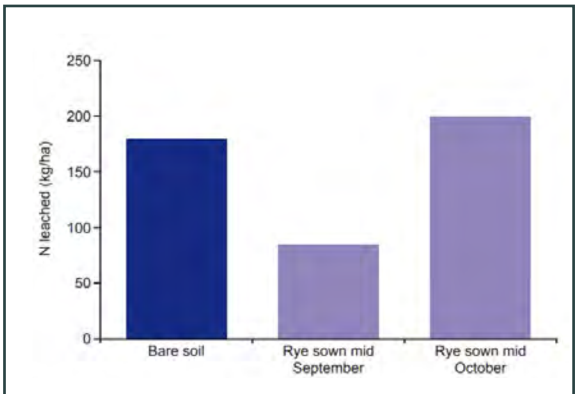
Benefits: Reduce N leaching

- Nitrate not strongly attracted to soil particles
- Leaching – the loss of water soluble nutrients from soil due to excess rainfall & irrigation
- Reducing leaching can be more important for soil fertility than fixing N – especially in winter when legumes are slow to fix
- Leaching affected by soil type & structure – light soils particularly at risk
- Heavily influenced by soil N levels
- Cultivations can also impact leaching by mineralising additional N, making it available for loss
- Important to establish significant root growth & biomass before onset of winter rains to prevent significant N loss
- Late-established covers may be counterproductive



AHDB UK Research
An example of the amount of nitrate leached overwinter, between September and April. This experiment followed an autumn ploughed grass/clover ley on a sandy loam soil.

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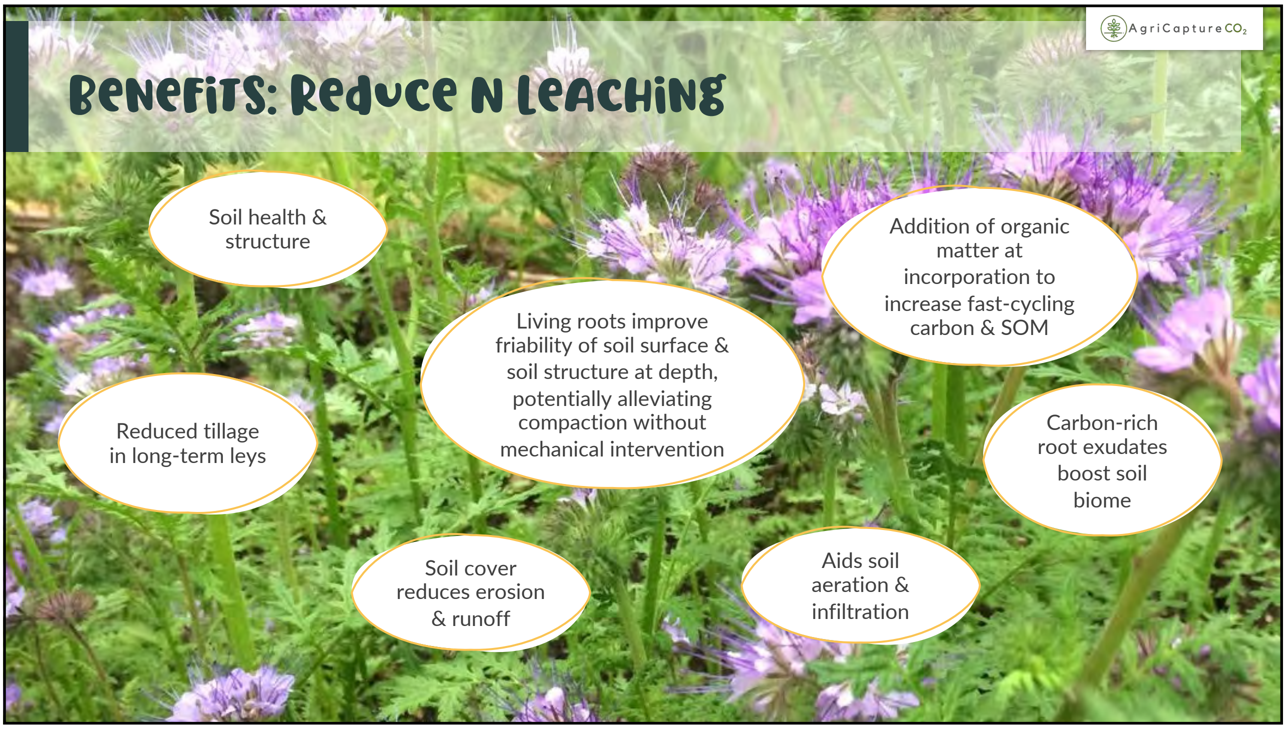
AgriCapture CO_2
Benefits: Reduce N leaching
Soil health & structure
Addition of organic matter at incorporation to increase fast-cycling carbon & SOM
Living roots improve friability of soil surface & soil structure at depth, potentially alleviating compaction without mechanical intervention
Reduced tillage in long-term leys
Carbon-rich root exudates boost soil biome
Soil cover reduces erosion & runoff
Aids soil aeration & infiltration

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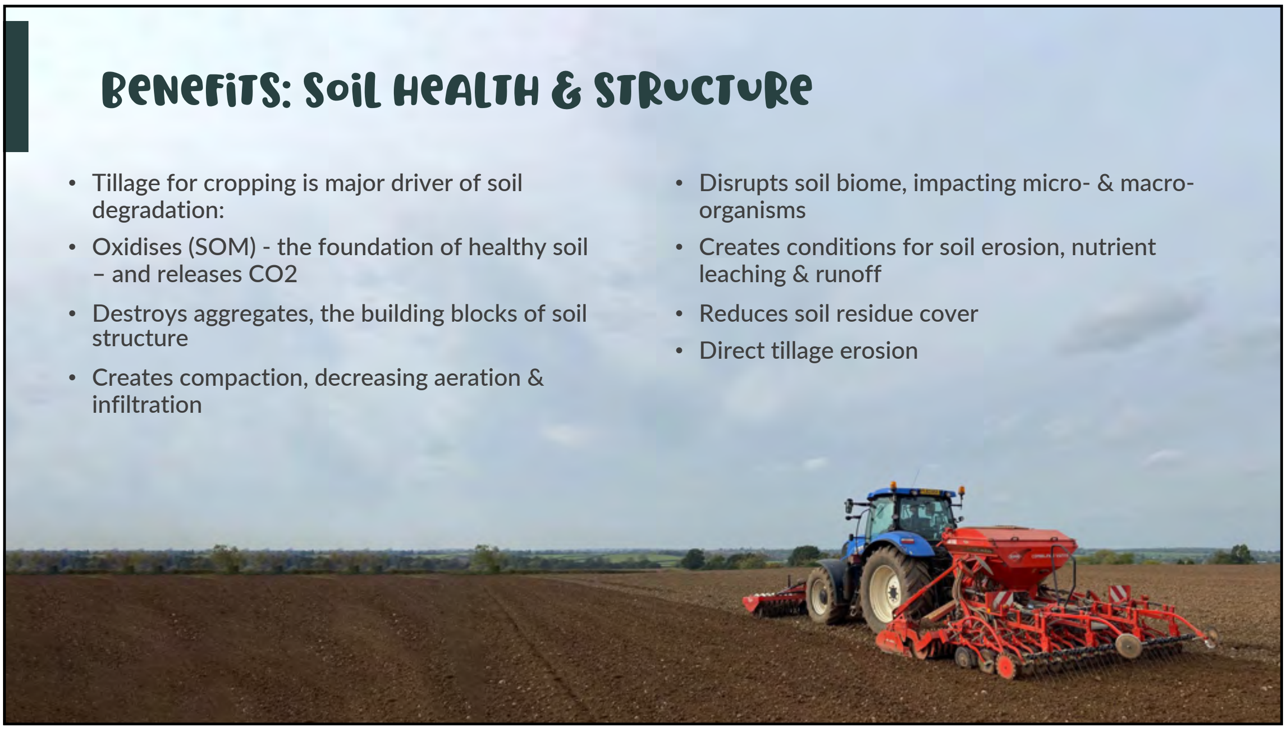
Benefits: Soil health & structure
• Tillage for cropping is major driver of soil degradation:
• Oxidises (SOM) - the foundation of healthy soil – and releases CO2
• Destroys aggregates, the building blocks of soil structure
• Creates compaction, decreasing aeration & infiltration
• Disrupts soil biome, impacting micro- & macro-organisms
• Creates conditions for soil erosion, nutrient leaching & runoff
• Reduces soil residue cover
• Direct tillage erosion

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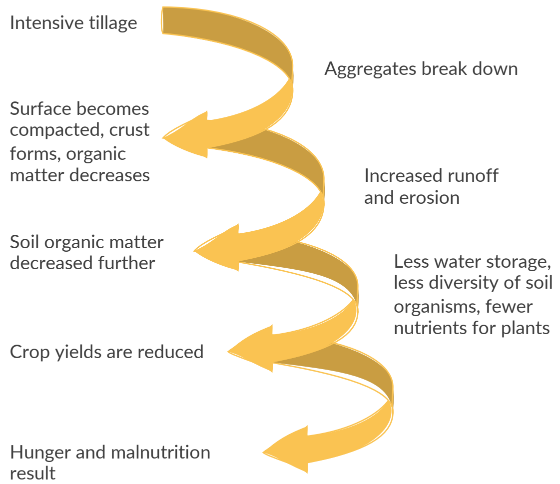
Tillage & Soil Health/Structure



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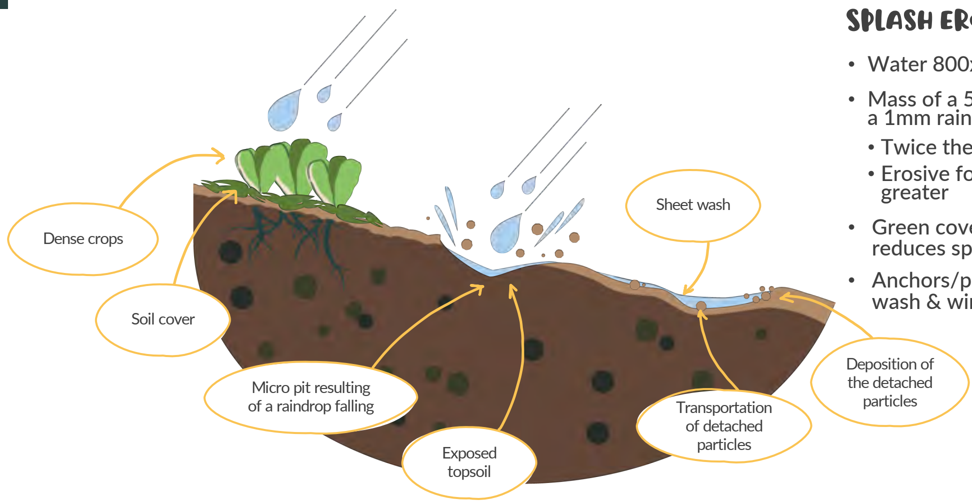
Benefits: Reduce Soil Erosion



Splash Erosion

- Water 800x heavier than air
- Mass of a 5mm raindrop 125x that of a 1mm raindrop
  - Twice the terminal speed
  - Erosive force on impact 500x greater
- Green cover intercepts rainfall & reduces splash erosion
- Anchors/protects soil & reduces wash & wind erosion

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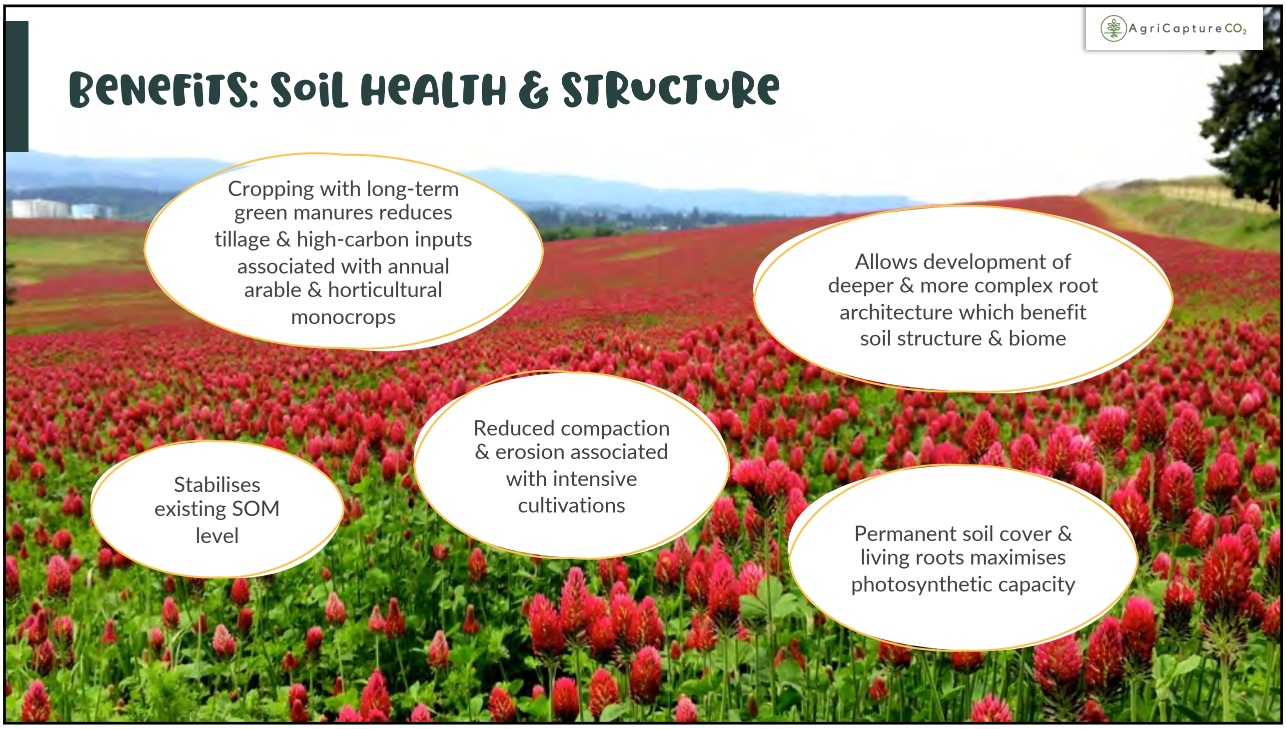
AgriCapture CO2
Benefits: Soil Health & Structure
Cropping with long-term green manures reduces tillage & high-carbon inputs associated with annual arable & horticultural monocrops
Allows development of deeper & more complex root architecture which benefit soil structure & biome
Reduced compaction & erosion associated with intensive cultivations
Stabilises existing SOM level
Permanent soil cover & living roots maximises photosynthetic capacity

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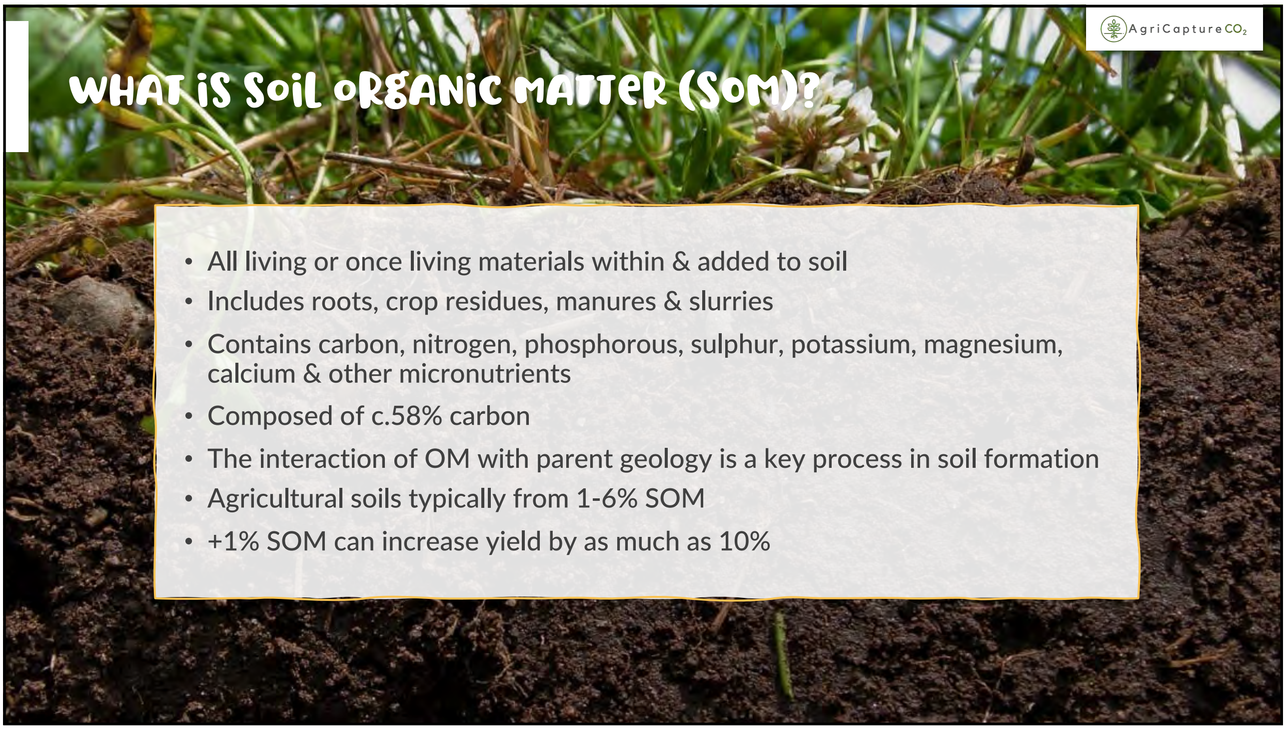
AgriCapture CO2
What is Soil Organic Matter (SOM)?
• All living or once living materials within & added to soil
• Includes roots, crop residues, manures & slurries
• Contains carbon, nitrogen, phosphorous, sulphur, potassium, magnesium, calcium & other micronutrients
• Composed of c.58% carbon
• The interaction of OM with parent geology is a key process in soil formation
• Agricultural soils typically from 1-6% SOM
• +1% SOM can increase yield by as much as 10%

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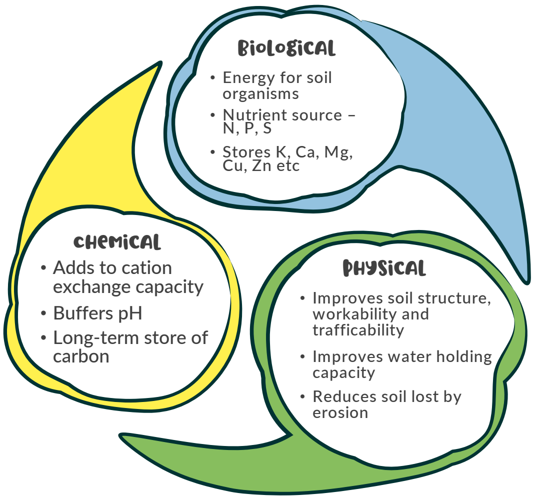
Benefits: Increase Soil Organic Matter - 2

- Cover crops produce biomass at large volumes above & below ground
- Incorporation of green manures boosts SOM
- Stimulates & feeds soil biological activity
- The amount of decomposing OM impacts on soil biology, nutrient cycling & structure
- The amount of humus alters the physical and chemical properties & processes in the soil
- Increased SOM = improved soil structure, water infiltration & holding capacity & cation exchange capacity



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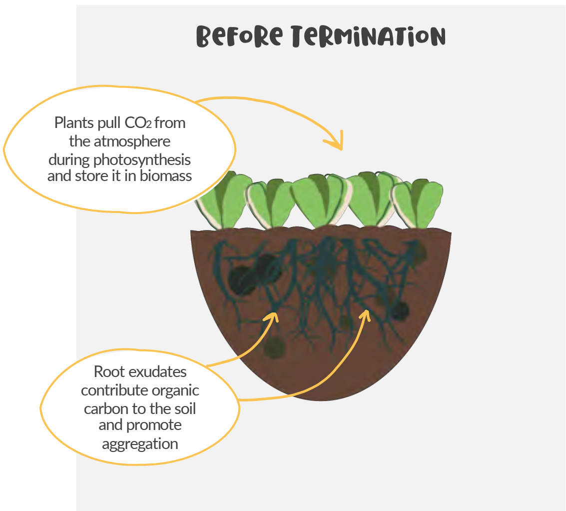
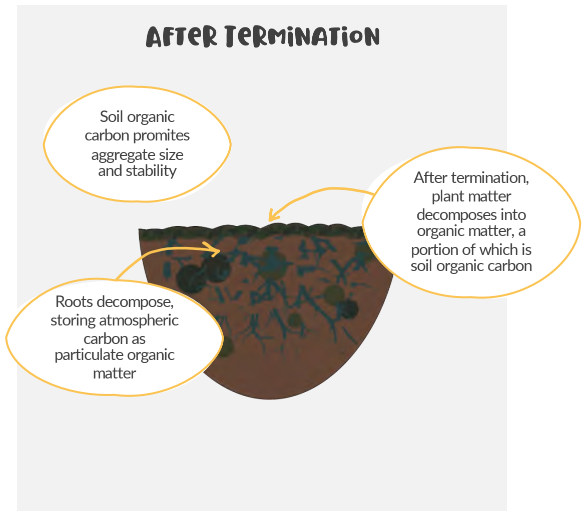
What is Soil Organic Matter (SOM)?





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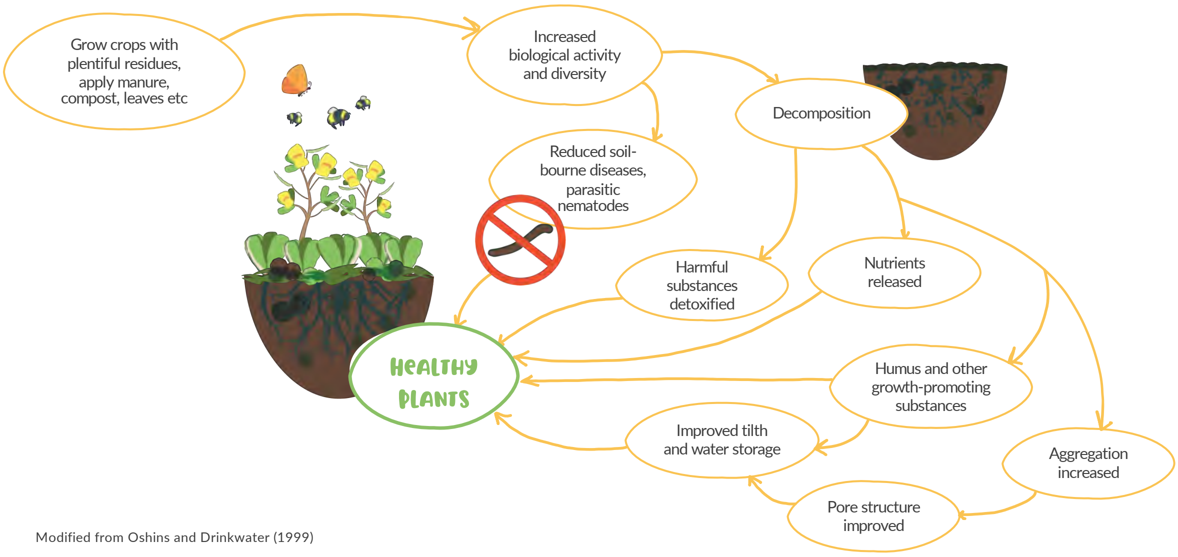
WHY IS SOIL ORGANIC MATTER IMPORTANT?



Modified from Oshins and Drinkwater (1999)

23

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BENEFITS: SOIL HEALTH & STRUCTURE - 2

- Plant roots excrete carbon-rich fluids called exudates into the rhizosphere – the thin area of soil immediately surrounding the root system
- Rich in amino acids, organic acids & sugars (proteins & carbohydrates)
- Up to 20% of photosynthetically fixed carbon is secreted into the rhizosphere in exudates
- An important food source for soil biome – especially bacteria & mycorrhizal fungi
- Diverse perennial leys/green manures provide significantly more exudates (through more of the year) than annual monocrops
- Healthy communities of organisms mine plant-unavailable nutrients & make them plant-available

24


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Benefits: Soil Health & Structure - 3
• Dead root cells also consumed & recycled by soil micro-organisms
• Resulting microbial metabolites include plant-growth promoting hormones & compounds that bolster plant health & aid in plant defence
• Some metabolites form stable carbon-rich deposits which encourage communities of beneficial bacteria in rhizosphere
• At high microbial densities communities coordinate the release of beneficial compounds which promote plant growth – triggering greater root exudation in a virtuous circle
• OM-consuming microbes in turn consumed by predatory arthropods, nematodes & protozoa, which excrete plant-available nutrients into rhizosphere

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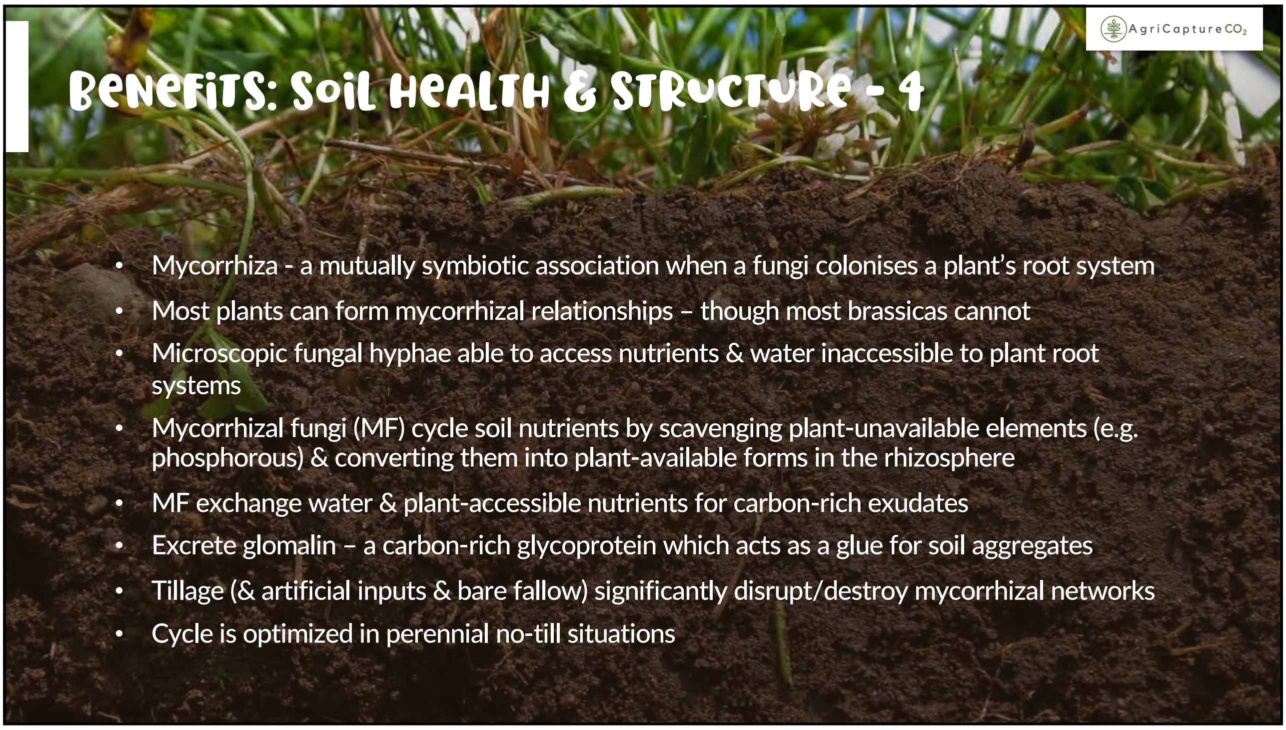
AgriCapture CO2
Benefits: Soil Health & Structure - 4
• Mycorrhiza - a mutually symbiotic association when a fungi colonises a plant's root system
• Most plants can form mycorrhizal relationships – though most brassicas cannot
• Microscopic fungal hyphae able to access nutrients & water inaccessible to plant root systems
• Mycorrhizal fungi (MF) cycle soil nutrients by scavenging plant-unavailable elements (e.g. phosphorous) & converting them into plant-available forms in the rhizosphere
• MF exchange water & plant-accessible nutrients for carbon-rich exudates
• Excrete glomalin – a carbon-rich glycoprotein which acts as a glue for soil aggregates
• Tillage (& artificial inputs & bare fallow) significantly disrupt/destroy mycorrhizal networks
• Cycle is optimized in perennial no-till situations

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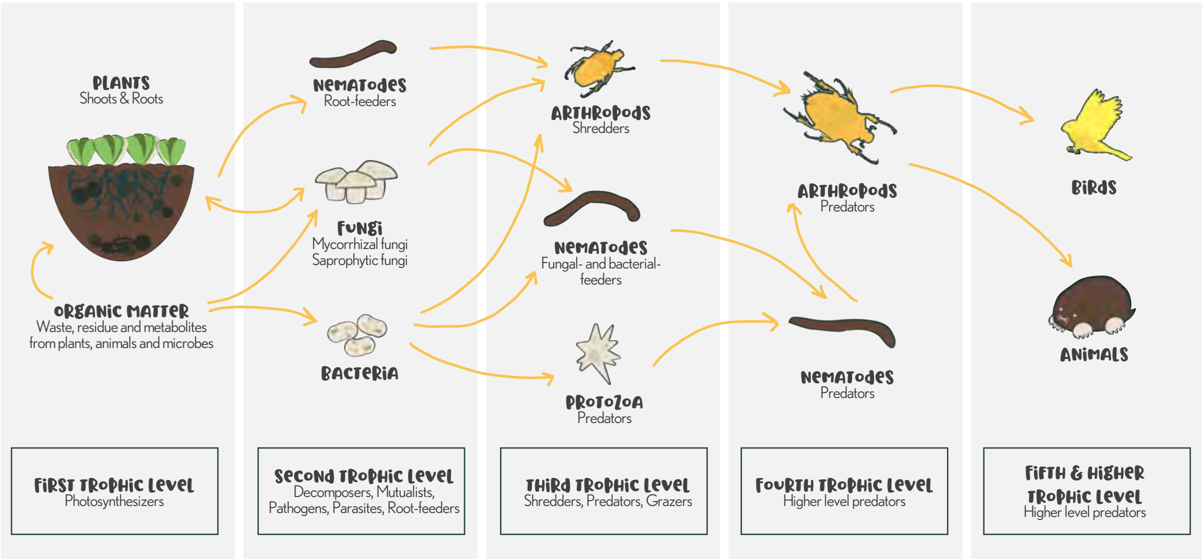
SOM & The Soil Food Web



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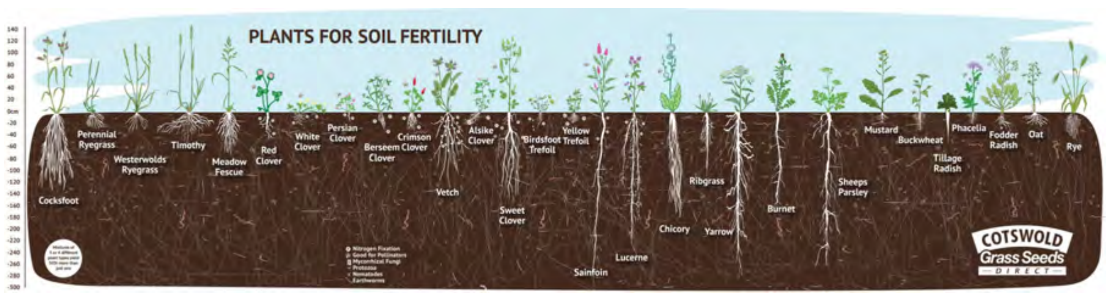
Benefits: Improve Soil Structure

- Green covers with a vigorous, active root system can help open up soil structure
- Impacts vary with species, soil type & cropping system
- Shallower rooting species with fibrous roots (such as rye or some clovers) can create a friable surface structure
- Deeper rooting plants (often brassicas/broadleaves) can reduce compaction at depth (>20cm) but may require full-season fallow; ill suited to short-duration green manures
- Finer roots of legumes can feed soil microbes while tap roots grow to depth
- Extensive rooting systems can aid in soil aeration & water infiltration



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Benefits: Managing Weeds & Pests

- Green manures can be used as part of an Integrated Pest Management (IPM) approach as a non-chemical, rotational control for weeds & pests, often involving frequent cutting & mulching to reduce seed return
- 5-year rotation including 2-year green manure reduced weed seed bank by 54% vs 5-year rotation of cash crops (Hartwig & Ammon, 2002)
- They can alter the environmental conditions at the soil surface, preventing or delaying germination of some weed species & reducing seeding potential
- Potential for allelopathic control of pest weeds – phytotoxic chemicals after green cover incorporation which may inhibit/retard germination, reduce plant growth & lower reproductive capacity
- Some potential for bio-fumigation in certain species against soil-borne pests
- Green covers add diversity & biological resilience to cropping system

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Benefits: Green Manures as Fodder

- Appropriate mixtures of green manures may be cut & removed for animal fodder, also as part of an IPM strategy
- Additional income
- Consider the removal of field nutrients, especially phosphate & potash
- Frequent cutting will stimulate additional beneficial root growth, with removal of early N-rich residues boosting biological nitrogen fixation in the long-term

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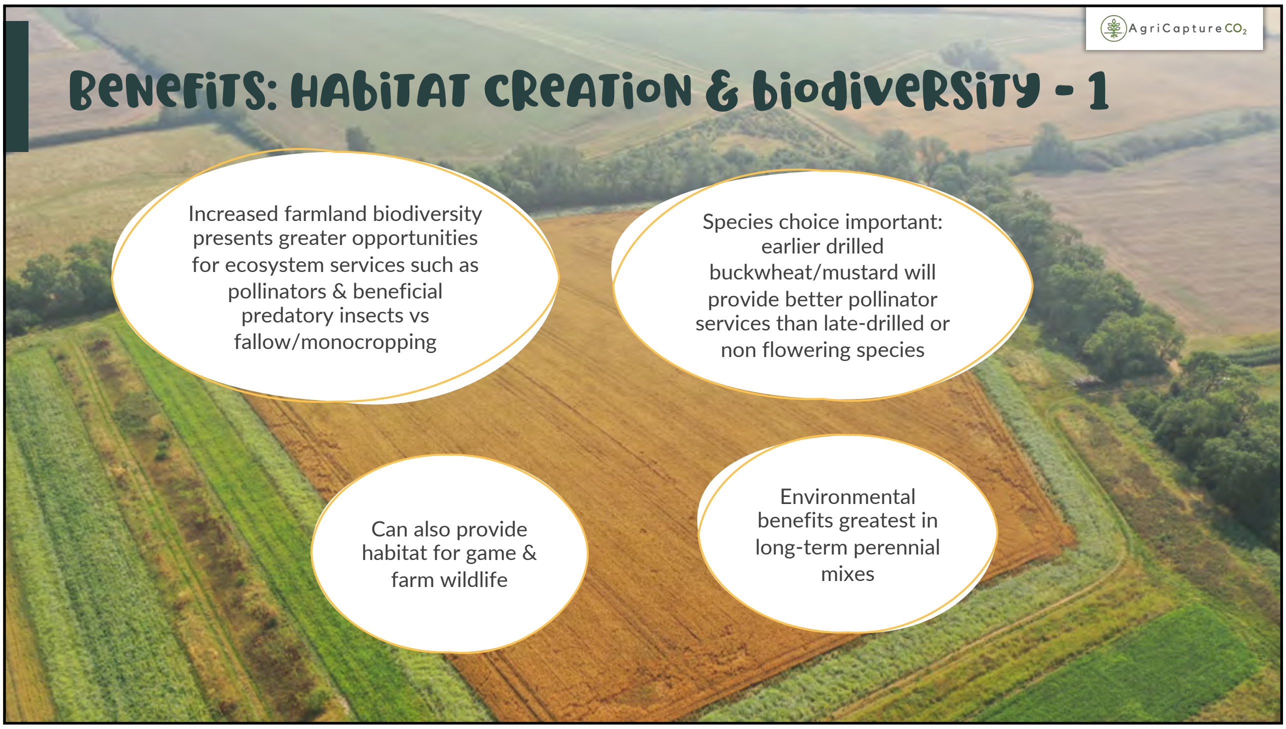

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HVALA VAM MERCI

DANKE DZIĘKUJĘ WAM

THANK YOU

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5 Principles of Regenerative Agriculture
Healthy Soil
Healthy Crops
Healthy Businesses
Optimise Synthetic Fertiliser Use
MODULES: REDUCED SOIL DISTURBANCE, BIOLOGICAL DIVERSITY
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1


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1. Biological Diversity
Maintain wide, healthy rotations and encourage beneficial flora & fauna through reduced artificial inputs
5 Principles of Regenerative Agriculture
Healthy Soil
Healthy Crops
Healthy Businesses
5. Integration of Organic Matter
Utilise livestock and cover crops to build soil organic matter
2. Maintain Living Roots
To boost soil biology, build soil structure and increase water infiltration
3. Soil Protection
Utilise crop residues and cover crops to provide biological armour to the soil surface and reduce water loss
4. Reduced Soil Disturbance
Reduce and optimise mechanical and chemical inputs to improve soil health and structure

2

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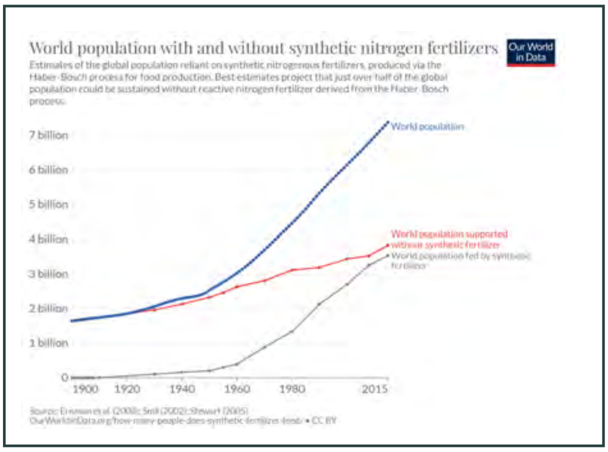
BACKGROUND

- Use of synthetic fertilisers one of the main pillars of the 'Green Revolution' of the 1950s & 60s
- Combined with new technologies, plant breeding & plant protection products
- Enabled a huge increase in agricultural productivity & thought to currently support approximately half of the global population



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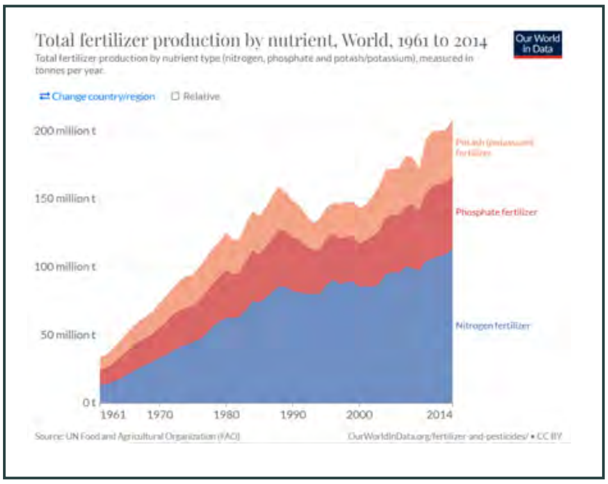
BACKGROUND

- Synthetic nitrogen (N) produced via the Haber-Bosch process
- Converts atmospheric nitrogen (N2) to ammonia (NH3) by a reaction with the hydrogen (H2) in natural gas under heat & pressure
- Ammonium nitrate (AN) & urea
- 800% increase in synthetic N use since 1961
- Phosphate (P) & potash (K) are mined & refined
- China world's largest producer of phosphate; Canada the largest of potash



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Background

- Significant environmental issues surround synthetic fertiliser use
- Mining & refining operations of P & K
- Embedded carbon footprint in ammonia production – c.500m tonnes (1.8% global CO2 emissions) per annum, or 5% of natural gas production
- Average 100% CO2e figure per kg applied AN = 5.6kg in EU
- Carbon footprint from on-farm use
- Release of nitrous oxide (N20) from nitrates via denitrifying bacteria: GWP100 of 298, especially in anaerobic soils
- Environmental issues from synthetic fertiliser use
- Release of pollutant ammonia (NH3) via volatilisation of ammonium in urea
- Leaching of nitrates into watercourses & groundwaters
- Phosphate runoff into watercourses & groundwaters
- Impact on soil biome & health of excessive N (loss of soil organic matter, impact on beneficial mycorrhizal networks)

5

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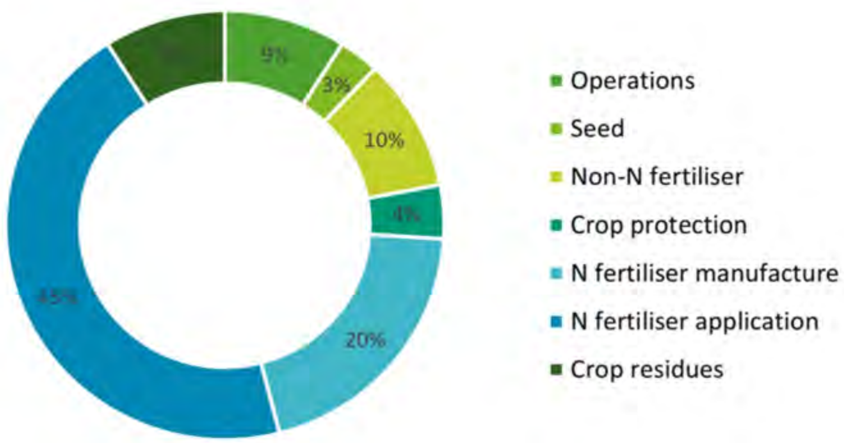
Average GHG emissions - UK winter wheat



Source: ADAS YEN Zero project, UK

6

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BACKGROUND

- Research at the Morrow Plots (US) indicates (Khan et al, 2007) that excessive synthetic N application degrades soil organic matter (SOM)
- After 40-50 years of synthetic N in test fields that exceeded grain N removal by 60 to 190%, researchers saw a net decline in soil carbon despite return of crop residues
- N stimulates growth in biomass of N-feeding soil microbes which consume OM, depleting soil supplies & reducing health & aggregation
- Feedback loop of decreased SOM levels, fertility & water holding capacity, leading to increased applications of synthetic N leading to soil leaching & erosion as aggregates break down
- Reduction in diversity of soil biome

7

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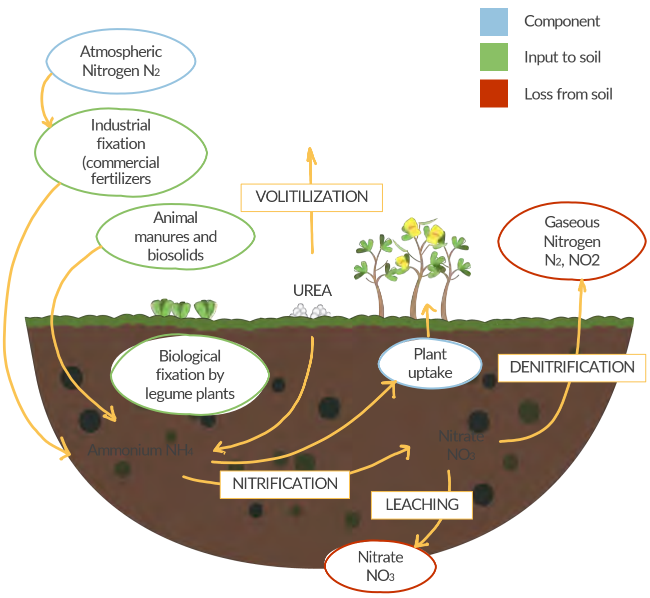
BACKGROUND

Regenerative agricultural systems seek to optimise (& ideally reduce) the volume of both plant protection products (PPPs) & synthetic fertilisers used to reduce:

- the farm's carbon footprint
- environmental impact
- chemical disturbance of the soil
- reliance on costly external inputs



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Nitrogen Supply

Soil Mineral Nitrogen (SMN)

- Nitrate-N & ammonium-N
- Both potentially available for crop uptake
- Volume in soil depends on recent crop history, application on organic material & synthetic fertiliser use

Soil Mineralised from Organic Matter

- Conversion of organic N to mineral N by soil microbes.
- Can be a significant volume in organic & peaty soils, in high-OM input systems (either livestock or green manures)

Atmospheric Nitrogen

- Small amounts from rainfall
- Fixed by legumes in plant-available forms

Nitrogen from Organic Additions

- Most organic materials contain some mineral N which is equivalent to mineral N in synthetic fertiliser
- Remaining organic N becomes available over time

Synthetic Nitrogen

- Used to make up any shortfall in crop requirements

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Nitrogen Losses

Leaching

- Nitrate is highly soluble in soil
- At field capacity can leach into watercourses or groundwater
- Predominant climate important for levels of leaching
- Ammonium-N is usually rapidly converted to Nitrate-N, and are therefore at similar risk of leaching

Denitrification

- Nitrate can be lost as nitrous oxide (N20) and nitrogen (N2)
- Warm, wet, anaerobic soils most at risk
- Most significant where there is a supply of nitrate after harvest or after N application with sufficient OM for microbes to feed on
- Some N20 also formed during nitrification of ammonium-N to nitrate-N

Runoff

- During heavy rainfall N in solution can move across soil surface/via drains into watercourses
- Field risk factors (slope/proximity to watercourses/N levels) dictate quantity of runoff

Volatilisation

- Nitrogen lost as ammonia gas (NH3)
- Organic manures a significant source but also urea fertilisers
- React with water in the soil via hydrolysis to form ammonium carbonate, which can be lost as ammonia if not rapidly captured and converted to ammonium

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Nitrogen use efficiency (NUE)

- The relationship between total nitrogen input vs nitrogen output
- Grain yield (kg) per unit (kg) of total available nitrogen (applied nitrogen + soil mineral nitrogen)
- Key data required (cereals)
  - Harvested grain yield (t or kg/ha)
  - Nitrogen supply:
    a. Soil mineral nitrogen
    b. Organic nitrogen applications
    c. Inorganic fertiliser applications
  - Harvested grain %N / protein content
- Fertiliser recovery efficiency can be as low as 33% - but can be as high as 80-90% depending on conditions & management

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Nitrogen use efficiency (NUE)

Within NUE are three other processes:

Nitrogen uptake efficiency (NUpTE)	Nitrogen utilisation efficiency (NUtE)	Nitrogen Harvest Index (NHI)
Efficiency with which N is taken up by the roots as they grow & explore the soil. Described by calculating the total above ground biomass N vs the amount available to the crop	The efficiency with which the plant converts the N that it has taken up into harvestable grain	Accounts for the total N harvested in the grain vs the total N taken up. Calculation therefore considers the efficiency of remobilisation, as the plant moves from being a green, solar radiation capturing canopy, to partitioning dry matter as grain fill starts & ripening begins

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Technology to optimise fertiliser use - 1

- Variable rate applications to optimise nutrient use
- N via remote observation/in-field sensing through the season
- P, K, Mg & pH via GPS-guided soil core sampling & applications on 3-4 year cycle
- Aims to optimise fertiliser use by reducing field & crop variability – often in conjunction with variable rate seeding
- Does not necessarily reduce overall level of inputs but optimises their use
- Matches inputs to crop need to reduce leaching & runoff
- Improves carbon efficiency/unit of production

Source: Frontier/SOYL

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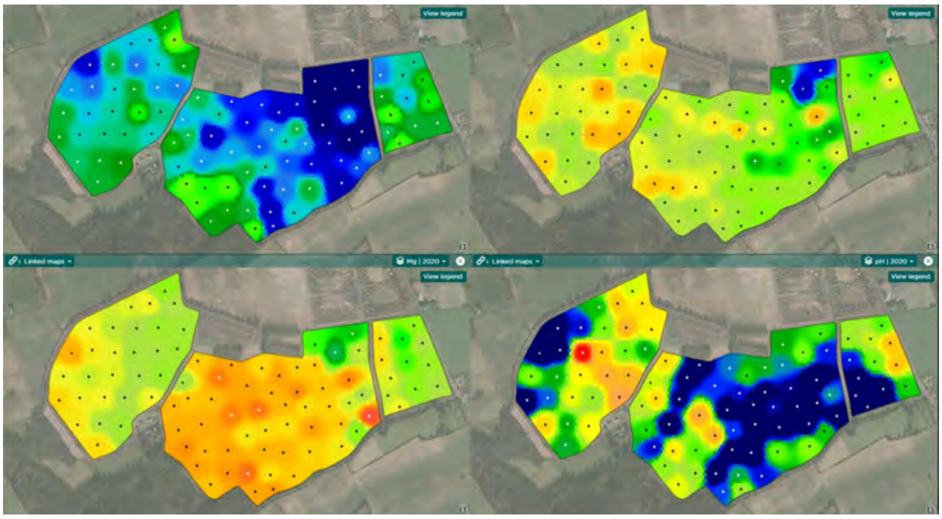
Technology to optimise fertiliser use



Frontier/SOYL variable rate P, K, Mg & pH mapping

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Technology to optimise fertiliser use - 2

Variable rate N via earth-observation (EO) imagery, radar, drone or real-time scanning

Application rates based on:

Green Area Index (GAI):
- the ratio of the total area of green plant tissue to the area of ground that the plant covers
- provides information on canopy size & aids decision-making on amount & timing of N applications

Normalised Difference Vegetative Index (NDVI):
- the relationship between visible light reflectance & near infrared reflectance of a crop canopy
- allows assessment of its size, nutrient status & health
- Healthy vegetation absorbs most of the visible light it receives & reflects a lot of the near-infrared light
- Unhealthy/sparse vegetation reflects more visible light & less near-infrared light

YARA N-SENSOR

Yara field trials in Germany found that use of N-Sensor increased yields by 6%, reduced N use by 12% & reduced grain carbon footprint by 10-30%

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Technology to optimise fertiliser use - 3

- Crop leaf testing e.g. Yara N-Tester
- Measures chlorophyll content of growing plant which is related to current nitrogen status
- Approx. 30 measurements per field to calculate an average requirement on a per-field basis
- Use as a tool to decide application timings when crop need is indicated and/or fine tune final applications to achieve desired grain protein & quality
- ‘Little & often’ applications can help improve Nitrogen Use Efficiency (NUE) on a field-by-field basis
- Apply N to service crop need but also with favourable weather conditions for uptake

YARA N-TESTER

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Technology to optimise fertiliser use - 4

Soil Mineral Nitrogen (SMN) lab sampling

- The nitrate-N + ammonium-N content of the soil within rooting depth of the crop
- Core samples taken before application of N, and not close to cultivations
- Feeds into assessment of Soil Nitrogen Supply (SNS):
- SNS = SMN + estimation of N already in the crop + Additionally Available Nitrogen (AAN)
- AAN = N that will be mineralised in the soil between the time of sampling and harvest and taken up by the crop
- Allows for optimal application of N to meet crop need

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Technology to optimise fertiliser use - 5

Key factors influencing SNS:

- Residues from synthetic N applied to previous crop
- Residues from organic manure applied to previous crops
- Soil type & SOM content
- Overwinter leaching
- N made available from mineralisation of SOM & crop residues during growing season

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Technology to optimise fertiliser use – 6

Application of novel crop additives

- Increasing availability of liquid carbon fertilisers designed to mimic carbon compounds of natural root exudates
- Often based on molasses
- Designed to increase nutrient availability & improve the efficiency of applied fertilisers
- Intended to feed microbes & mycorrhizal fungi in plant's rhizosphere to boost nutrient uptake & resource use efficiency
- Some claims to stimulate specific microbes to improve the stabilisation of applied nitrogen, cutting applications by up to 10%
- Multiple applications through a growing season

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Cultural measures to optimise fertiliser use – 1

Soil properties

Soil type & texture

- Important for making accurate decisions on lime & fertiliser use – how retentive is the soil?

Soil structure

- Good structure vital to ensure roots are able to grow unimpeded & access required water & nutrients
- Reduced tillage to improve structure & reduce compaction

Soil organic matter

- Vital in building soil structure
- Holds P & K ions weakly so they are readily available for root uptake
- Holds a store of organic forms of N, P & Su which can be mineralised by microbial action
- Reduced tillage & application of organic manures to increase SOM

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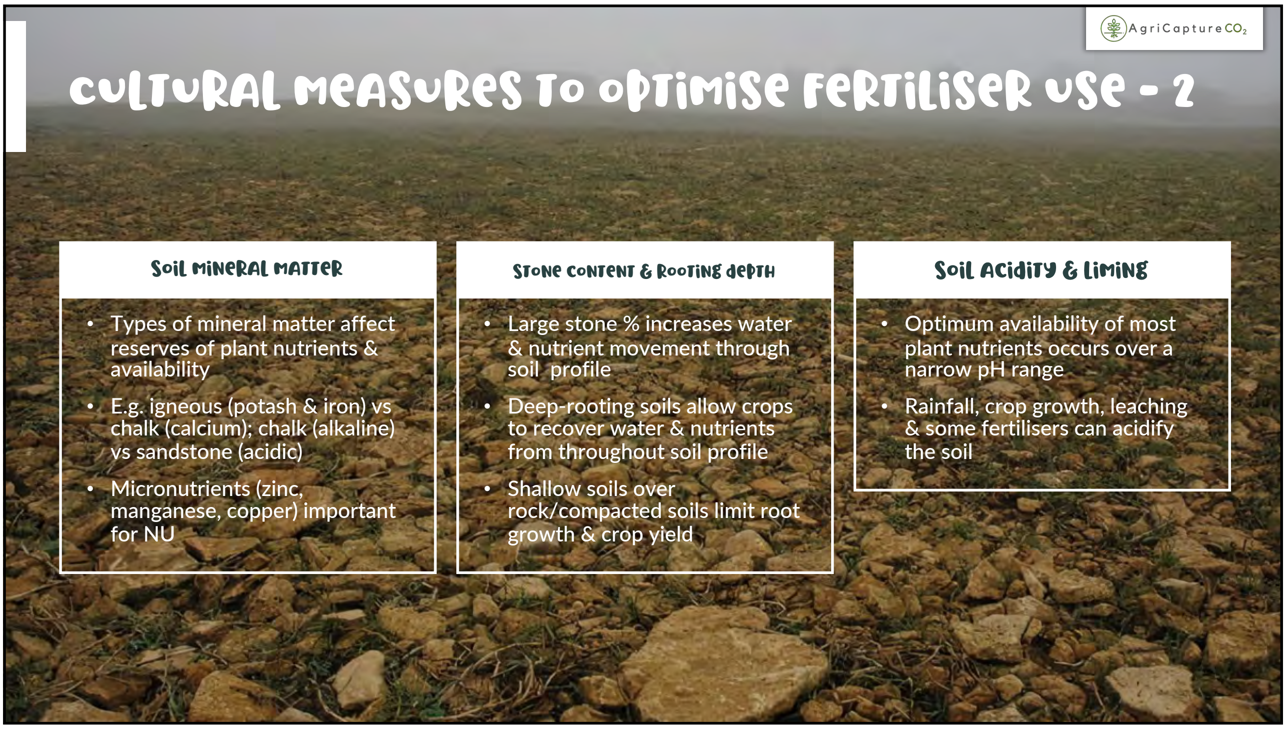
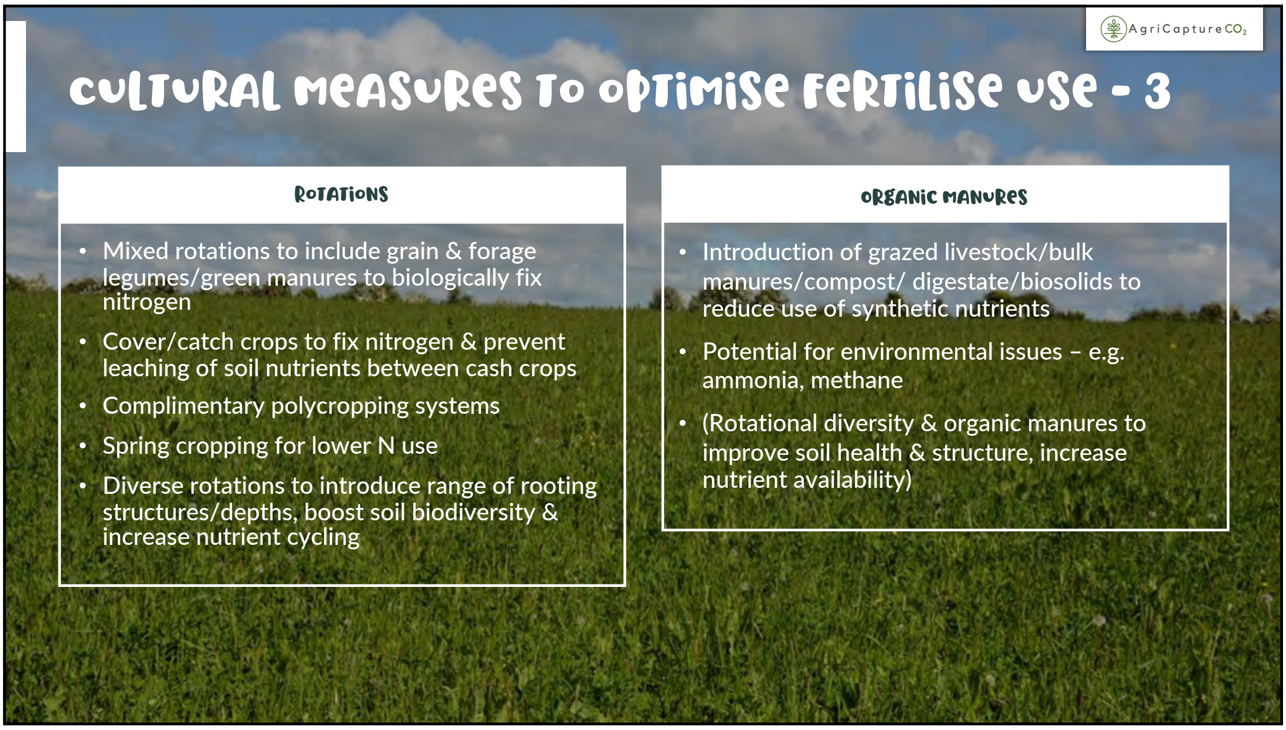

AgriCapture CO2
CULTURAL MEASURES TO OPTIMISE FERTILISER USE - 2
Soil mineral matter
• Types of mineral matter affect reserves of plant nutrients & availability
• E.g. igneous (potash & iron) vs chalk (calcium); chalk (alkaline) vs sandstone (acidic)
• Micronutrients (zinc, manganese, copper) important for NU
Stone content & rooting depth
• Large stone % increases water & nutrient movement through soil profile
• Deep-rooting soils allow crops to recover water & nutrients from throughout soil profile
• Shallow soils over rock/compacted soils limit root growth & crop yield
Soil Acidity & Liming
• Optimum availability of most plant nutrients occurs over a narrow pH range
• Rainfall, crop growth, leaching & some fertilisers can acidify the soil

21


AgriCapture CO2
CULTURAL MEASURES TO OPTIMISE FERTILISE USE - 3
Rotations
• Mixed rotations to include grain & forage legumes/green manures to biologically fix nitrogen
• Cover/catch crops to fix nitrogen & prevent leaching of soil nutrients between cash crops
• Complimentary polycropping systems
• Spring cropping for lower N use
• Diverse rotations to introduce range of rooting structures/depths, boost soil biodiversity & increase nutrient cycling
Organic manures
• Introduction of grazed livestock/bulk manures/compost/ digestate/biosolids to reduce use of synthetic nutrients
• Potential for environmental issues – e.g. ammonia, methane
• (Rotational diversity & organic manures to improve soil health & structure, increase nutrient availability)

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Cultural measures to optimise fertiliser use - 4

Fertigation

- Irrigation water & fertiliser applied using the same irrigation distribution system
- Combining fertigation with pressurised irrigation systems, such as drip or advanced sprinklers:
  - Reduces/eliminates mechanical applications
  - Reduces total irrigation volumes
  - Increased automation
  - Optimisation of inputs to crop growth
- Increased EU focus on reducing both water & nutrient use in fruit, vegetable & ornamental production
- Modern fertigation strategies include nutrient recovery at the end of the 'fertigation sequence' to further reduce environmental impact
- EU Horizon 2020 FERTINNOWA (Transfer of INNOvative techniques for sustainable WAter use in FERtigated crops)

FERTINNOWA

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Best practice to optimise fertiliser use - 1

- 4-R Plus principles
- Synthetic fertiliser application using:

Right rate	Right time	Right place	Right amount
consider split applications; a little & often increase NUE	do not apply if leaching/ runoff/ volatilisation/ denitrification likely	consider localised placement of fertiliser below soil surface where possible – e.g. DAP alongside oilseed rape?	apply nutrients to feed crop need)

- Reduce tillage – use cover crops – include perennial forage crops in rotation

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Best Practice to Optimise Fertiliser Use - 2

Machine Testing & Calibration

- Ensure all spreading equipment is calibrated & tray tested to achieve optimal coefficient of variation (CV) – a figure of accuracy - for each machine & product
- CV of 10% possible in field conditions. 15-20% is poor; >20% unacceptable (SRUC)
- N fertiliser pattern can vary by up to 20% before visual striping can be seen in crop
- Particle size distribution, bulk density & flow rate vary between products & manufacturers
- Spread Pattern 'SP' rating 1-5, low to high

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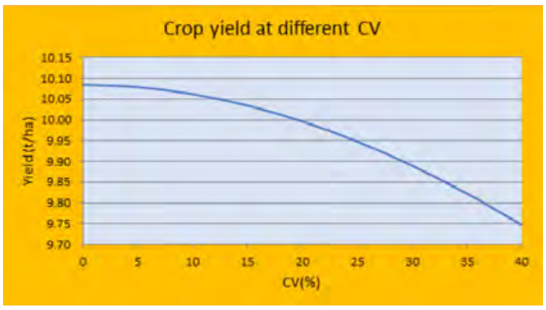
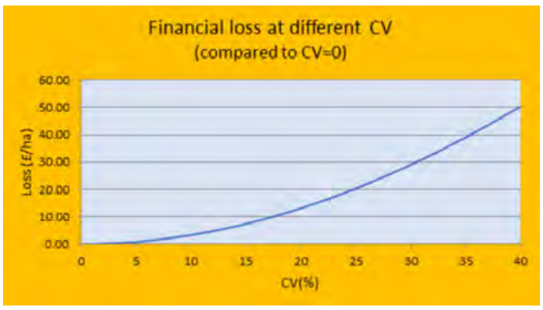
Best Practice to Optimise Fertiliser Use - 2





For wheat crop at €180/t & nitrogen fertiliser at €300/t
Source: National Sprayer Testing Scheme

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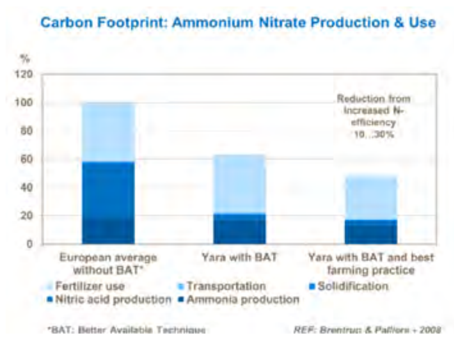
Best practice to optimise fertiliser use - 3

Product choice

- Ammonium nitrate (ammonia & nitric acid) is the most common synthetic N source in the EU
- Carbon footprint depends on the energy consumption, feedstock used in the ammonia production & the N2O emissions from nitric acid production
- EU has defined "best available techniques" (BAT) for these processes
- BAT = total emission of 3.6 kg CO2-eqv per kg N for fertilizers that use ammonium nitrate as the nitrogen source
- 50% less than the emissions of an average non-BAT European plant
- Non-European plants generally less efficient
- How is the energy used generated? Coal? Renewables?



Source: Yara International

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Best practice to optimise fertiliser use - 4

Product choice

- Urea vs AN
- Lower CO2 emissions from production of urea but much of this subsequently released in-field during nitrification
- Urea cheaper source of N than AN but ammonia emissions via volatilisation found to average c.25% in UK trials (Defra UK NT26 research programme) requiring greater loads for optimum N applications
- Varied from 2-58% N loss depending on weather conditions (warm & dry = high loss) vs 2% from AN
- However, potential for highly mobile nitrate losses from AN into water in high-rainfall conditions
- Quality of product impacts spread quality: lower density urea requires greater calibration & small prills may pose significant issues at width

Carbon life cycle of nitrogen fertiliser

Source: Yara International

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Best Practice to Optimise Fertiliser Use – 5

Product choice – inhibitors

Nitrification inhibitors

- Substances that inhibit conversion (biological oxidation) of ammonium to nitrate
- Retain N in ammonium form by inhibiting Nitrosomonas bacteria, delaying conversion 4-10 weeks depending on soil temperature & pH
- Can reduce N loss from leaching & denitrification in fertilizers that either contain or are converted to ammonium – e.g. urea

Urease inhibitors

- Substances that inhibit conversion (hydrolysis) of urea to ammonia & CO2
- Reduce ammonia volatilisation losses in absence of rainfall
- Effective for 10-14 days

Slow release coatings

- Slow-release fertilizers minimize the potential of nutrient losses to the environment by slowly converting to ammonium and/or nitrate over time
- Release is limited mostly by temperature and/or moisture
- Common fertilizers such as urea, coated with a polymer or with sulpur. The coating delays the availability of the nutrients for plant uptake after application & controls nutrient release over time

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Best Practice to Optimise Fertiliser Use – 6

Liquid fertiliser UAN

More accurate, optimal placement especially at wide application widths & with GPS & auto-section technology

Quicker foliar uptake

Improved quality in some crops (e.g. grain protein)

Less weather-dependent

Addition of micronutrients

However, loss of ammonia through volatilisation still an issue at 14% average (Defra UK NT26)

Potential for crop scorch

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CONCLUSIONS

- Key aim of regenerative agriculture to optimise & ideally reduce use of synthetic fertilisers to reduce chemical disturbance of soil & soil biome
- More efficient & precise applications
- Better cultural practices & substitutions
- Best practice & product life-cycle considerations
- Input cost savings
- Greater soil & farm resilience
- Reduced environmental impact

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THANK YOU

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ELGO - DIMITRA HELLENIC AGRICULTURAL ORGANIZATION - DIMITRA mellow yellow EnvirometriX Lancashire County Council AGRICULTURAL UNIVERSITY OF ATHENS ARTHUR'S LEGAL

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5 PRINCIPLES OF REGENERATIVE AGRICULTURE

HEALTHY SOIL · HEALTHY CROPS · HEALTHY BUSINESSES

OPTIMISE SYNTHETIC FERTILISER USE

MODULES: REDUCED SOIL DISTURBANCE, BIOLOGICAL DIVERSITY

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1

2

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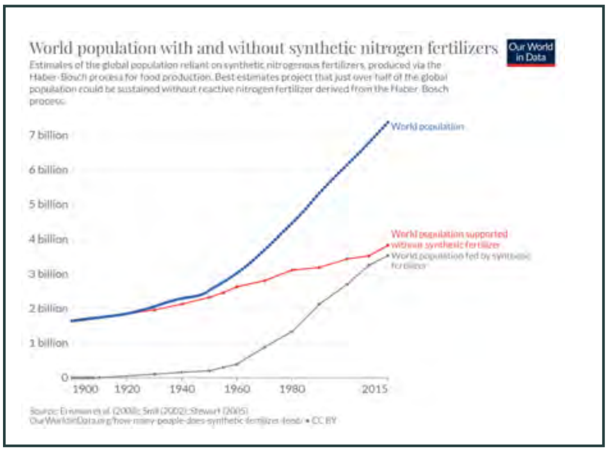
BACKGROUND

- Use of synthetic fertilisers one of the main pillars of the ‘Green Revolution’ of the 1950s & 60s
- Combined with new technologies, plant breeding & plant protection products
- Enabled a huge increase in agricultural productivity & thought to currently support approximately half of the global population



3

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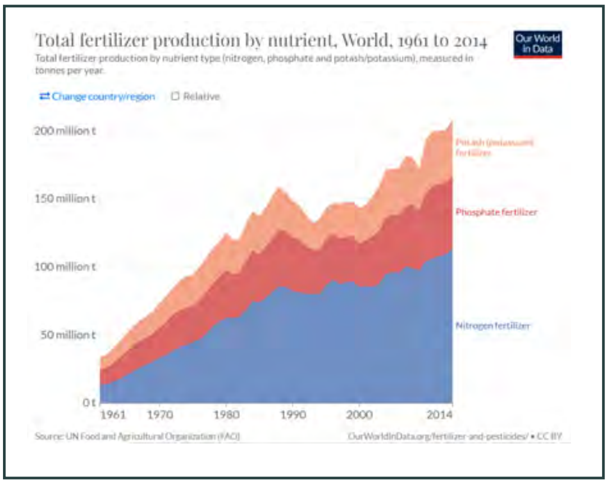
BACKGROUND

- Synthetic nitrogen (N) produced via the Haber-Bosch process
- Converts atmospheric nitrogen (N2) to ammonia (NH3) by a reaction with the hydrogen (H2) in natural gas under heat & pressure
- Ammonium nitrate (AN) & urea
- 800% increase in synthetic N use since 1961
- Phosphate (P) & potash (K) are mined & refined
- China world’s largest producer of phosphate; Canada the largest of potash



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Background

- Significant environmental issues surround synthetic fertiliser use
- Mining & refining operations of P & K
- Embedded carbon footprint in ammonia production – c.500m tonnes (1.8% global CO2 emissions) per annum, or 5% of natural gas production
- Average 100% CO2e figure per kg applied AN = 5.6kg in EU
- Carbon footprint from on-farm use
- Release of nitrous oxide (N20) from nitrates via denitrifying bacteria: GWP100 of 298, especially in anaerobic soils
- Environmental issues from synthetic fertiliser use
- Release of pollutant ammonia (NH3) via volatilisation of ammonium in urea
- Leaching of nitrates into watercourses & groundwaters
- Phosphate runoff into watercourses & groundwaters
- Impact on soil biome & health of excessive N (loss of soil organic matter, impact on beneficial mycorrhizal networks)

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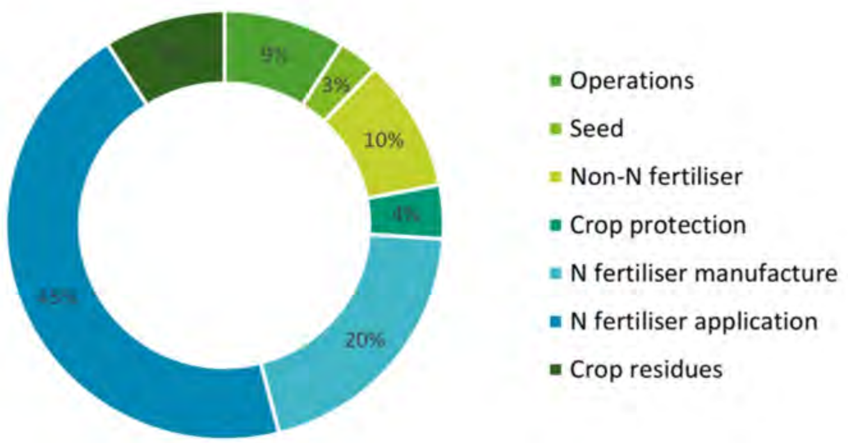
Average GHG emissions - UK winter wheat



Source: ADAS YEN Zero project, UK

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BACKGROUND

- Research at the Morrow Plots (US) indicates (Khan et al, 2007) that excessive synthetic N application degrades soil organic matter (SOM)
- After 40-50 years of synthetic N in test fields that exceeded grain N removal by 60 to 190%, researchers saw a net decline in soil carbon despite return of crop residues
- N stimulates growth in biomass of N-feeding soil microbes which consume OM, depleting soil supplies & reducing health & aggregation
- Feedback loop of decreased SOM levels, fertility & water holding capacity, leading to increased applications of synthetic N leading to soil leaching & erosion as aggregates break down
- Reduction in diversity of soil biome

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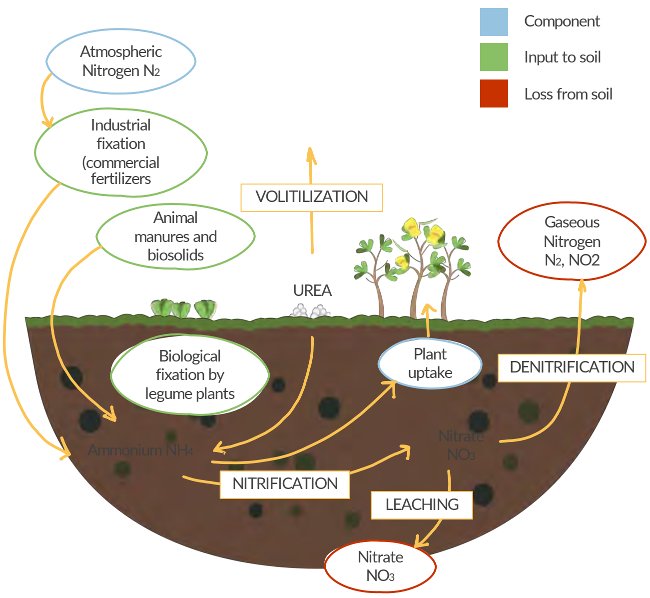
BACKGROUND

Regenerative agricultural systems seek to optimise (& ideally reduce) the volume of both plant protection products (PPPs) & synthetic fertilisers used to reduce:

- the farm's carbon footprint
- environmental impact
- chemical disturbance of the soil
- reliance on costly external inputs



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Nitrogen Supply

Soil Mineral Nitrogen (SMN)

- Nitrate-N & ammonium-N
- Both potentially available for crop uptake
- Volume in soil depends on recent crop history, application on organic material & synthetic fertiliser use

Soil mineralised from organic matter

- Conversion of organic N to mineral N by soil microbes.
- Can be a significant volume in organic & peaty soils, in high-OM input systems (either livestock or green manures)

Atmospheric Nitrogen

- Small amounts from rainfall
- Fixed by legumes in plant-available forms

Nitrogen from organic additions

- Most organic materials contain some mineral N which is equivalent to mineral N in synthetic fertiliser
- Remaining organic N becomes available over time

Synthetic Nitrogen

- Used to make up any shortfall in crop requirements

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Nitrogen Losses

Leaching

- Nitrate is highly soluble in soil
- At field capacity can leach into watercourses or groundwater
- Predominant climate important for levels of leaching
- Ammonium-N is usually rapidly converted to Nitrate-N, and are therefore at similar risk of leaching

Denitrification

- Nitrate can be lost as nitrous oxide (N20) and nitrogen (N2)
- Warm, wet, anaerobic soils most at risk
- Most significant where there is a supply of nitrate after harvest or after N application with sufficient OM for microbes to feed on
- Some N20 also formed during nitrification of ammonium-N to nitrate-N

Runoff

- During heavy rainfall N in solution can move across soil surface/via drains into watercourses
- Field risk factors (slope/proximity to watercourses/N levels) dictate quantity of runoff

Volatilisation

- Nitrogen lost as ammonia gas (NH3)
- Organic manures a significant source but also urea fertilisers
- React with water in the soil via hydrolysis to form ammonium carbonate, which can be lost as ammonia if not rapidly captured and converted to ammonium

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Nitrogen Use Efficiency (NUE)

- The relationship between total nitrogen input vs nitrogen output
- Grain yield (kg) per unit (kg) of total available nitrogen (applied nitrogen + soil mineral nitrogen)
- Key data required (cereals)
  - Harvested grain yield (t or kg/ha)
  - Nitrogen supply:
    a. Soil mineral nitrogen
    b. Organic nitrogen applications
    c. Inorganic fertiliser applications
  - Harvested grain %N / protein content
- Fertiliser recovery efficiency can be as low as 33% - but can be as high as 80-90% depending on conditions & management

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Nitrogen Use Efficiency (NUE)

Within NUE are three other processes:

Nitrogen Uptake Efficiency (NUpTE)	Nitrogen Utilisation Efficiency (NUTE)	Nitrogen Harvest Index (NHI)
Efficiency with which N is taken up by the roots as they grow & explore the soil. Described by calculating the total above ground biomass N vs the amount available to the crop	The efficiency with which the plant converts the N that it has taken up into harvestable grain	Accounts for the total N harvested in the grain vs the total N taken up. Calculation therefore considers the efficiency of remobilisation, as the plant moves from being a green, solar radiation capturing canopy, to partitioning dry matter as grain fill starts & ripening begins

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Technology to optimise fertiliser use - 1

- Variable rate applications to optimise nutrient use
- N via remote observation/in-field sensing through the season
- P, K, Mg & pH via GPS-guided soil core sampling & applications on 3-4 year cycle
- Aims to optimise fertiliser use by reducing field & crop variability – often in conjunction with variable rate seeding
- Does not necessarily reduce overall level of inputs but optimises their use
- Matches inputs to crop need to reduce leaching & runoff
- Improves carbon efficiency/unit of production

Source: Frontier/SOYL

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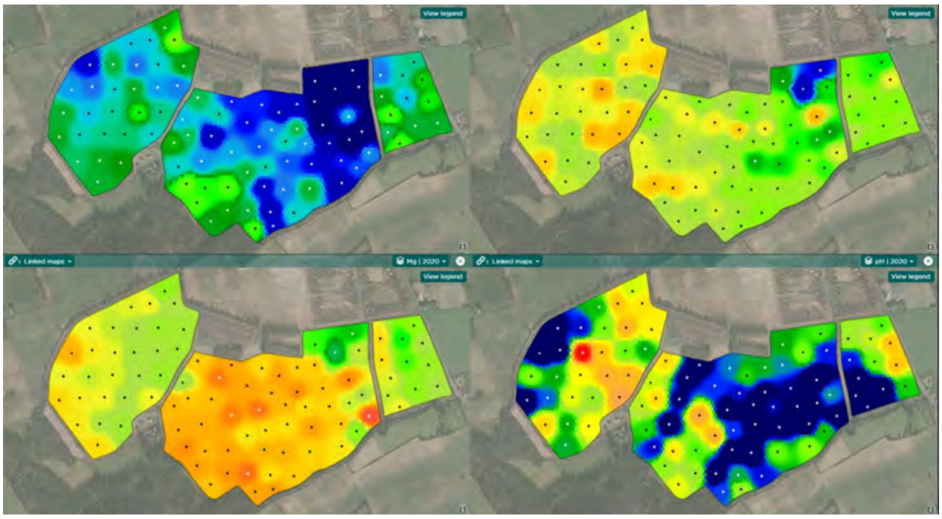
Technology to optimise fertiliser use



Frontier/SOYL variable rate P, K, Mg & pH mapping

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Technology to optimise fertiliser use - 2

Variable rate N via earth-observation (EO) imagery, radar, drone or real-time scanning

Application rates based on:

Green Area Index (GAI):

- the ratio of the total area of green plant tissue to the area of ground that the plant covers
- provides information on canopy size & aids decision-making on amount & timing of N applications

Normalised Difference Vegetative Index (NDVI):

- the relationship between visible light reflectance & near infrared reflectance of a crop canopy
- allows assessment of its size, nutrient status & health
- Healthy vegetation absorbs most of the visible light it receives & reflects a lot of the near-infrared light
- Unhealthy/sparse vegetation reflects more visible light & less near-infrared light

YARA N-SENSOR

Yara field trials in Germany found that use of N-Sensor increased yields by 6%, reduced N use by 12% & reduced grain carbon footprint by 10-30%

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Technology to optimise fertiliser use - 3

- Crop leaf testing e.g. Yara N-Tester
- Measures chlorophyll content of growing plant which is related to current nitrogen status
- Approx. 30 measurements per field to calculate an average requirement on a per-field basis
- Use as a tool to decide application timings when crop need is indicated and/or fine tune final applications to achieve desired grain protein & quality
- 'Little & often' applications can help improve Nitrogen Use Efficiency (NUE) on a field-by-field basis
- Apply N to service crop need but also with favourable weather conditions for uptake

YARA N-TESTER

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Technology to optimise fertiliser use - 4

Soil Mineral Nitrogen (SMN) lab sampling

- The nitrate-N + ammonium-N content of the soil within rooting depth of the crop
- Core samples taken before application of N, and not close to cultivations
- Feeds into assessment of Soil Nitrogen Supply (SNS):
- SNS = SMN + estimation of N already in the crop + Additionally Available Nitrogen (AAN)
- AAN = N that will be mineralised in the soil between the time of sampling and harvest and taken up by the crop
- Allows for optimal application of N to meet crop need

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Technology to optimise fertiliser use - 5

Key factors influencing SNS:

- Residues from synthetic N applied to previous crop
- Residues from organic manure applied to previous crops
- Soil type & SOM content
- Overwinter leaching
- N made available from mineralisation of SOM & crop residues during growing season

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Technology to optimise fertiliser use - 6

Application of novel crop additives

- Increasing availability of liquid carbon fertilisers designed to mimic carbon compounds of natural root exudates
- Often based on molasses
- Designed to increase nutrient availability & improve the efficiency of applied fertilisers
- Intended to feed microbes & mycorrhizal fungi in plant's rhizosphere to boost nutrient uptake & resource use efficiency
- Some claims to stimulate specific microbes to improve the stabilisation of applied nitrogen, cutting applications by up to 10%
- Multiple applications through a growing season

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Cultural measures to optimise fertiliser use - 1

Soil properties

Soil type & texture

- Important for making accurate decisions on lime & fertiliser use – how retentive is the soil?

Soil structure

- Good structure vital to ensure roots are able to grow unimpeded & access required water & nutrients
- Reduced tillage to improve structure & reduce compaction

Soil organic matter

- Vital in building soil structure
- Holds P & K ions weakly so they are readily available for root uptake
- Holds a store of organic forms of N, P & Su which can be mineralised by microbial action
- Reduced tillage & application of organic manures to increase SOM

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CULTURAL MEASURES TO OPTIMISE FERTILISER USE – 2

Soil mineral matter

- Types of mineral matter affect reserves of plant nutrients & availability
- E.g. igneous (potash & iron) vs chalk (calcium); chalk (alkaline) vs sandstone (acidic)
- Micronutrients (zinc, manganese, copper) important for NU

Stone content & rooting depth

- Large stone % increases water & nutrient movement through soil profile
- Deep-rooting soils allow crops to recover water & nutrients from throughout soil profile
- Shallow soils over rock/compacted soils limit root growth & crop yield

Soil acidity & liming

- Optimum availability of most plant nutrients occurs over a narrow pH range
- Rainfall, crop growth, leaching & some fertilisers can acidify the soil

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CULTURAL MEASURES TO OPTIMISE FERTILISE USE – 3

Rotations

- Mixed rotations to include grain & forage legumes/green manures to biologically fix nitrogen
- Cover/catch crops to fix nitrogen & prevent leaching of soil nutrients between cash crops
- Complimentary polycropping systems
- Spring cropping for lower N use
- Diverse rotations to introduce range of rooting structures/depths, boost soil biodiversity & increase nutrient cycling

Organic manures

- Introduction of grazed livestock/bulk manures/compost/ digestate/biosolids to reduce use of synthetic nutrients
- Potential for environmental issues – e.g. ammonia, methane
- (Rotational diversity & organic manures to improve soil health & structure, increase nutrient availability)

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CULTURAL MEASURES TO OPTIMISE FERTILISER USE - 4

FERTIGATION

- Irrigation water & fertiliser applied using the same irrigation distribution system
- Combining fertigation with pressurised irrigation systems, such as drip or advanced sprinklers:
  - Reduces/eliminates mechanical applications
  - Reduces total irrigation volumes
  - Increased automation
  - Optimisation of inputs to crop growth
- Increased EU focus on reducing both water & nutrient use in fruit, vegetable & ornamental production
- Modern fertigation strategies include nutrient recovery at the end of the ‘fertigation sequence’ to further reduce environmental impact
- EU Horizon 2020 FERTINNOWA (Transfer of INNOvative techniques for sustainable WAter use in FERtigated crops)

FERTINNOWA

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BEST PRACTICE TO OPTIMISE FERTILISER USE - 1

- 4-R Plus principles
- Synthetic fertiliser application using:

RIGHT RATE	RIGHT TIME	RIGHT PLACE	RIGHT AMOUNT
consider split applications; a little & often increase NUE	do not apply if leaching/ runoff/ volatilisation/ denitrification likely	consider localised placement of fertiliser below soil surface where possible – e.g. DAP alongside oilseed rape?	apply nutrients to feed crop need)

- Reduce tillage – use cover crops – include perennial forage crops in rotation

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BEST PRACTICE TO OPTIMISE FERTILISER USE - 2

MACHINE TESTING & CALIBRATION

- Ensure all spreading equipment is calibrated & tray tested to achieve optimal coefficient of variation (CV) – a figure of accuracy - for each machine & product
- CV of 10% possible in field conditions. 15-20% is poor; >20% unacceptable (SRUC)
- N fertiliser pattern can vary by up to 20% before visual striping can be seen in crop
- Particle size distribution, bulk density & flow rate vary between products & manufacturers
- Spread Pattern 'SP' rating 1-5, low to high

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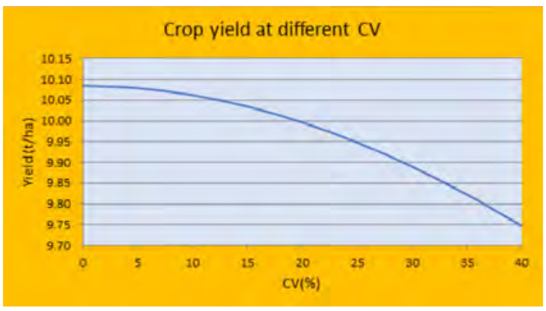
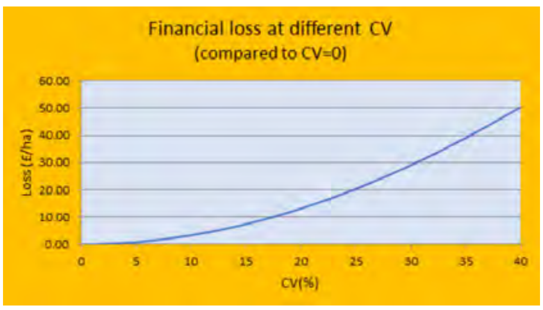
BEST PRACTICE TO OPTIMISE FERTILISER USE - 2





For wheat crop at €180/t & nitrogen fertiliser at €300/t
Source: National Sprayer Testing Scheme

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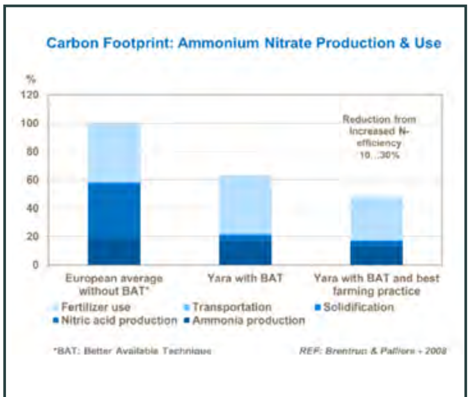
Best practice to optimise fertiliser use - 3

Product choice

- Ammonium nitrate (ammonia & nitric acid) is the most common synthetic N source in the EU
- Carbon footprint depends on the energy consumption, feedstock used in the ammonia production & the N2O emissions from nitric acid production
- EU has defined “best available techniques” (BAT) for these processes
- BAT = total emission of 3.6 kg CO2-eqv per kg N for fertilizers that use ammonium nitrate as the nitrogen source
- 50% less than the emissions of an average non-BAT European plant
- Non-European plants generally less efficient
- How is the energy used generated? Coal? Renewables?



Source: Yara International

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Best practice to optimise fertiliser use - 4

Product choice

- Urea vs AN
- Lower CO2 emissions from production of urea but much of this subsequently released in-field during nitrification
- Urea cheaper source of N than AN but ammonia emissions via volatilisation found to average c.25% in UK trials (Defra UK NT26 research programme) requiring greater loads for optimum N applications
- Varied from 2-58% N loss depending on weather conditions (warm & dry = high loss) vs 2% from AN
- However, potential for highly mobile nitrate losses from AN into water in high-rainfall conditions
- Quality of product impacts spread quality: lower density urea requires greater calibration & small prills may pose significant issues at width

Carbon life cycle of nitrogen fertiliser

Source: Yara International

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Best practice to optimise fertiliser use - 5

Product choice - inhibitors

Nitrification inhibitors	Urease inhibitors	Slow release coatings
• Substances that inhibit conversion (biological oxidation) of ammonium to nitrate • Retain N in ammonium form by inhibiting Nitrosomonas bacteria, delaying conversion 4-10 weeks depending on soil temperature & pH • Can reduce N loss from leaching & denitrification in fertilizers that either contain or are converted to ammonium – e.g. urea	• Substances that inhibit conversion (hydrolysis) of urea to ammonia & CO2 • Reduce ammonia volatilisation losses in absence of rainfall • Effective for 10-14 days	• Slow-release fertilizers minimize the potential of nutrient losses to the environment by slowly converting to ammonium and/or nitrate over time • Release is limited mostly by temperature and/or moisture • Common fertilizers such as urea, coated with a polymer or with sulpur. The coating delays the availability of the nutrients for plant uptake after application & controls nutrient release over time

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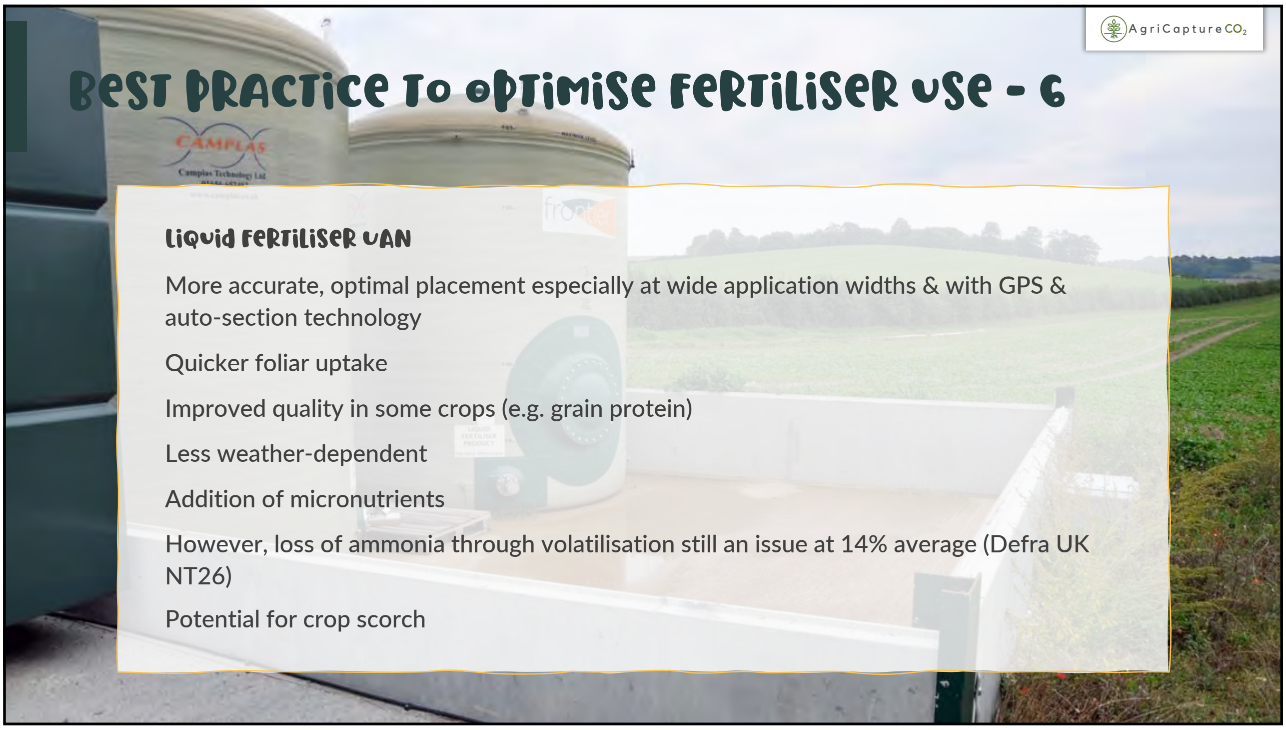

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CONCLUSIONS

- Key aim of regenerative agriculture to optimise & ideally reduce use of synthetic fertilisers to reduce chemical disturbance of soil & soil biome
- More efficient & precise applications
- Better cultural practices & substitutions
- Best practice & product life-cycle considerations
- Input cost savings
- Greater soil & farm resilience
- Reduced environmental impact

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BEDANKT EFHARISTO POLI

HVALA VAM MERCI

DANKE DZIĘKUJĘ WAM

THANK YOU

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Healthy Soil
Healthy Crops
5
Principles of Regenerative Agriculture
Healthy Businesses
Optimise Water Management
MODULES: SOIL PROTECTION
AgriCapture CO2
GWCT
THE ALLERTON PROJECT

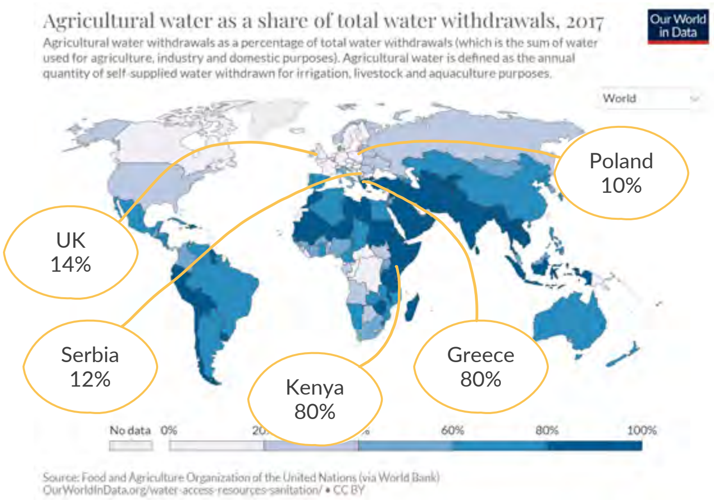
1


AgriCapture CO2
AgriCapture CO2
1. Biological Diversity
Maintain wide, healthy rotations and encourage beneficial flora & fauna through reduced artificial inputs
Healthy Soil
Healthy Crops
5
Principles of Regenerative Agriculture
Healthy Businesses
5. Integration of Organic Matter
Utilise livestock and cover crops to build soil organic matter
2. Maintain Living Roots
To boost soil biology, build soil structure and increase water infiltration
3. Soil Protection
Utilise crop residues and cover crops to provide biological armour to the soil surface and reduce water loss
4. Reduced Soil Disturbance
Reduce and optimise mechanical and chemical inputs to improve soil health and structure

2

BACKGROUND

- Water is essential for plant survival & growth, vital for:
  - Photosynthesis
  - Nutrient uptake & transport
  - Cell pressure
  - Cooling agent
- Deficits/excesses of water single largest yield limiting factors
- Agriculture utilises 70% of global freshwater withdrawals



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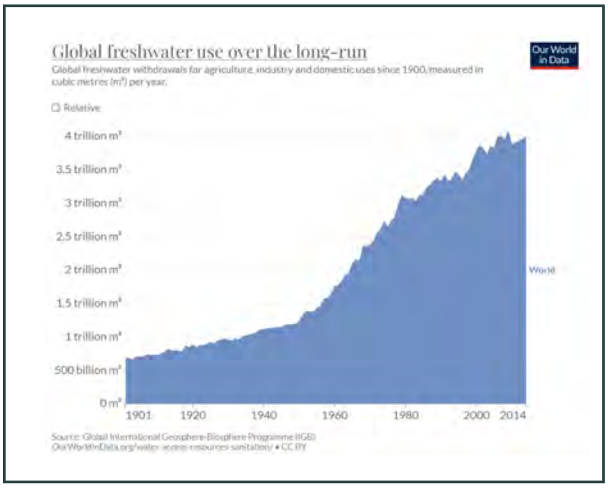
BACKGROUND

- 20th century water withdrawals increased at twice the rate of population growth
- Huge increase in irrigated agriculture
- Driving environmental degradation & salination in some regions
- Decreasing availability in many regions due to overexploitation, climate change & changing regulation
- Requirement to optimise use of water & maximise water use efficiency (WUE)



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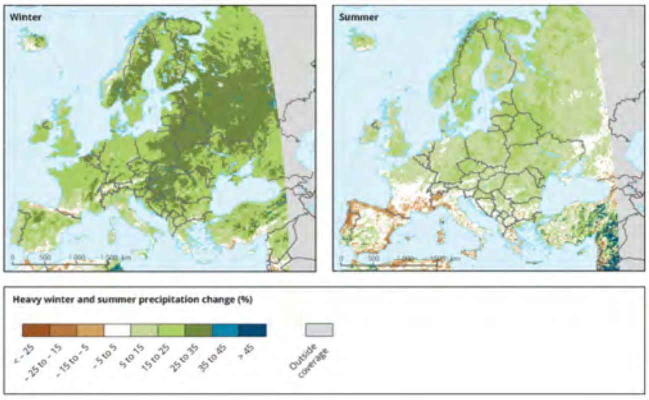
BACKGROUND

- Global warming is projected to lead to a higher intensity of precipitation & longer dry periods in Europe
- Projections show an increase in heavy daily precipitation in most parts of Europe in winter, by up to 35 % during the 21st century
- Worsening droughts in S & SW Europe



Source: European Environment Agency

5

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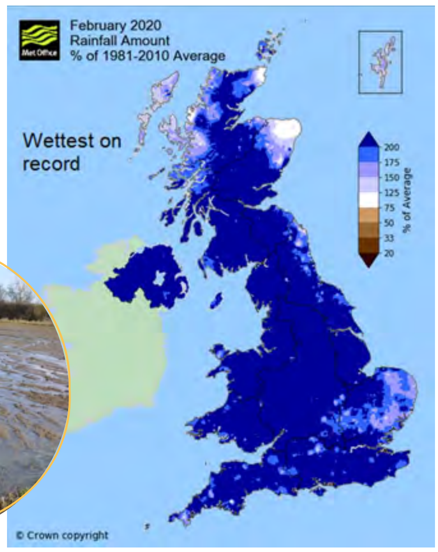
BACKGROUND

- Increasingly intense patterns of winter rainfall overwhelming degraded soils & drainage systems
- Cause crop damage & soil erosion
- Leaching/runoff of nutrients & environmental pollution



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Background

How plants take up water

- Roots absorb water via osmosis
- A higher root salt % than surrounding water creates a suction force through semi-permeable cell membranes
- Water loss via leaf transpiration causes water to move through the osmotic system from root to leaf
- Water absorption primarily via young roots with more fine root hairs (large surface area)
- Transpiration of water back into the air via leaf stomata
- Evaporation = loss of soil moisture to air
- Evapotranspiration (ET) = combination of two processes

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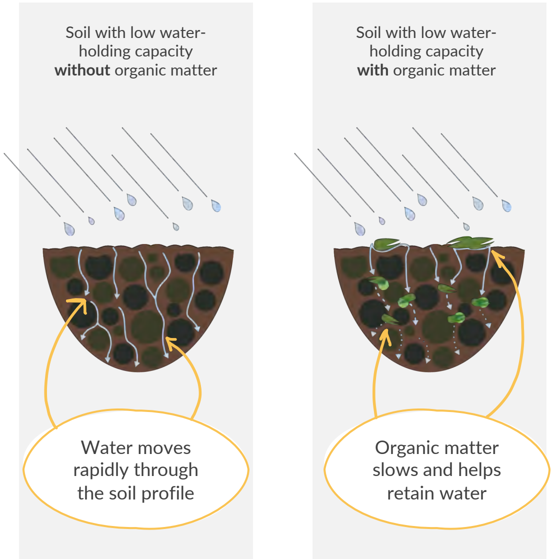
Optimising water use

8

Benefits of Soil Health & Structure - 1

- Water holding capacity (WHC) of soil largely determined by type & texture – i.e. sand vs clay
- But, healthier, well structured soils with a high % of soil organic matter (SOM) more likely to be resilient in face of drought & intense rainfall
- SOM can hold up to 90% of its own weight in moisture & helps form stable soil aggregates with ample macropore spaces to increase WHC
- Healthy, well structured soils with high SOM also more likely to encourage high populations of soil macrofauna such as deep-burrowing earthworms to increase soil water infiltration rates
- Well structured soils allow for easier, deeper rooting & water uptake
- Compacted, degraded soils encourage poor rooting, low water infiltration, high water runoff & erosion



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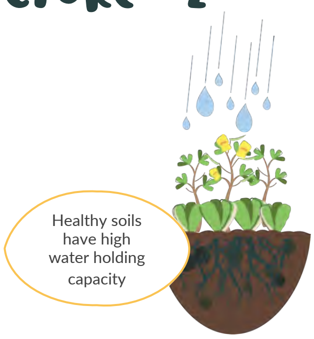
Benefits of Soil Health & Structure - 2

- Reduced tillage & inputs of organic matter to improve soil health & structure
- Reduced tillage can also increase field surface crop residues – from >90% in no-till systems to <5% in inversion tillage
- Does not disrupt/invert soil surface allowing soil moisture to be lost
- WHC of a silt loam containing 4% organic matter more than double that of a silt loam containing 1% (Hudson 1994)
- Use of biochar & bulkier organic matter sources (e.g. compost, farmyard manures) for most effect



Every **1%** increase in organic matter can result in up to **20,000** gallons of available soil water per acre*

Healthy soils with high organic matter will equate to higher water holding capacity
*USDA-NRCS

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Benefits of Soil Health & Structure - 3

- Arbuscular mycorrhizal fungi (AMF)
- Encouraged by reduced tillage & reduced synthetic inputs
- Form symbiotic relationship with plant roots in rhizosphere
- Enlarge crop's root surface & rooting area, mobilising water & nutrients otherwise unavailable to the crop
- Mycorrhizal colonised plants have higher water stress tolerance & produce higher yields in water scare conditions
- Also important for soil aggregate stability, helping improve WHC

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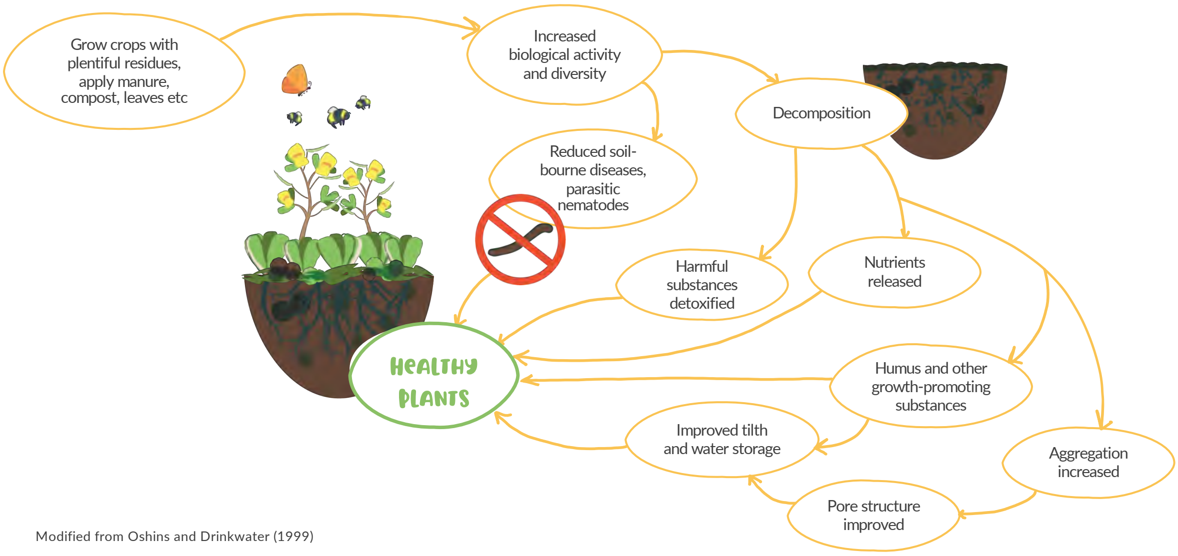
Why is Soil Organic Matter Important?



Modified from Oshins and Drinkwater (1999)

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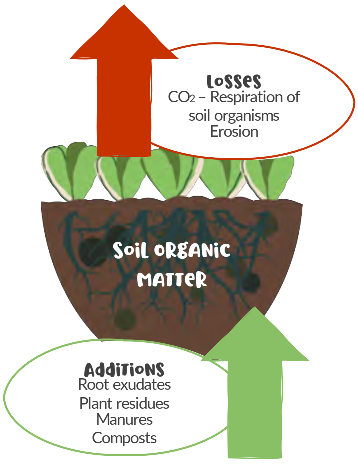
Why is soil organic matter important?

- Levels of soil organic matter = equilibrium between inputs & decomposition of SOM by soil organisms. Inputs must exceed losses to build SOM.
- Levels of SOM present in soil can be affected by natural processes such as
  - Temperature
  - Rainfall
  - Soil type & texture
- But also human processes such as
  - Tillage
  - Removal of crops/crop residues
  - Application of artificial N
- Important to adapt management practices to reverse losses before increases can be gained



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Benefits: Crop residues & mulches

- Act as 'soil armour' to protect soil from high-intensity rainfall & erosion
- Conserve soil moisture & regulate temperature
- Provide an insulating cover, helping regulate extremes of temperature (hot & cold) & reducing evaporative loss
- Possess a higher albedo than bare soil, reflecting more sunlight
- Soil temperature beneath mulch demonstrated to be up to 10°c lower than bare soil (Mitchell & Tell, 1976)
- Beneficial impact on relative humidity beneath residues/mulches
- Beneficial impact on soil biological activity & improvements in chemical properties (Doran, 1980)

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ROTATIONS & CROPPING

- Consider risk factors (e.g. soil type, peak water needs, weather patterns) & rotations (e.g. winter/spring, crop type) when making cropping choices
- Local, heritage varieties vs modern hybrids? Region-appropriate cropping?
- Utilise cover/catch cropping to manage soil moisture & provide soil cover
- Cover/catch crops to create root channels to aid infiltration
- Cover crops/polycropping systems also create system resilience by providing a range of rooting depths & architectures to optimise water uptake through the soil profile

Source: Cotswold Seeds

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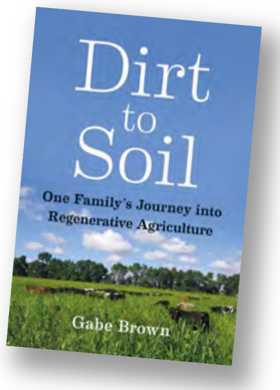
DIRT TO SOIL – GABE BROWN (NORTH DAKOTA, USA)

- 'Effective rainfall' – that part of rainfall total which remains available for crop uptake
- Total rainfall, minus losses to evaporation, deep percolation & runoff
- Building soil structure to increase effective rainfall & build soil resilience
- Between 1991 & 2009 water infiltration rate increased from 0.5in/hour to 10in/hour after adoption of regenerative agricultural practices
- 1991 – average SOM content 2% storing c.370,000l/ha water
- 2017 – average SOM content 6% storing c.940,000l/ha water



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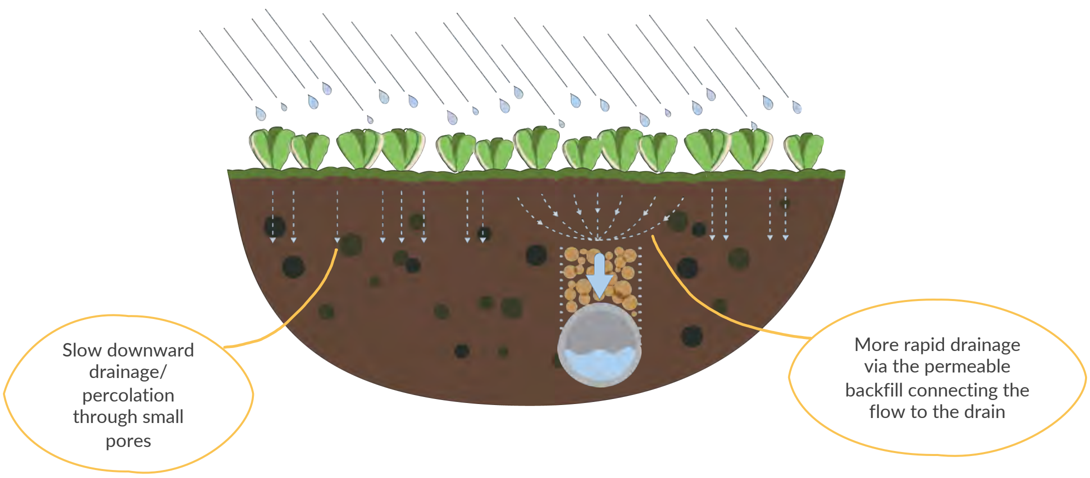
Benefits - effective field drainage

- Designed to rapidly remove excess soil water to reduce or eliminate waterlogging & return soils to their natural field capacity
- Can be used to control a water table or facilitate removal of excess water in upper horizons of the soil
- Reduces risk of detrimental waterlogging to acceptable levels
- Waterlogging increases risk of soil runoff, loss of nutrients, environmental pollution, and erosion, also creates anaerobic soil conditions directly impacting crop productivity
- Reduces peak water runoff by increasing soil water storage capacity as water percolates into drainage channels
- Generally required except in coarse textured & very thin agricultural soils
- Reduction of SOM leaves soils more reliant on artificial drainage

17

Benefits - effective field drainage



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Benefits: effective field drainage - 2

Improved crop performance	Better access to land	Soil structure & environment
• Optimised crop yield • Improved environment for soil biome • Improved rooting conditions • Improved uptake of soil mineral nitrogen (SMN)	• Reduced risk of waterlogging • Inputs applied at right time • Extended field seasons • Improved field working conditions	• Reduced soil structural damage • Reduced livestock damage • Improved water infiltration • Reduced run-off, erosion & pollution

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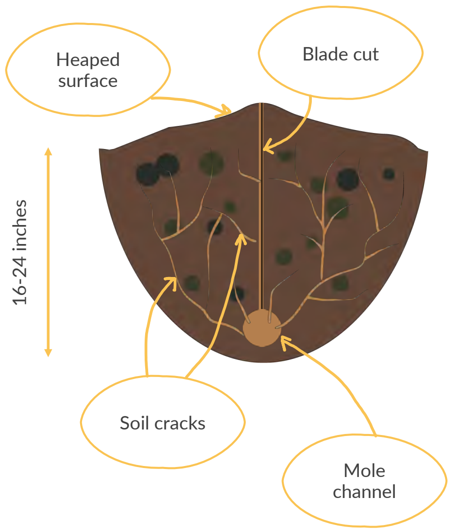
Benefits: effective field drainage - 3

Mole drains

- Unlined channels formed in a clay subsoil
- Supplement to engineered drainage scheme in very heavy clay soils (30% min)
- Conduct water to permanent pipe drains or ditches
- Bullet & expander to form semi-permanent channel with fissuring in the soil above, 500-600mm depth
- Duration up to 10 years in good soil conditions/good soil management
- Essential moling channels are drawn through permeable backfill over drains



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Calculating irrigation need

Soil can hold significant volumes of watervine pores & hydrostatically bound to the surface of soil particles. Pore water is more readily available

Field capacity

the amount of water remaining in a soil after saturation & draining

Permanent wilting point

moisture content of a soil at which plant fail to recover even if provided with sufficient water

Readily available water (RAW)

the amount of water in a soil that plants can easily access before water stress occurs

Available water capacity (AWC)

difference between field capacity & wilting point – the maximum amount of plant available water a soil can hold. An indicator of a soil's ability to retain water

Soil water tension

adhesion force by which water is bound to soil particles. Plant roots must overcome soil water tension to absorb water. When tension in the soil is higher than the root, wilting occurs

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Calculating irrigation need - 2

- AWC differs depending on soil type – lower in sandy soils vs loams/clays
- But in sandy soils most of the water is readily available, while much water in clay is strongly bound to soil particles by hygroscopic force
- Different crops experience different levels of water stress – e.g. leafy vegetables vs sorghum
- Irrigate to compensate for evapotranspiration, but not to supply excess water for saturation & runoff

Fig 3. Soil water availability and crop water stress

The readily available water (RAW) allows best crop growth.

Source: FiBL: 'Good agricultural practice in irrigation management' (2020)

22

Calculating irrigation need - 3

- Calculate RAW
- To determine optimum water requirement, consider soil's ability to retain water & crop stress boundaries. Determine:
  - Soil type & profile
  - Rooting depth & tolerable water stress
  - % soil gravel/stones
  - Calculate RAW

Table 3. Gross RAW in relation to soil type and crop water stress tolerance

Tolerable water stress	Very low	Low	Moderate	High
Maximum soil water tension	−20 kPa	−40 kPa	−60 kPa	−100 kPa
Soil type	Gross RAW (mm or l per m²)			
Sand	30	35	35	40
Loamy sand	45	50	55	60
Sandy loam	45	60	65	70
Loam	50	70	85	90
Sandy clay loam	40	60	70	80
Clay loam	30	55	65	80
Light clay	25	45	55	70

Adapted from: Calculating RAW, Dep. of Primary Industries and Regional Development, Gov. of W. Australia

Source: FiBL: 'Good agricultural practice in irrigation management' (2020)

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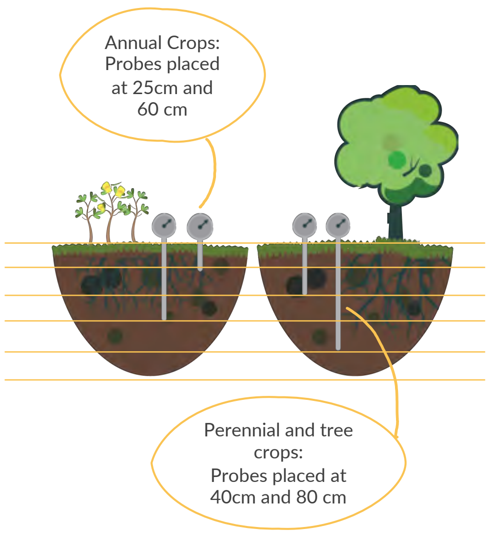
Calculating irrigation need - 4

- Water demand can also be determined by measuring soil moisture with sensors and/or measuring ET of the crop:
  - Tensiometers
  - Gypsum blocks
  - Frequency Domain Reflectometry (FDR)
- Measurements taken both at & below active root zone
- Root zone probe indicates when RAW must be replenished; probe below active root zone indicates if more water was applied than could be retained by soil – and was wasted
- Water stress results in increased leaf temperatures that can be detected with thermal or near infrared imaging



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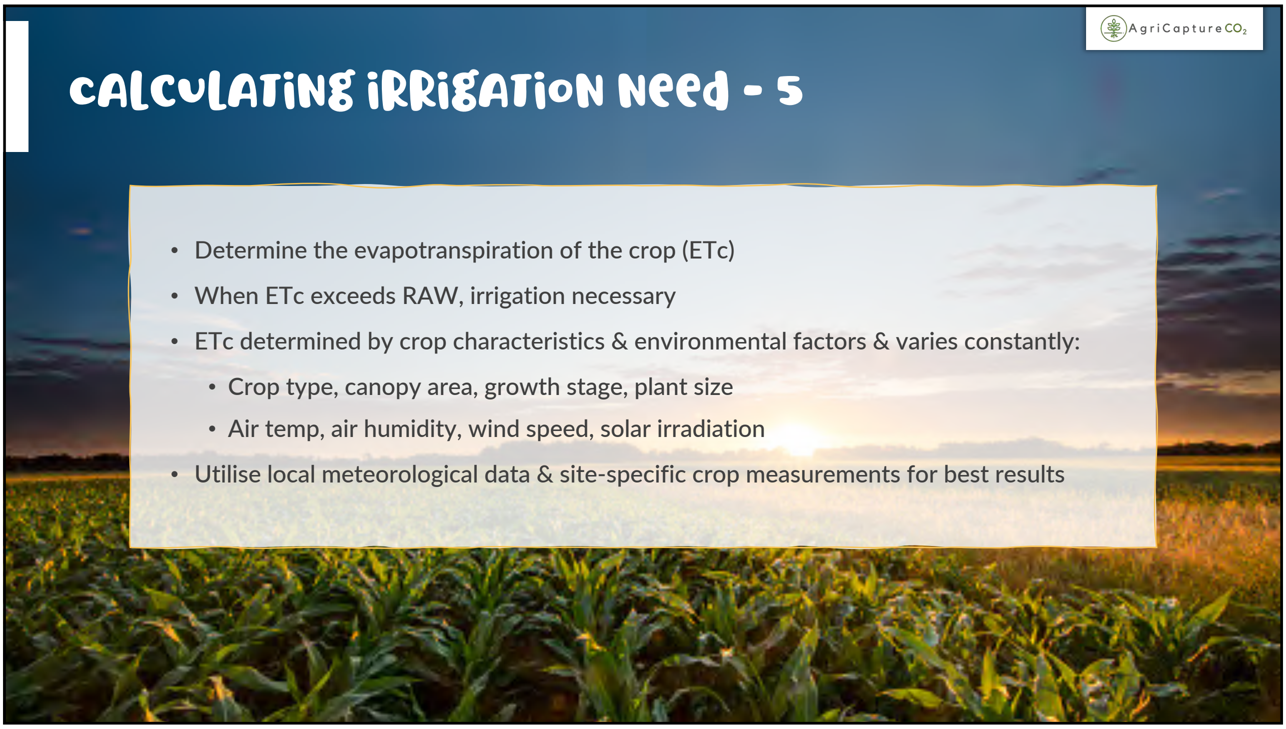
AgriCapture CO2
CALCULATING IRRIGATION NEED - 5
• Determine the evapotranspiration of the crop (ETc)
• When ETc exceeds RAW, irrigation necessary
• ETc determined by crop characteristics & environmental factors & varies constantly:
• Crop type, canopy area, growth stage, plant size
• Air temp, air humidity, wind speed, solar irradiation
• Utilise local meteorological data & site-specific crop measurements for best results

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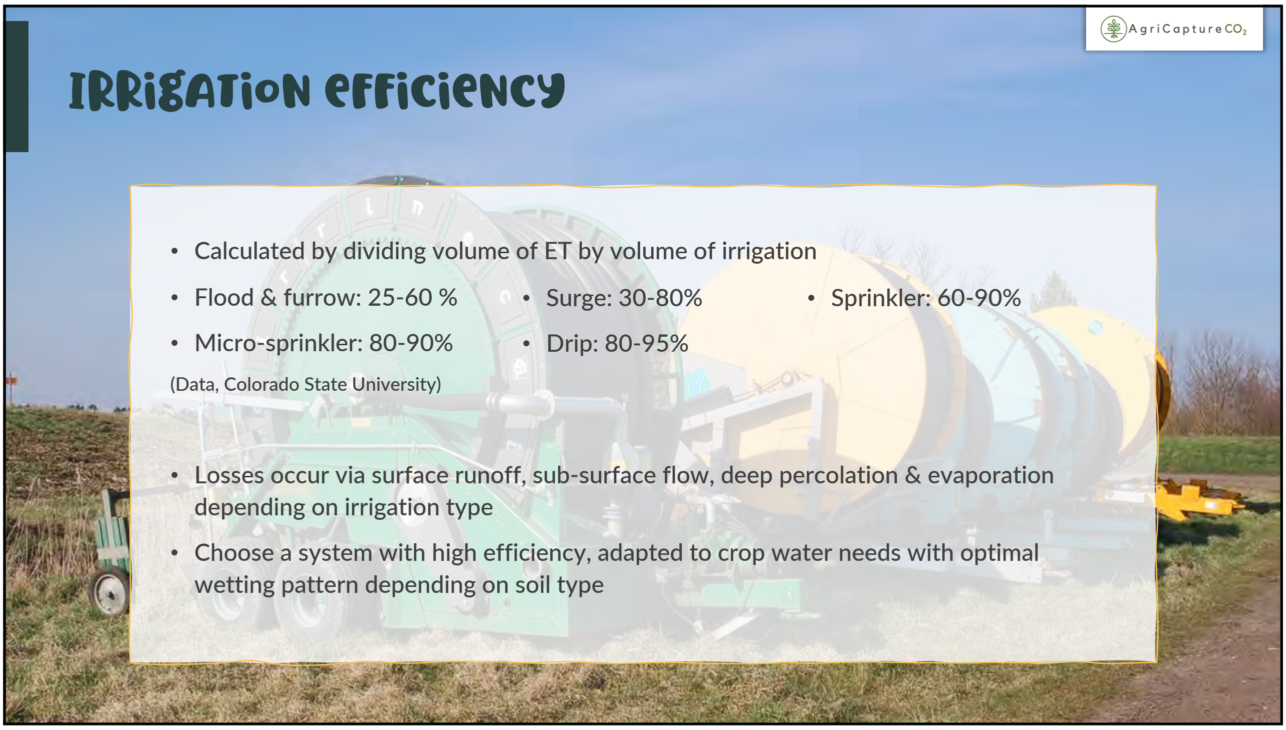
AgriCapture CO2
IRRIGATION EFFICIENCY
• Calculated by dividing volume of ET by volume of irrigation
• Flood & furrow: 25-60 %
• Surge: 30-80%
• Sprinkler: 60-90%
• Micro-sprinkler: 80-90%
• Drip: 80-95%
(Data, Colorado State University)
• Losses occur via surface runoff, sub-surface flow, deep percolation & evaporation depending on irrigation type
• Choose a system with high efficiency, adapted to crop water needs with optimal wetting pattern depending on soil type

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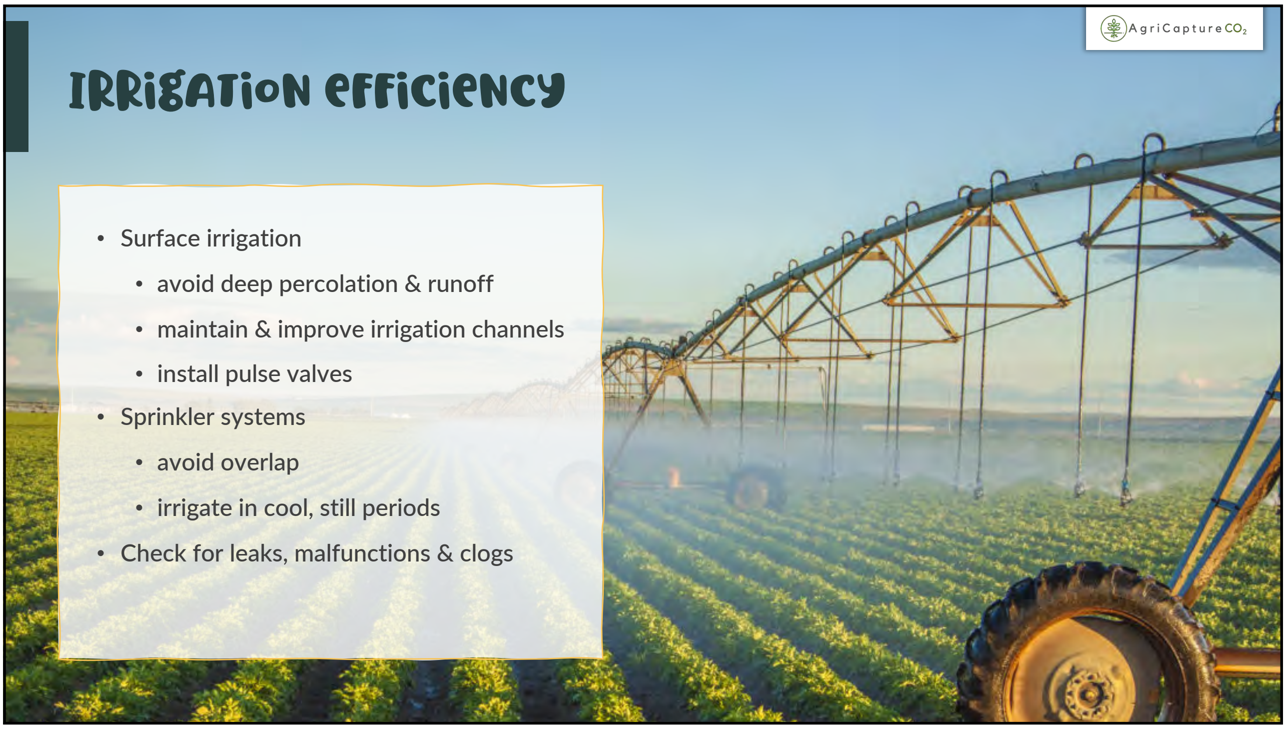
AgriCaptureCO_2
IRRIGATION EFFICIENCY
• Surface irrigation
• avoid deep percolation & runoff
• maintain & improve irrigation channels
• install pulse valves
• Sprinkler systems
• avoid overlap
• irrigate in cool, still periods
• Check for leaks, malfunctions & clogs

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OPTIMISING IRRIGATION SYSTEMS
MICRO-SPRINKLER/DRIP IRRIGATION
• Reduced water volumes
• High/ very high efficiency vs surface/ main sprinkler irrigation – minimal water loss via evaporation/percolation
• Irrigation limited to root zone of crop
• Precision irrigation according to plant need
• Drip irrigation eliminates canopy wetting & potential disease issues – can be combined with fertigation systems
• However, potentially high investment costs & infrastructure which hinders field operations. Suitable for smaller scale/high value/perennial crops

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OPTIMISING IRRIGATION SYSTEMS - 2

CLIMATE SMART IRRIGATION (CSI) PRACTICES

DEFICIT IRRIGATION (DI)

- Increase water use efficiency by maximising yield per volume of water
- Providing less water than calculated ETc of crop.
- In most crops, DI causes reductions from potential yield
- Acceptable if water costs are high/availability limited
- In olive production, DI can improve oil extraction & nutritional values of crop
- In less drought tolerant crops DI can be used for less water-intensive periods of growth cycle

SUPPLEMENTAL IRRIGATION (SI)

- Used in rain-fed crops in situations of late/irregular/insufficient rain
- Supply the crop with limited water in critical development stages
- Can improve yield & WUE in semi-arid regions

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OPTIMISING IRRIGATION SYSTEMS - 3

WATER HARVESTING

- Important in regions with scarce water resources, or seasonal imbalances
- Rainwater collection (roofs?), field runoff (drainage systems?) reservoir creation
- Hold water in tanks or impermeable lagoons: cover to avoid evaporative loss?
- Reduce water costs

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Case Study: Soil water content in Greek olive groves (Arampatzis et al, 2018)

- Mediterranean projected to become increasingly water stressed as a result of climate change
- Soil water availability already the biggest limiting factor in Mediterranean agricultural production (Zuazo et al, 2009)
- Water content of 6 rainfed & 6 irrigated olive fields monitored at a range of soil depths for 3 years
- 50% 'regenerative' (return of organic mulches, no-till) 50% 'intensive' (no mulches, intensively tilled)
- Higher (6.8%) soil water content in irrigated vs non-irrigated groves
- Higher (5.6%) soil water content in 'regenerative' vs 'intensive' groves
- Higher yields (39%) from 'regenerative' vs 'intensive' groves
- Increased SOM in 'regenerative' groves, plus organic mulches, contributed to higher soil water contents & crop yield

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BEDANKT EFHARISTO POLI

HVALA VAM MERCI

DANKE DZIĘKUJĘ WAM

THANK YOU

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5 PRINCIPLES OF REGENERATIVE AGRICULTURE
HEALTHY SOIL · HEALTHY CROPS · HEALTHY BUSINESSES

POLYCULTURES

MODULES: SOIL PROTECTION, MAINTAIN LIVING ROOTS, BIOLOGICAL DIVERSITY

AgriCapture CO2 · GWCT THE ALLERTON PROJECT

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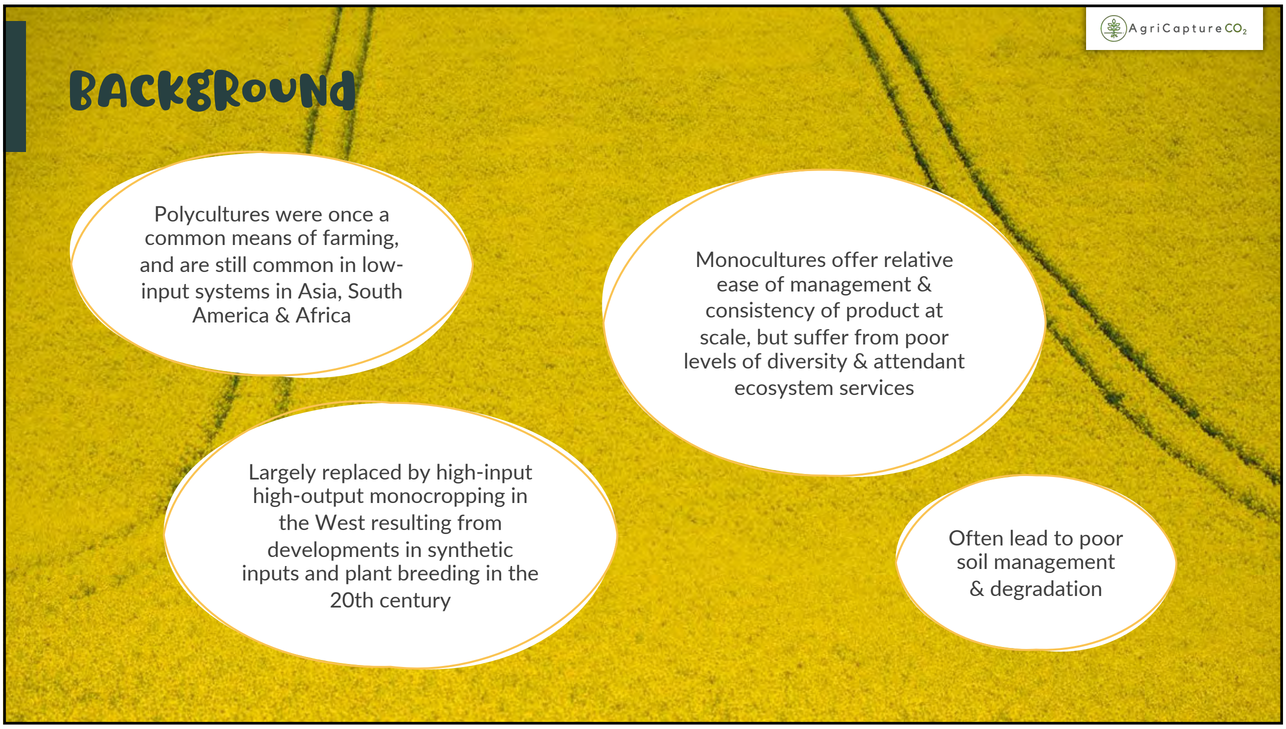
AgriCapture CO2
BACKGROUND
Polycultures were once a common means of farming, and are still common in low-input systems in Asia, South America & Africa
Monocultures offer relative ease of management & consistency of product at scale, but suffer from poor levels of diversity & attendant ecosystem services
Largely replaced by high-input high-output monocropping in the West resulting from developments in synthetic inputs and plant breeding in the 20th century
Often lead to poor soil management & degradation

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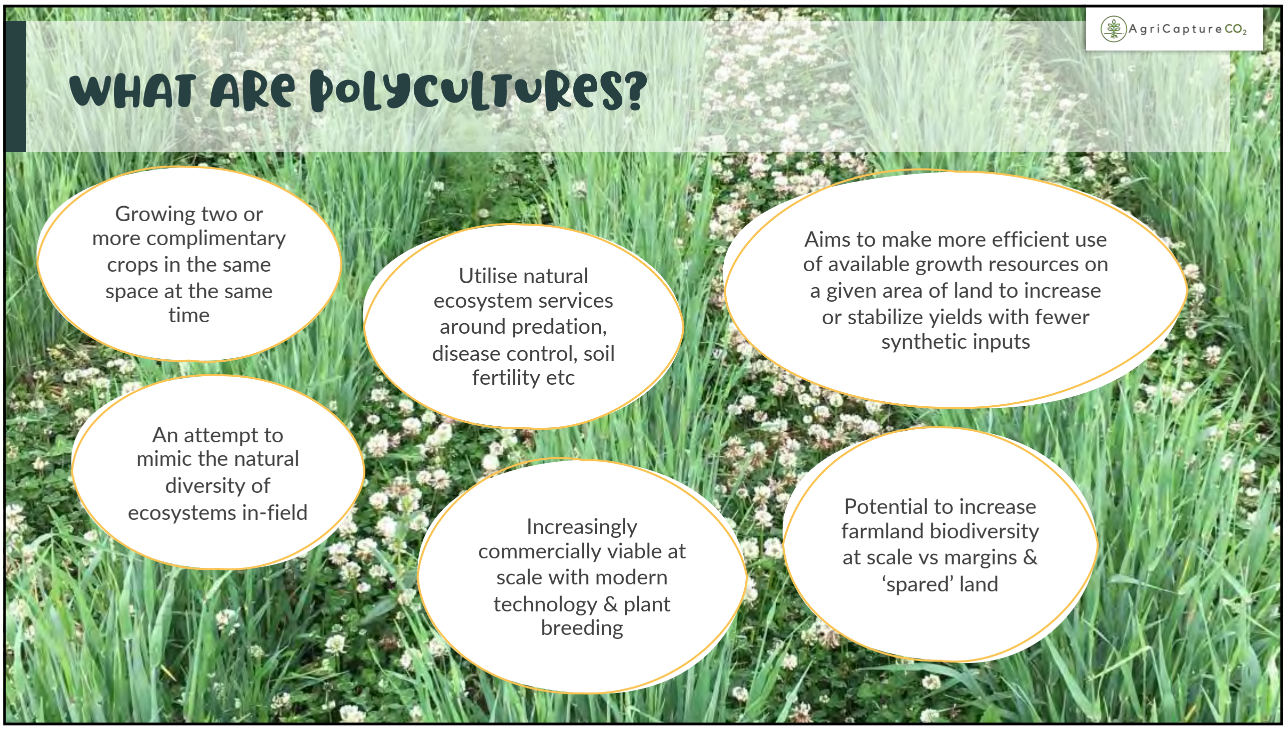
AgriCapture CO2
WHAT ARE POLYCULTURES?
Growing two or more complimentary crops in the same space at the same time
Utilise natural ecosystem services around predation, disease control, soil fertility etc
Aims to make more efficient use of available growth resources on a given area of land to increase or stabilize yields with fewer synthetic inputs
An attempt to mimic the natural diversity of ecosystems in-field
Increasingly commercially viable at scale with modern technology & plant breeding
Potential to increase farmland biodiversity at scale vs margins & 'spared' land

4

EXAMPLES OF POLYCULTURE

INTERCROPPING	COVER CROPPING	STRIP CROPPING	UNDERSOWING
Two or more crops in complete temporal & spatial overlap (common in legume/cereal mixes	Commonly mixtures of grasses, brassicas & legumes used as a non-cash crop to manage soil health & reduce erosion	Alternating rows of distinct plants - often cash crops alternated with green covers to reduce soil erosion	Establishing a polyculture in a standing crop; e.g. grass ley in spring barley
RELAY CROPPING	**COMPANION CROPPING**	**LIVING MULCH**	**PERMACULTURES**
Planting a second crop in a growing crop with a different harvesting date	Planted alongside cash crops to give protection from pests, provide nutrients to aid crop establishment or prevent lodging	Establishment of a perennial forage legume as semi-permanent ground cover to provide weed suppression & nutrient fixation & cycling for the main crop	e.g. agroforestry systems; silvopastoral or silvoarable, with annual or perennial crops integrated with trees which provide benefits to the crop, but may also produce fruits/nuts/fuel

5

WHAT ARE POLYCULTURES?

SIMILAR TO PRINCIPLES OF GREEN MANURES & COVER CROPS WITH FOUR MAIN MODES OF ACTION:

- Improving soil fertility
- Improving soil structure
- Managing weeds & pests
- Environmental management

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Benefits: Polyculture

- Enhanced resource efficiency via complimentary species – e.g. biological nitrogen fixation & enhanced nutrient cycling alongside cash cropping
- Integrated Pest Management: pest, weed & disease control
- Reduced synthetic inputs
- Improved soil health, protection & structure via living roots, green cover & biological diversity
- Soil organic matter & carbon
- Biodiversity enhancement

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Benefits: Polycultures

- Two mechanisms which explain these benefits:

Facilitation	Niche complimentarity
An interaction "in which the presence of one species alters the environment in a way that enhances growth, survival, or reproduction of a second, neighbouring species" (Bronstein 2009)	An interaction by which the component species of the plant team utilise resources differently, either spatially and/or temporally, resulting in the mixture filling out niche space more completely than the components in monocultures.

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Benefits: Polycultures

- Yield advantage in polycrops due to growth resources (light/water/nutrients) more completely absorbed & converted to biomass over time & space
- Result of the differences in competitive ability of the plant teams which exploit variation in characteristics such as:
  - Canopy development
  - Canopy size
  - Photosynthetic adaptation of canopy to conditions
  - Rooting depth & structure
- Complimentary use of resources when plant teams use different resources or compete for same resources at different times
- Crops which differ in time & space for same resources lead to successful polycrops

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Benefits: Polycultures

- Facilitation is achieved by combining plants that increase the phytoavailability of water, phosphorus (P) micronutrients or nitrogen (N) available to the system through N2 fixation either directly or indirectly
- Also via the attraction of beneficial organisms, such as natural enemies and pollinators, the deterrence of pests and pathogens, and the suppression of weeds
- Resource sharing can be enhanced via common mycorrhizal fungal networks
- Niche complementarity - allowing maximal exploitation of light & soil resources - is observed between species with contrasting root & shoot architectures or when plants acquire minerals in different chemical forms

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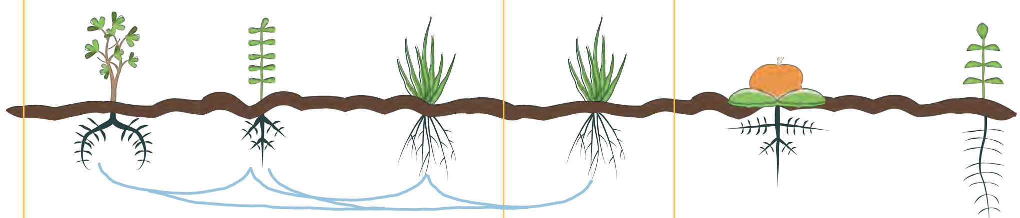
Benefits: Polycultures



	Facilitation			Resource sharing	Complimentarity	
CHARACTER	Nitrogen Fixation	Phosphorus acquisition	Micronutrient acquisition	Mycorrhial fungal connections	Canopy architecture	Root architecture
	Protection against mineral toxicities Protection against pests and pathogens Attraction of beneficial organisms Suppression of weeds			Leaf litter Root turnover		
BENEFIT	Nitrogen (NUE)	Phosphorus (PUE)	Micronutrient (MUE)	Water (WUE) Carbon (RUE) Minerals (MUE)	Humidity (WUE) Temperature (WUE) Light Harvesting (LUE) Weed competition (RUE)	Hydraulic Lift (WUE) Mineral acquisition (MUE) Reduced Leaching (WUE), (MUE)

Brooker et al, 2014
(UE = Use Efficiency)

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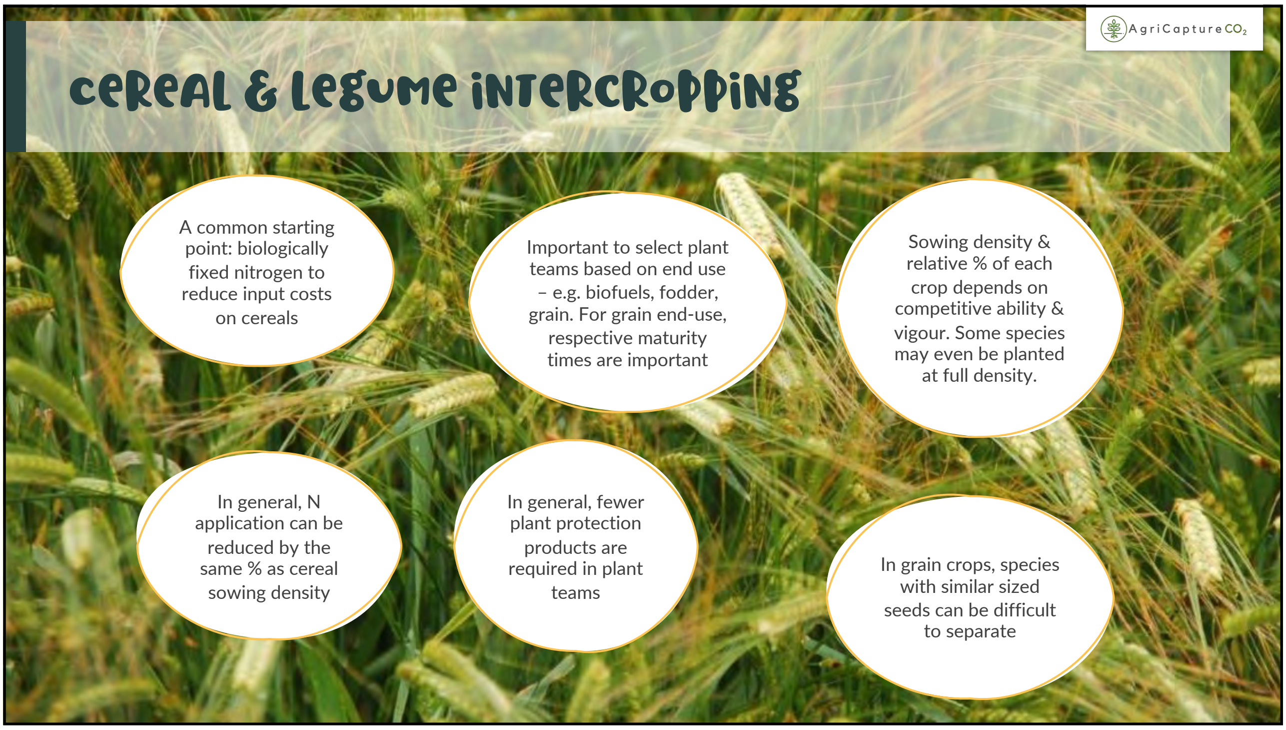

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Benefits: biological nitrogen fixation (BNF)

- Legume crop teams provide N via biological nitrogen fixation (BNF) from the atmosphere
- Convert atmospheric N (N2) to ammonia (NH3) then ammonium (NH4)
- Early establishment (late summer/early autumn) is key, as fixation can take up to 6 weeks to commence
- N fixation most effective above 7°c (limited in winter in N Europe)
- Available to following crops and other soil biology after incorporation & mineralisation (short term) or increasing soil mineralizable nitrogen SMN (longer term)
- Commonly undersown in spring cereals for reduction in carbon-heavy & expensive synthetic N

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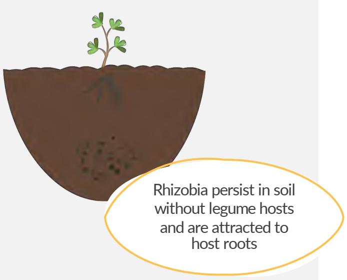
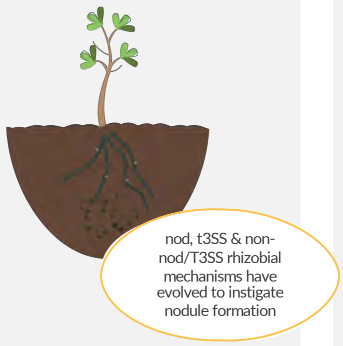
Benefits: biological nitrogen fixation (BNF)

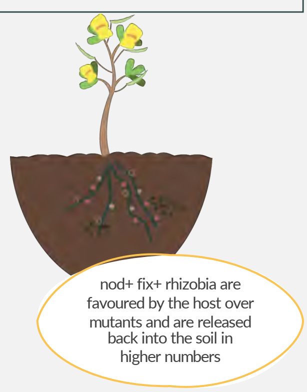
Pre-symbiosis
- Rhizobia thrive in soil
- Host seedlings must acquire symbionts in each generation



I: Nodule formation & invasion
- Rhizobia instigate nodule formation through at least three different mechanisms
- A suite of other rhizobial functions promote nodule infection and modulate host range
- Hosts select for rhizobial compatibility



II: Symbiotic nitrogen-fixation
- Nitrogen fixation requires the nitrogenase enzyme and microaerobic conditions in the nodule
- Hosts sanction ineffective rhizobia, selecting for nitrogen fixation



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Benefits: Biological Nitrogen Fixation (BNF)

Many factors determine leguminous N fixation:

- Species & biomass
- Established legumes fix more N than newly established plants
- Establishment of effective root nodules via Rhizobia bacteria
- Existing levels of soil N – legumes may also scavenge available soil N before fixing it themselves (though this too will eventually be released)
- Volume of plant biomass
- Soil type
- Climate
- Carbon to nitrogen (C:N) ratio

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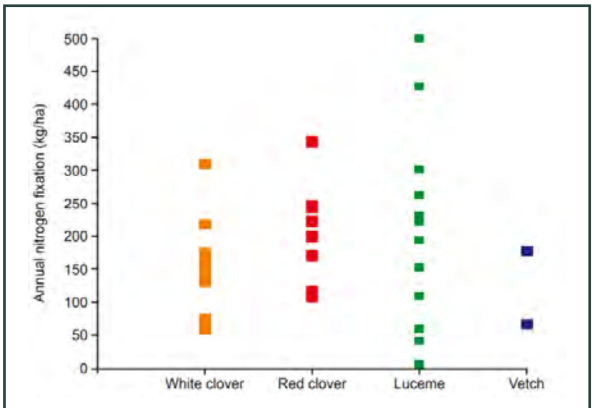
Benefits: biological Nitrogen Fixation (BNF)

- Significant variability in N fixation depending on species, location, climate
- Specific bacterial species interact with specific legumes
- Repeated growing of certain legumes will usually ensure good populations of complimentary bacteria
- Seed inoculants available
- N fixation broadly related to biomass production & soil N availability: poor growth/high residual N will impede fixation
- General soil macro/micro nutrient status also important – green manures are still a crop!



Nitrogen fixation by different leguminous green manures showing the range of measurements that have been made (data from DEFRA Project OG0316

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Undersowing in Traditional Rotations

- Reduce soil erosion & runoff
- Increase water infiltration
- Reduce nutrient leaching
- May provide BNF if legumes present
- Increase field travelability at harvest
- Provide possible grazing/forage crop
- Control injurious weeds
- Provide uncultivated overwinter bridge to support invertebrate populations & wider food web

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Undersowing in Traditional Rotations

- Undersowing in spring-sown cereal usually at time of crop drilling or pre-emergence
- Broadcast into established winter crops in the spring
- Consider wider cereal row spacing/lower seed rates to reduce competition
- Potential harvest difficulties with crop/straw moisture content
- Into maize crops post-establishment
- In leguminous leys, use of herbicides likely to be limited – clover can be added in a second year if ley retained

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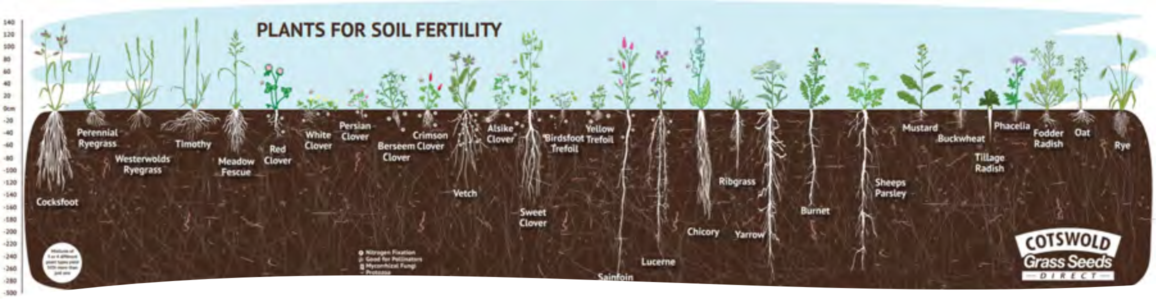
Benefits: Soil Organic Matter, Carbon & Nutrients

- On average, plant roots store 2x amount of carbon as plant shoots (Rasse et al, 2005)
- Maximising rooting potential of rotation with polycropping can help boost soil organic matter (SOM)
- Promote soil health, structure, fertility, water holding capacity & soil organic carbon (SOC)
- Growing plants with varying root structures & depths (spatial variety) or temporal requirements – e.g. in relay cropping – can optimise root production & resource use



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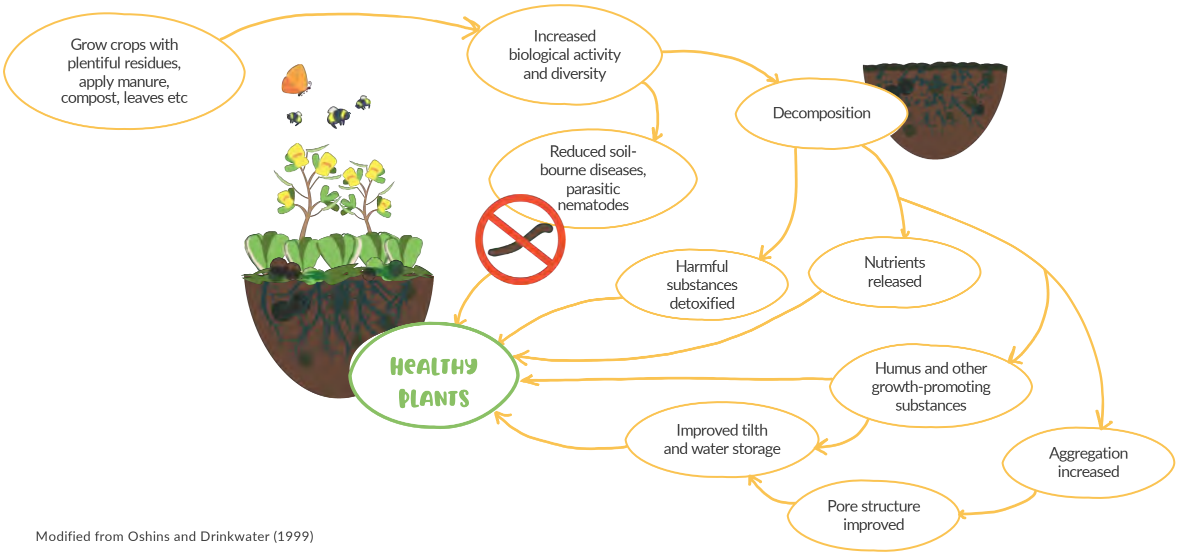
Why is Soil Organic Matter Important?



Modified from Oshins and Drinkwater (1999)

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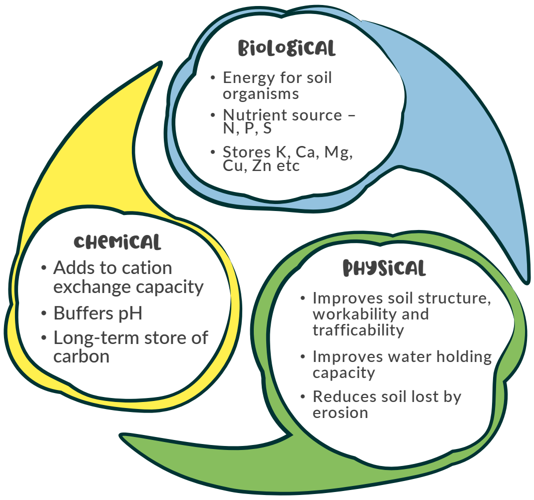
Soil organic matter (SOM)

- Essential for soil biological, physical & chemical processes
- The living, the 'dead' & decomposing (detritus) & the 'very dead' (humus) – actively cycling vs stable, long-term soil organic carbon (SOC)
- Provides nutrients & energy for soil biome
- Keystone of healthy soil structure
- Boosts water holding capacity (WHC)
- Buffers pH & aids cation exchange capacity (CEC)



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Benefits: SOM, carbon & nutrients - 3

- Plant roots excrete carbon-rich fluids called exudates into the rhizosphere – the thin area of soil immediately surrounding the root system
- Rich in amino acids, organic acids & sugars (proteins & carbohydrates)
- Up to 20% of photosynthetically fixed carbon is secreted into the rhizosphere in exudates
- An important food source for soil biome – especially bacteria & mycorrhizal fungi
- Diverse perennial leys/green manures provide significantly more exudates (through more of the year) than annual monocrops
- Healthy communities of organisms mine plant-unavailable nutrients & make them plant-available

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AgriCapture CO_2
Benefits: SOM, Carbon & Nutrients - 4
• Dead root cells also consumed & recycled by soil micro-organisms
• Resulting microbial metabolites include plant-growth promoting hormones & compounds that bolster plant health & aid in plant defence
• Some metabolites form stable carbon-rich deposits which encourage communities of beneficial bacteria in rhizosphere
• At high microbial densities communities coordinate the release of beneficial compounds which promote plant growth – triggering greater root exudation in a virtuous circle
• OM-consuming microbes in turn consumed by predatory arthropods, nematodes & protozoa, which excrete plant-available nutrients into rhizosphere

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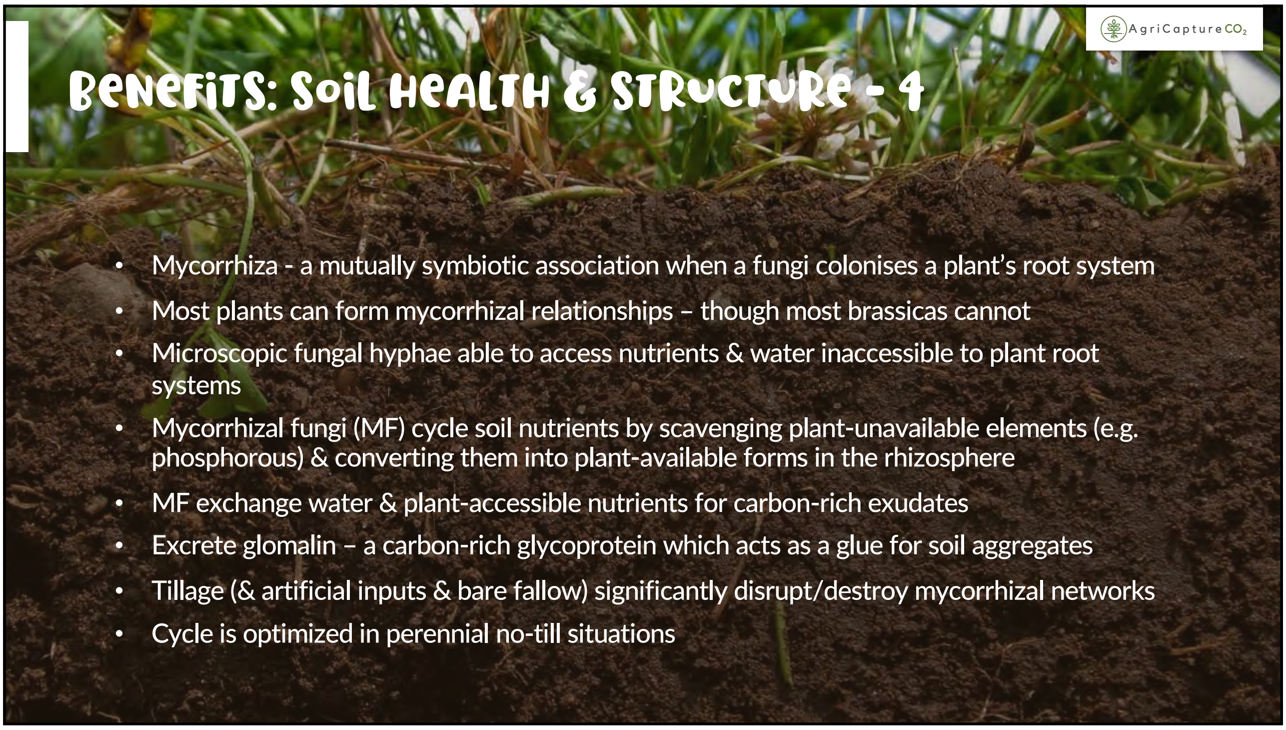
AgriCapture CO_2
Benefits: Soil Health & Structure - 4
• Mycorrhiza - a mutually symbiotic association when a fungi colonises a plant's root system
• Most plants can form mycorrhizal relationships – though most brassicas cannot
• Microscopic fungal hyphae able to access nutrients & water inaccessible to plant root systems
• Mycorrhizal fungi (MF) cycle soil nutrients by scavenging plant-unavailable elements (e.g. phosphorous) & converting them into plant-available forms in the rhizosphere
• MF exchange water & plant-accessible nutrients for carbon-rich exudates
• Excrete glomalin – a carbon-rich glycoprotein which acts as a glue for soil aggregates
• Tillage (& artificial inputs & bare fallow) significantly disrupt/destroy mycorrhizal networks
• Cycle is optimized in perennial no-till situations

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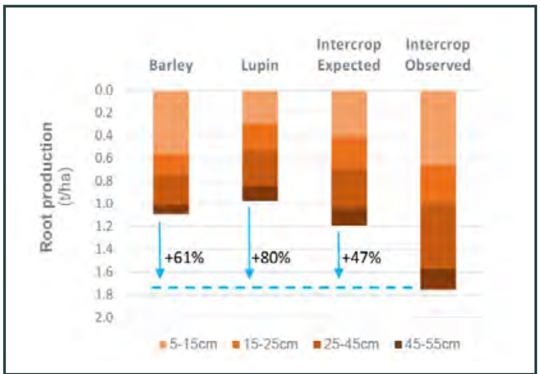
Benefits: SOM, Carbon & Nutrients - 6

- Intercropped lupin (100%) & barley (20%)
- Root mass overyielding of 47% vs expected average
- Equalled an increase in root tissue carbon of 0.25t/ha in the first 50cm soil profile



Roots overyeilding in a lupin and barley intercrop (100%:20% in different soil layers

DIVERSify

Results from the EU Horizon 2020 DIVERSify project

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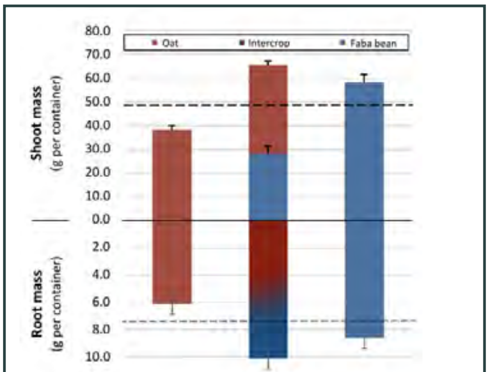
AgriCaptureCO_2

Benefits: SOM, Carbon & Nutrients - 6

- Intercropped faba bean & oat
- Sown 50:50 ratio
- Overyielding of root (38%) & shoot (32%) mass
- Even small increases in root mass could have a large impact on SOM/SOC levels over a large area national/international
- Improved root mass also beneficial to improve soil aggregation/reduce risk of erosion
- Species & rooting variety for complimentarity in macro/micro nutrient cycling from full soil profile



Root and shoot overyielding in a faba bean and oat intercrop (50%:50%). Broken lines mark the monocrop averages

DIVERSify

Results from the EU Horizon 2020 DIVERSify project

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Benefits: drought tolerance

- Polycultures with a range of rooting architecture able to access water at a range of depths, increasing resource use efficiency
- Root growth dependent on plant physiology & environmental conditions
- Increased ground cover from polycultures reduces evapotranspiration
- Increased SOM levels from reduced tillage/diverse cropping improves water holding capacity
- Agroforestry systems also act to bring water up from great depths & provide shade to crops & livestock

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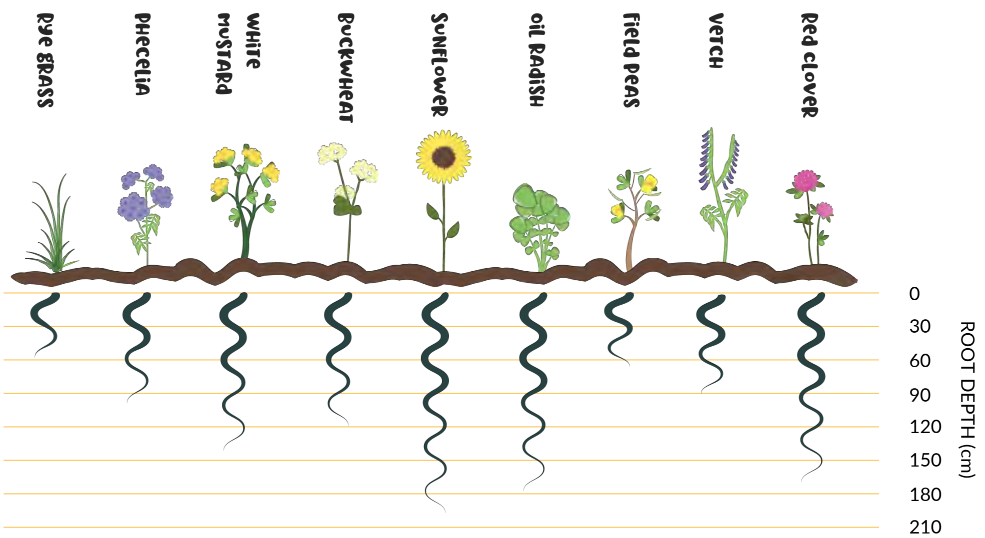
AgriCaptureCO_2

Benefits: drought tolerance



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Benefits: Integrated Pest Management (IPM)

- Beneficial effects of polycultures to reduce pest, weed & disease burdens can be significant but generally do not offer complete protection
- Dependent on seasonal factors
- Do offer the potential to reduce use of plant protection products (PPPs) in some circumstances
- An additional tool in the IPM toolkit

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Benefits: Integrated Pest Management (IPM)

How do polycultures impact pests & disease?

- Modify wind/rain splash/vector dispersal
- Modify crop microclimate
- Alter crop morphology/physiology
- Act as trap crops for pests
- Encourage natural pest predators

Naturally occurring IPM may require augmentation with additional pest control measures

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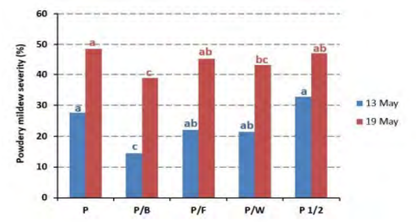
Benefits: Integrated Pest Management

Disease:

- Spanish pea/cereal intercrops showed a reduction in powdery mildew as a result of 'barrier effect' of polyculture on spore movement
- Similar reduction in rust & chocolate spot for faba bean/cereal intercrop
- Downward trend in disease for wheat with clover understory in UK trials
- Hauggaard-Nielsen et al, 2008, found that intercropping of grain legumes with barley reduced disease by an average of 20-40%
- Also found that some disease (e.g. brown spot in lupins) received up to 80% control, but that others received almost none



Disease management: example on evolution of powedry mildew disease on pea growing in Córdoba in 2019
P = pea monocrop P/B = pea barley
P/F = pea/faba P/W = pea /wheat
P1/2 = pea at half density
Different letter scoring date indicated differences (Tikey test p<0.05)

Results from the EU Horizon 2020 DIVERSify project

31

Benefits: Integrated Pest Management

Weeds:

- Weed control important in intercropping as herbicide selection often limited in polycultures
- Weed suppression achieved if plant teams usurp resources (light, water, nurtients) from weeds or suppress them via allelopathy
- Intercrops of sorghum with fodder cowpea intercepted more light, captured greater quantities of macronutrients (N, P, K) produced higher crop yields & contained lower weed densities & less weed dry matter compared with sole-cropped sorghum (Abraham and Singh, 1984)
- Allelopathy – the stimulatory or inhibitory effect of chemical compounds produced by one plant on another
- Phytotoxic chemicals can enter the environment via volatilisation, foliar leaching, root exudation, residue decomposition or leaching from plant litter
- Allelochemicals can inhibit/retard germination, reduce plant growth & lower reproductive capacity
- Allelopathic effects can be inconsistent and narrow, but mustard/radish/rye often cited as effective species

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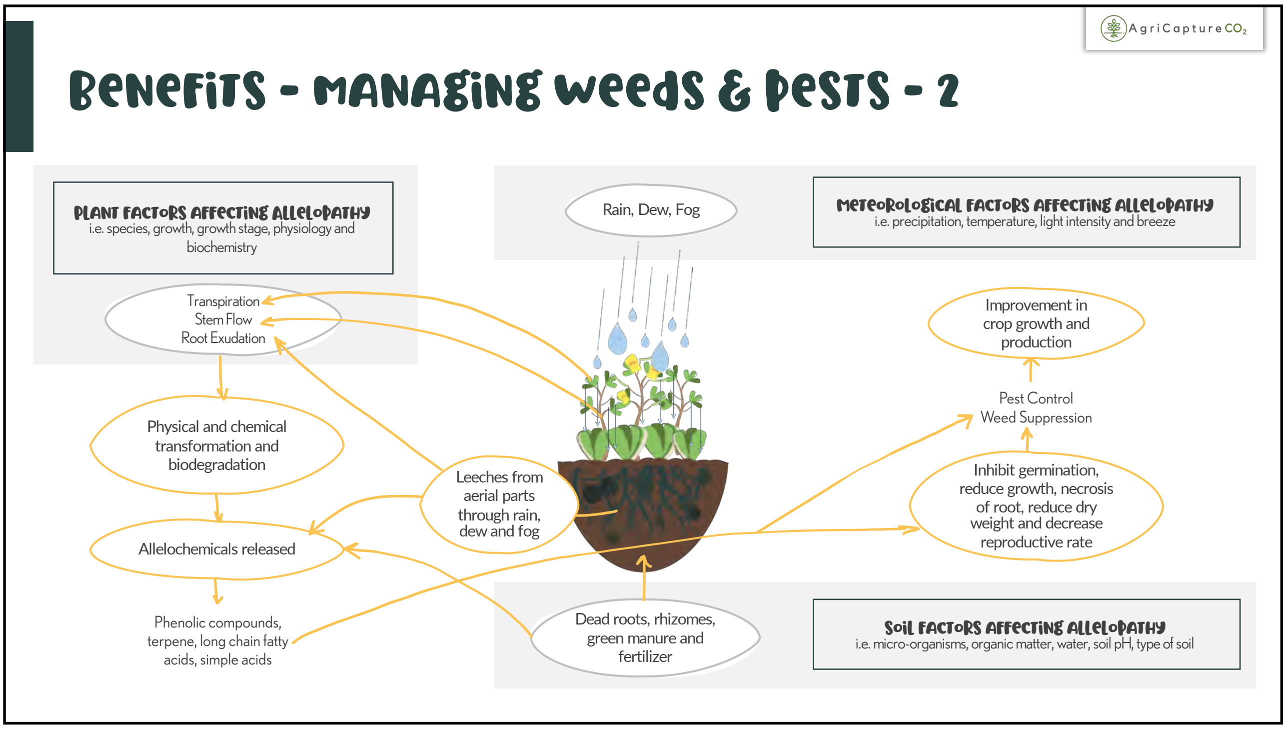
AgriCapture CO2
Benefits - Managing weeds & pests - 2
Plant factors affecting allelopathy
i.e. species, growth, growth stage, physiology and biochemistry
Rain, Dew, Fog
Meteorological factors affecting allelopathy
i.e. precipitation, temperature, light intensity and breeze
Transpiration
Stem Flow
Root Exudation
Improvement in crop growth and production
Pest Control
Weed Suppression
Physical and chemical transformation and biodegradation
Leeches from aerial parts through rain, dew and fog
Inhibit germination, reduce growth, necrosis of root, reduce dry weight and decrease reproductive rate
Allelochemicals released
Phenolic compounds, terpene, long chain fatty acids, simple acids
Dead roots, rhizomes, green manure and fertilizer
Soil factors affecting allelopathy
i.e. micro-organisms, organic matter, water, soil pH, type of soil

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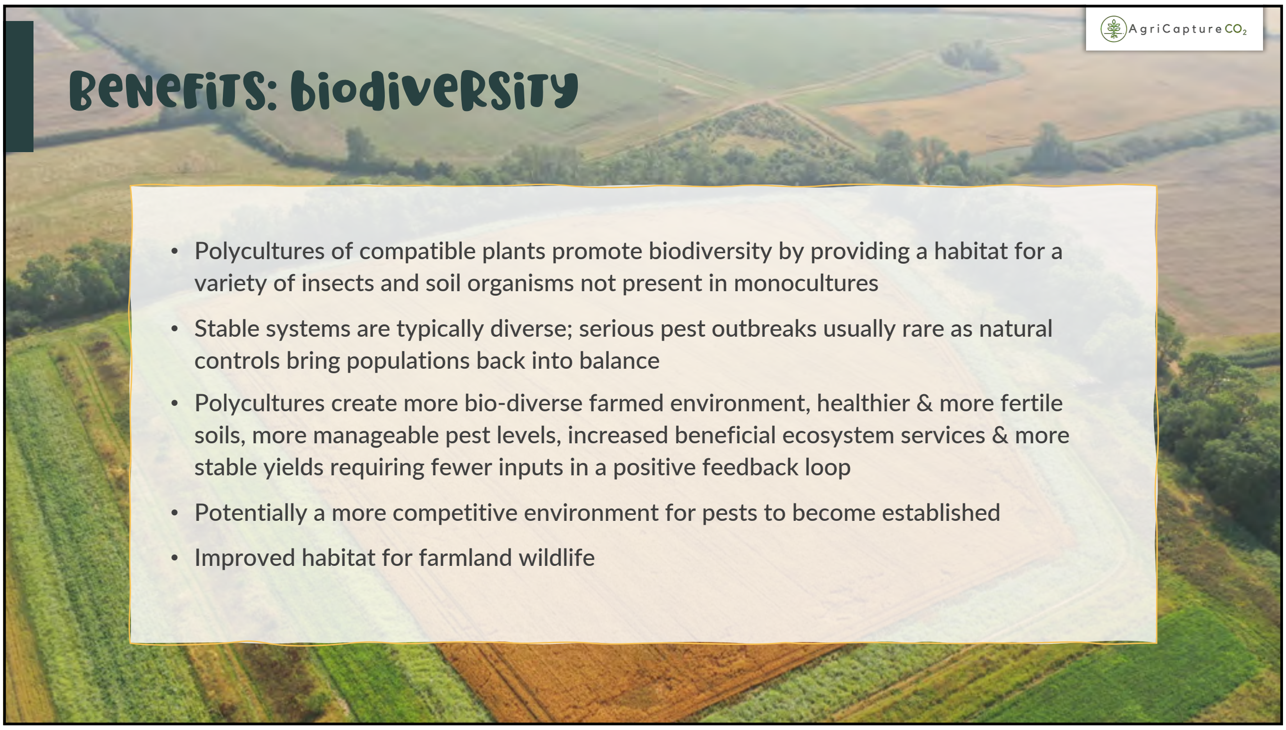
AgriCapture CO2
Benefits: biodiversity
• Polycultures of compatible plants promote biodiversity by providing a habitat for a variety of insects and soil organisms not present in monocultures
• Stable systems are typically diverse; serious pest outbreaks usually rare as natural controls bring populations back into balance
• Polycultures create more bio-diverse farmed environment, healthier & more fertile soils, more manageable pest levels, increased beneficial ecosystem services & more stable yields requiring fewer inputs in a positive feedback loop
• Potentially a more competitive environment for pests to become established
• Improved habitat for farmland wildlife

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Benefits: biodiversity

- Wheat/faba bean intercropping experiment in Germany as part of DIVERSify (Brandmeier et al, 2021)
- High/low intensity management of monocrops & polycrops
- Polycrops increased abundance & diversity of arthropods – especially pollinator & natural enemies
- Low-input monocultures lower in arthropod diversity vs polycultures - though not necessarily in abundance (indicating impact of synthetic inputs)
- Monocrop yields were higher – but total yield of intercropped plots (land equivalent ratio) were higher
- Demonstrates potential for biodiversity & yield in polycultures

DIVERSify

Results from the EU Horizon 2020 DIVERSify project

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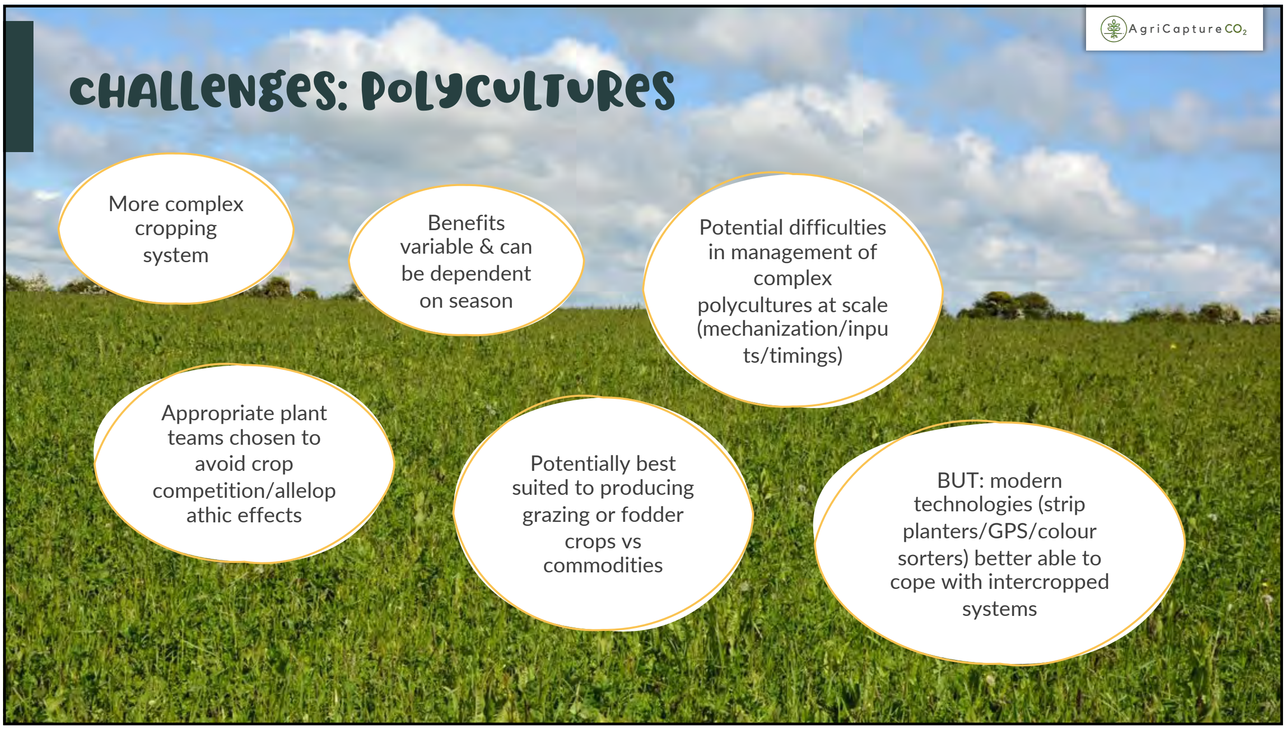
Challenges: polycultures



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AgriCapture CO2
Bedankt
Efharisto poli
Hvala vam
Merci
Danke
Dziękuję wam
Thank you

37

Healthy Soil · Healthy Crops · Healthy Businesses

5 Principles of Regenerative Agriculture

Optimise Synthetic PPP Use

MODULES: BIOLOGICAL DIVERSITY, REDUCED SOIL DISTURBANCE

AgriCapture CO2 · GWCT THE ALLERTON PROJECT

1

2

Background

- Synthetic Plant Protection Products (PPPs) are chemicals used to protect crops against weeds, insect pests & disease
- Important tools to help produce affordable, safe & sustainable food in most production systems
- However, broad agreement that they have been over-utilised in the age of 'chemical agriculture' since the 1960s which has contributed to ecological loss, poor cultural practice & target pest resistance
- Associated carbon footprint of production & application
- Potential cumulative impact on soil biome
- Impact on beneficial crop pest predators & habitat
- Ongoing loss of active ingredients in the EU & UK highlight need to improve cultural practices of pest control

3

Background: Carbon Footprint

- Synthetic PPPs a relatively small % of crop carbon footprint
- Average 94kg/ha carbon dioxide equivalent (CO2e) in UK arable cropping (Audsley et al, 2009)
- 100-200 MJ/t of crop
- Approx 9% total energy usage
- Range from 6% (triticale) to 16% potatoes. Lower for spring cropping
- Based on data from Green, 1987. Published data indicates improved energy efficiency of up to 47% in modern manufacturing processes
- Also dependent on energy type, e.g. renewable vs coal

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Background: Carbon Footprint

Table 1. Standard pesticide energy input to arable crops, MJ per hectare

	Fungicide	Herbicide	Insecticide	Molluscide	Growth regulator	Seed treatment	TOTAL
Wheat	475	792	28	11	340	35	**1681**
Winter barley	301	802	10	2	230	15	**1359**
Spring barley	254	225	6	0	18	14	**516**
Oats	130	154	6	0	201	21	**512**
Rye	85	1005	11	2	97	20	**1220**
Triticale	63	248	3	0	36	7	**357**
Oilseed rape	188	752	17	29	0	15	**1001**
Linseed	42	756	4	0	0	132	**934**
Potatoes	2912	896	751	37	132	154	**4883**
Peas	330	979	31	0	0	60	**1401**
Beans	363	645	15	1	0	0	**1025**
Sugar beet	66	2283	18	1	0	300	**2667**
Set-aside	32	395	3	5	1	4	**439**
Forage Maize	0	540	4	1	0	27	**571**
Weighted average	**396**	**706**	**41**	**10**	**175**	**36**	**1364**
Weighted average pesticide production energy, MJ/kg ai							
	423	**386**	**274**	**154**	**276**	**511**	**370**

A factor of 0.069 kg CO_2 equivalent per MJ pesticide energy can be used to convert these to the Global Warming Potential (100 years). The pesticide energy input of 1364 MJ/ha thus corresponds to a weighted average greenhouse gas emission of 94 kg CO_2 equivalent per hectare of arable crop.

From Audsley et al, 2009. 'Estimation of the greenhouse gas emissions from agricultural pesticide manufacture and use'.

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Background: Carbon Footprint

	Bread Wheat	Feed Wheat	Winter Barley	Spring Barley	Oilseed Rape	Potatoes maincrop	Potatoes 1st Earlies	Potatoes 2nd Earlies	All potatoes	Field Beans	Maize Silage
Summarised values per t											
Energy used, MJ	2567	2351	2467	22478	5468	1531	1,493	878	1465	2602	1732
GWP, kg 100 year CO_2e	551	491	449	399	1131	150	216	115	165	491	325
EP, kg PO_4 Equiv.	2.9	2.8	2.3	2.0	8.6	0.4	2.0	0.5	0.9	5.8	1.8
AP, kg SO_2 Equiv.	2.6	2.2	2.2	1.4	7.4	0.5	0.6	0.3	0.5	2.2	1.2
Pesticides used, dose ha	0.8	0.8	0.8	0.3	1.0	0.4	0.6	0.4	0.5	1.2	0.3
Abiotic depletion, kg Sb Equiv.	1.3	1.2	1.3	1.2	2.5	0.9	0.6	0.4	0.8	1.4	1.7
Land, ha	0.14	0.13	0.16	0.18	0.32	0.02	0.04	0.04	0.03	0.31	0.09
Proportion of emission from pesticides, %											
GWP, kg 100 year CO_2e	**2.9**	**3.0**	**3.5**	**1.8**	**1.9**	**6.5**	**6.7**	**9.3**		**4.4**	**1.1**
Summary of energy consumption by activity, %											
Field diesel	24	25	27	32	26	22	45	43	30	52	29
Machinery manufacture	10	11	12	14	10	7	13	13	9	22	10
Crop storage & processing	5	5	6	7	3	45	0	0	29	6	4
Pesticide manufacture	**8.9**	**9.2**	**8.7**	**4.1**	**6.5**	**8.2**	**12.5**	**12.5**	**9.8**	**12.5**	**3.1**
Fertiliser manufacture	52	50	47	43	55	18	28	27	21	7	54
Field diesel (or drying fuel), MJ/t											
Cultivation	396	358	415	455	879	110	230	118		882	270
Spraying	53	48	42	33	114	22	37	24		81	46
Fertiliser application	54	49	60	69	121	91	137	84		124	36
Harvest	136	124	147	164	284	71	175	98		276	142
Grain storage	115	109	128	128	131	525	0	0		141	76
Manufacturing, MJ/t											
Cultivation	134	121	142	158	292	27	57	29		295	89
Spraying	41	37	32	25	89	14	22	15		63	36
Fertiliser application	17	15	19	20	43	10	14	9		33	10
Harvest	89	81	95	107	137	40	73	42		184	37
Grain storage	21	20	20	20	20	70	0	0		21	0
Pesticide manufacture	**240**	**217**	**214**	**93**	**353**	**108**	**159**	**116**		**325**	**53**
Fertiliser manufacture	1390	1172	1153	976	3004	235	365	205		179	938

GWP= Global Warming Potential, EP= Eutrophication Potential, AP = Acidification Potential

Life cycle inventory of major crops (per tonne at farm gate) UK. (Audsley et al, 2009)

Carbon footprint of spray applications relatively small vs cultivations, harvest & storage

Synthetic nitrogen much more significant

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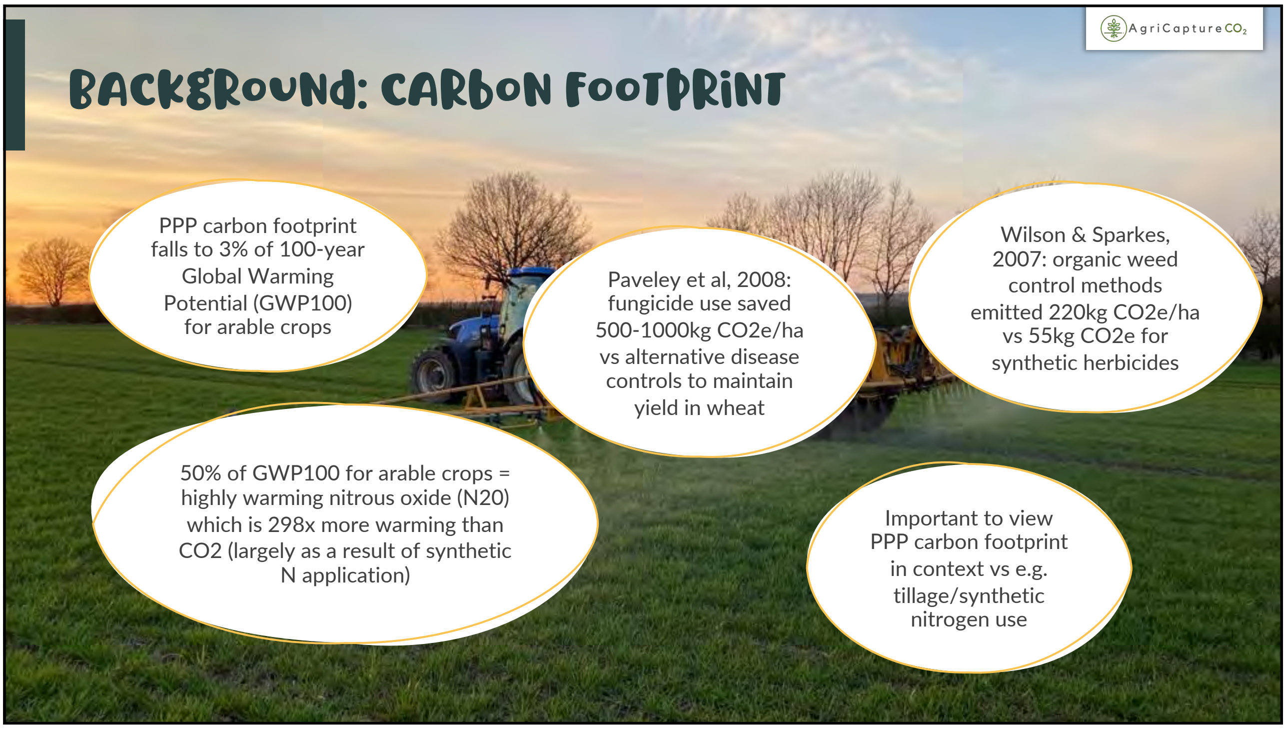
AgriCapture CO2
BACKGROUND: CARBON FOOTPRINT
PPP carbon footprint falls to 3% of 100-year Global Warming Potential (GWP100) for arable crops
Paveley et al, 2008: fungicide use saved 500-1000kg CO2e/ha vs alternative disease controls to maintain yield in wheat
Wilson & Sparkes, 2007: organic weed control methods emitted 220kg CO2e/ha vs 55kg CO2e for synthetic herbicides
50% of GWP100 for arable crops = highly warming nitrous oxide (N20) which is 298x more warming than CO2 (largely as a result of synthetic N application)
Important to view PPP carbon footprint in context vs e.g. tillage/synthetic nitrogen use

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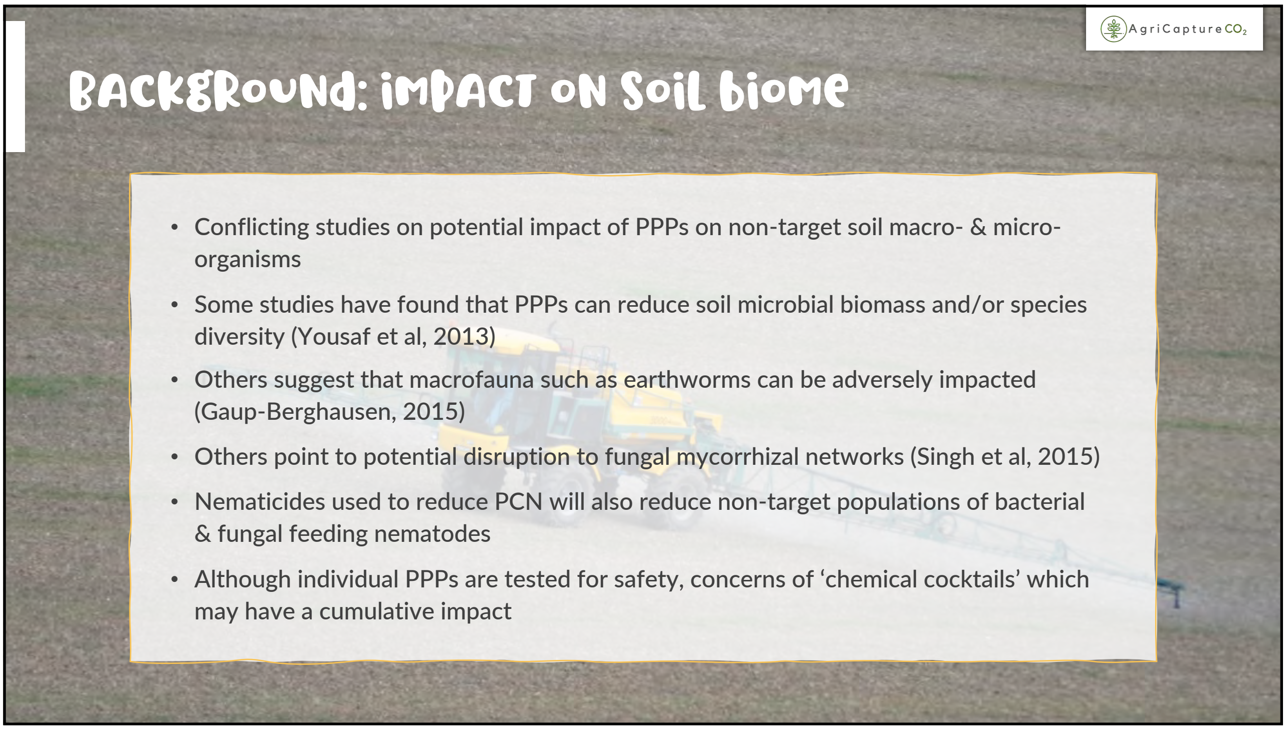
AgriCapture CO2
BACKGROUND: IMPACT ON SOIL BIOME
• Conflicting studies on potential impact of PPPs on non-target soil macro- & micro-organisms
• Some studies have found that PPPs can reduce soil microbial biomass and/or species diversity (Yousaf et al, 2013)
• Others suggest that macrofauna such as earthworms can be adversely impacted (Gaup-Berghausen, 2015)
• Others point to potential disruption to fungal mycorrhizal networks (Singh et al, 2015)
• Nematicides used to reduce PCN will also reduce non-target populations of bacterial & fungal feeding nematodes
• Although individual PPPs are tested for safety, concerns of 'chemical cocktails' which may have a cumulative impact

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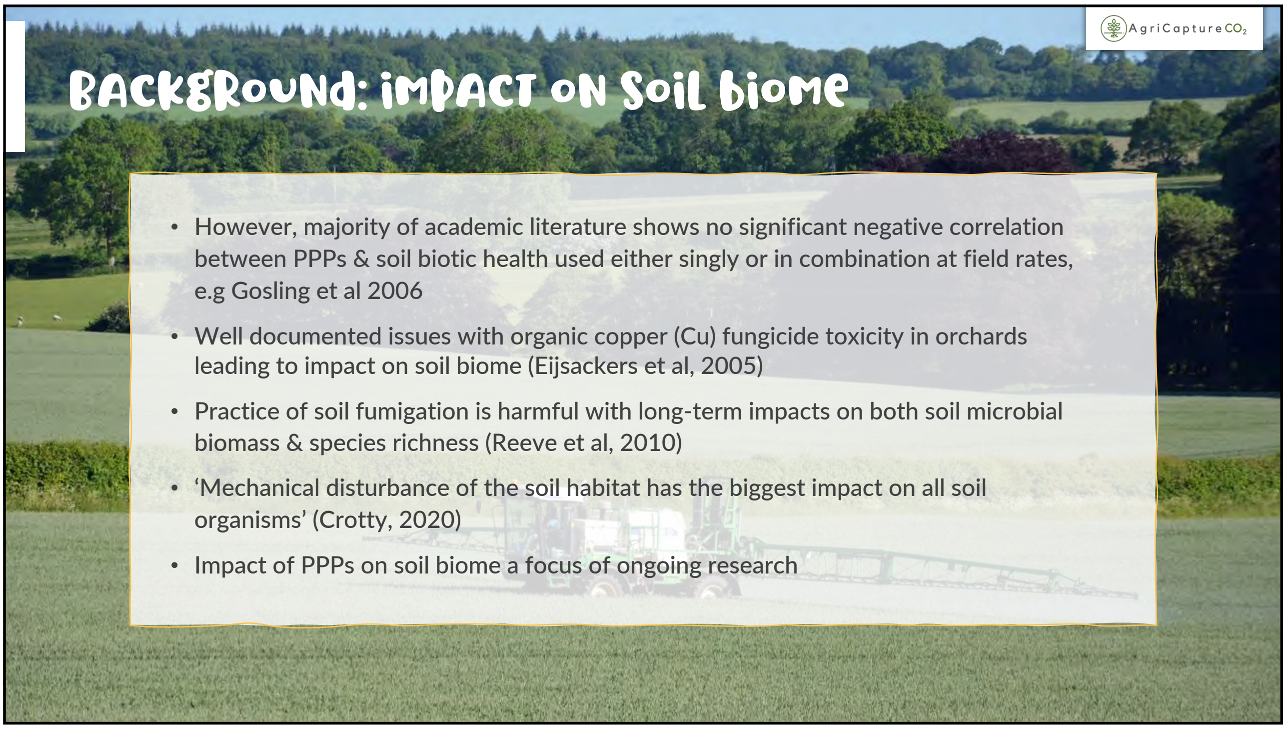
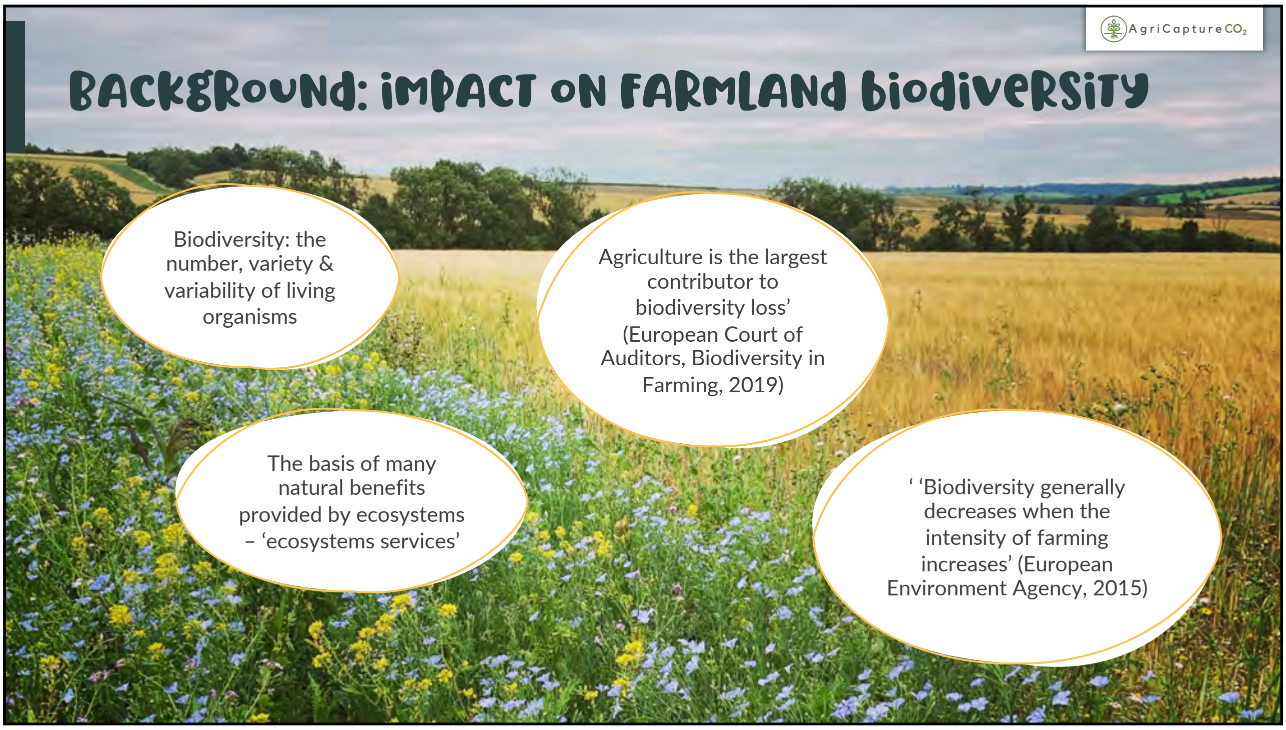

AgriCaptureCO_2
Background: impact on Soil biome
• However, majority of academic literature shows no significant negative correlation between PPPs & soil biotic health used either singly or in combination at field rates, e.g Gosling et al 2006
• Well documented issues with organic copper (Cu) fungicide toxicity in orchards leading to impact on soil biome (Eijsackers et al, 2005)
• Practice of soil fumigation is harmful with long-term impacts on both soil microbial biomass & species richness (Reeve et al, 2010)
• 'Mechanical disturbance of the soil habitat has the biggest impact on all soil organisms' (Crotty, 2020)
• Impact of PPPs on soil biome a focus of ongoing research

9


AgriCaptureCO_2
Background: impact on farmland biodiversity
Biodiversity: the number, variety & variability of living organisms
Agriculture is the largest contributor to biodiversity loss' (European Court of Auditors, Biodiversity in Farming, 2019)
The basis of many natural benefits provided by ecosystems – 'ecosystems services'
' 'Biodiversity generally decreases when the intensity of farming increases' (European Environment Agency, 2015)

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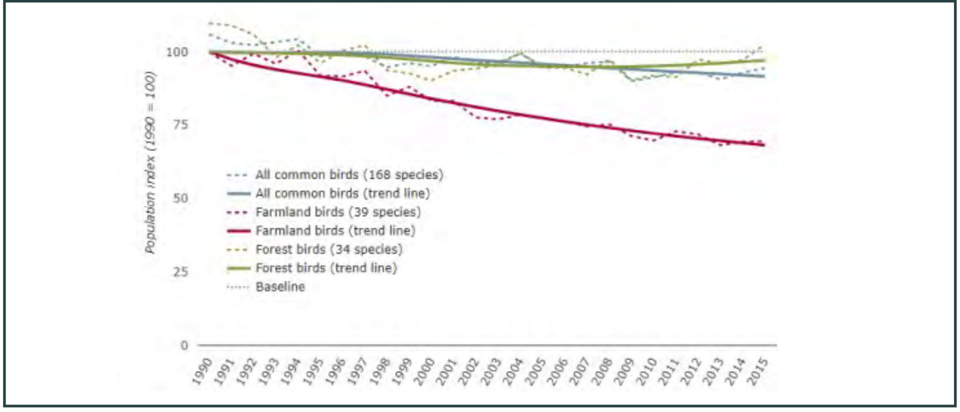
BACKGROUND: IMPACT ON FARMLAND BIODIVERSITY

EU Common Birds Index



Source: European Environment Agency

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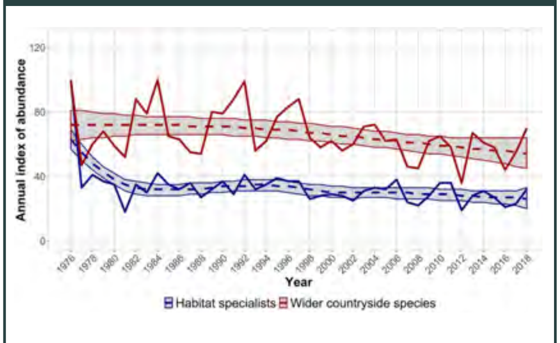
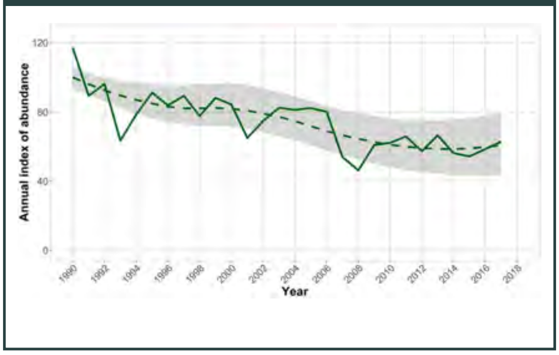
BACKGROUND: IMPACT ON FARMLAND BIODIVERSITY

UK butterfly index, 1976-2018



EU Grassland Butterfly Indicator, 1990-2017



Source, Warren et al, 2020

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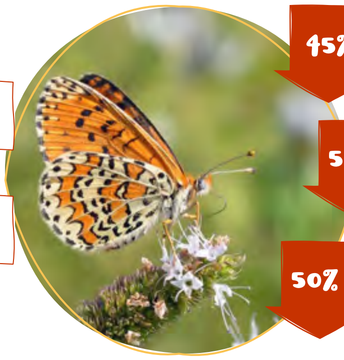
Background: impact on farmland biodiversity

- EU Commission uses Farmland Bird Index (FBI) to gauge biodiversity

30% population decrease since 1990

40% EU cropland bird species in decline



45% decline in FBI in UK since 1970

50% decline in UK butterfly numbers since 1976

50% decline in EU grassland butterfly numbers since 1990

- 'Pesticides of all types pose a clear hazard to soil invertebrates' with 70.5% of tested parameters indicating a negative impact on non-target species from a meta study of 400 studies (Gunstone et al, 2021)

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Background: impact on farmland biodiversity

- Habitat loss, climate change & modern farming practices all contributary factors in biodiversity declines
- Increase in PPP use – especially herbicides & insecticides – a significant factor in decline of farmland biodiversity, including wild plant species & invertebrates
- Impact on non-target species & entire food web
- Intensification of modern cropping systems has led to a decrease in aboveground & belowground biodiversity
- Increasing plant diversity enhances soil biodiversity (McDaniel et al, 2014) leading to increased soil health & resilience

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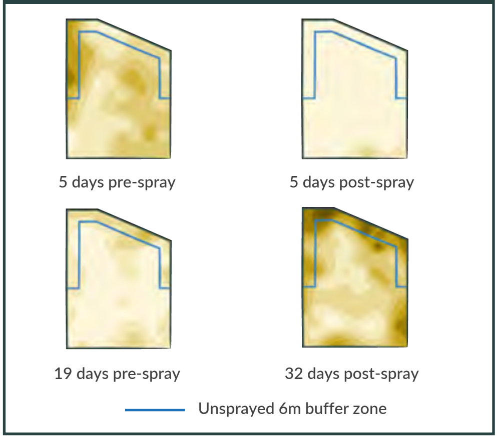
Background: Impact on farmland biodiversity

- GWCT IPM research measured the abundance & distribution of natural pest predators from the field to landscape scales
- Primarily located <60m from margins & in-field habitats
- Due to diversity of plants & habitat outside monocropped area
- An application of dimethoate insecticide severely reduced most species.
- Recovery was slow, with beneficial predator species recovering most slowly

Impact of the insecticide dimethoate on the distribution of beetles



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Background: How to optimise PPP use?

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Integrated Pest Management (IPM)

- 'Integrated Pest Management' is the careful consideration of all available plant protection methods and subsequent integration of appropriate measures that discourage the development of populations of harmful organisms and keep the use of plant protection products and other forms of intervention to levels that are economically and ecologically justified and reduce or minimise risks to human health and the environment.
- (Sustainable Use Directive, 2009)

LEAF Integrated Farm Management wheel

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Integrated Pest Management (IPM)

- EU Directive 2009/128/EC 'aims to achieve a sustainable use of pesticides in the EU by reducing the risks and impacts of pesticide use on human health and the environment and promoting the use of Integrated Pest Management (IPM) and of alternative approaches or techniques, such as non-chemical alternatives to pesticides'
- Many of the actions taken by member states under the Directive also relevant to the Biodiversity Strategy 2030 & the Farm to Fork Strategy
- EU countries required to adopt National Action Plans (NAPs) to implement the Directive
- Adopted into UK law post-Brexit

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Integrated Pest Management (IPM)

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- Aerial spraying is banned and exceptions are only granted under strict conditions
- Four million farmers have been trained to use pesticide safely
- 900,000 sprayers have ben tested for accurate and safe application
- The number of EU approved low risk and/or non-chemical pesticide substances has doubled since 2009
- Pesticide use us prohibited or minimised in public parks, sports grounds, hospitals and schools
- Rivers, lakes, ground water and drinking water must be protected against pesticides
- Farmers must implement Integrated Pest Management and give preference to non-chemical methods if they provide satisfactory pest control
- Organic farming crops now cover 6.7% of the EU Agricultural Area and organic production has increased by 18.7% from 2012 to 2016according to Eurostat

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Integrated Pest Management (IPM)

AgriCapture CO2

- IPM can play a significant role in making farming more environmentally, economically & socially sustainable
- It allows producers to make informed decisions to manage crops & minimise reliance on pesticides
- IPM can help maintain biodiversity, decrease pollution & lower the build-up of pesticide resistance as well as potentially reduce costs/increase margins
- The diversity of solutions available in IPM helps ensure the long-term sustainability of control measures
- Targeted use of PPPs as a final resort

IPM Hierarchy

1. Achieving prevention and suppression of harmful organisms
2. Monitoring of harmful organisms
3. Decisions made based on monitoring and thresholds
4. Non-chemical methods
5. Pesticide Selection
6. Reduced Use
7. Anti-resistance strategies
8. Evaluation
9. PREVENT – DETECT – CONTROL

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Integrated Pest Management (IPM)

- Select low-risk locations
- Healthy rotations (including cover & break cropping)
- Cultivation techniques
- Crop varieties & varietal mixtures
- Seed rates & plant densities
- Sowing date & conditions
- Machinery hygiene
- Effective field nutrition
- Effective field drainage
- Protection & enhancement of beneficial field organisms
- Physical/manual weed control
- Mulching & green covers
- Biopesticides/stimulants
- Monitoring & application of pest thresholds
- Polycultures
- Trap crops, allelopathy & biofumigation
- Organic amendments
- Improve soil health
- Use clean & tested seeds/saplings
- Spot treatment of injurious species, e.g. weed wiping
- Reduced rate applications of PPPs
- Precision/variable rate application
- Preventative action based on risk factors, e.g. weather, variety

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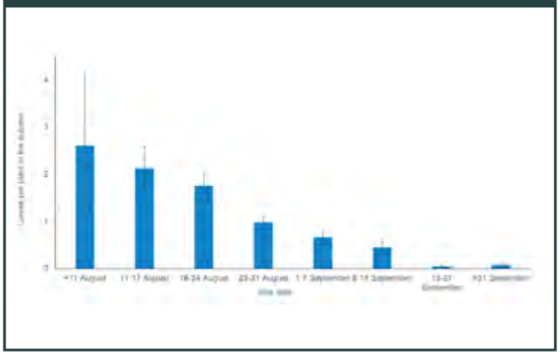
Integrated Pest Management (IPM)

- Example of drilling date in oilseed rape as a cultural pest control method (White et al, 2020)
- Cabbage Stem Flea Beetle (CSFB) pressure reduces Aug-Sept meaning fewer eggs are laid
- Hatch more slowly as temperatures drop & larval development is slower
- Lower levels of crop damage from emerging larvae in the spring from later drilled crops
- Later drilled crops may also miss main predation window from adult CSFB in the autumn
- Reduction in need for insecticides in a target pest with high resistance
- Later drilling/emergence also beneficial vs autumn disease pressures

OSR drilling date vs CSFB larval infestation (AHDB UK)



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Integrated Pest Management (IPM)

- 'IPM Decisions' www.ipmdecisions.net
- 27-partner consortium, 5 year EU Horizon 2020 project (from June 2019) to create an online platform that is easy to use for the monitoring and management of pests
- The online platform will be available across the EU with Decision Support Systems, data, tools & resources tailored to individual regions
- Form a community of users & stakeholders – the IPM decisions network

IPM DECISIONS

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Precision Applications

Manual application/ weed wiping

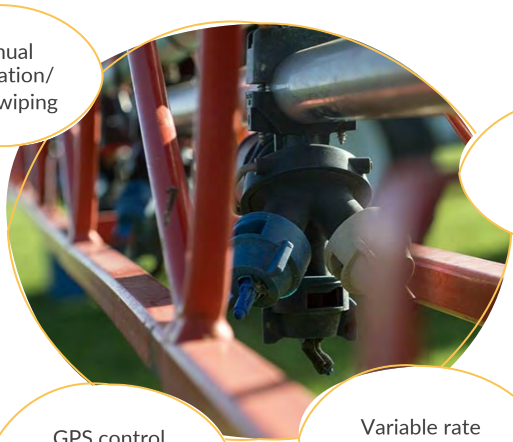
AI & autonomous robotics

Low drift spray technology (e.g. 3* rated nozzles)

Intelligent spot-spraying camera technology

GPS control with auto section on/off

Variable rate PPP application



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Precision Applications

- Intelligent spot spraying
- 12 high-resolution cameras along boom utilise Red, Green, Blue (RGB) technology & onboard CPUs
- Detect all plants against soil ('green on brown') or weed plants within a crop ('green on green')
- Individually actuated spray nozzles
- Reductions 70-90% in herbicide use
- Split tanks & dual lines enable whole-field applications, e.g. fungicide, simultaneously

Photo – Dyson Farming with the Bilberry Greenview system (2021)

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Precision Applications

- Guided band spraying/weeding
- Combination of mechanical weed control between vegetable rows & herbicide application within rows
- Front-mounted spray tank
- Reductions in herbicide applications 40-60%
- GPS guided with sectional shut-off
- Avoids blanket prophylactic applications

Photo – Lemken Steketee 'EC-Weeder'

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Precision Applications

- 'Per plant farming'
- Small Robot Company (UK)
- Three phase system:
  - 'Tom' – scans, monitors & measures 'green on green' weeds
  - 'Wilma' – AI operating system, analysis & advice engine with a per plant field map
  - 'Dick' – targets individual weeds with electric current
- Eliminates soil compaction
- Beneficial/non-injurious weeds can be retained to increase field biodiversity


Photo – Tom & Dick, Small Robot Company

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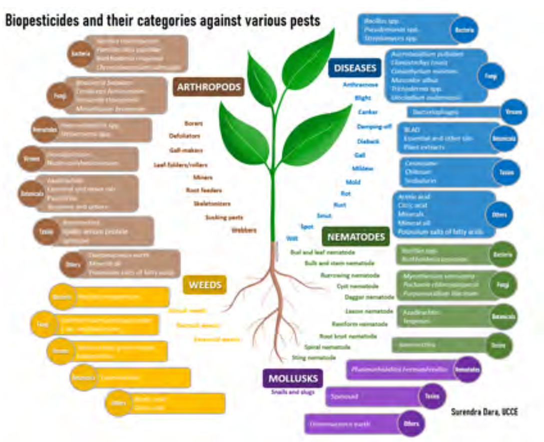
Biopesticides

- Crop protection products based on living micro-organisms, plant extracts and other natural compounds such as insect alarm pheromones
- 3 main types: **micro-organisms, botanicals & semiochemicals**
- Increasing focus on biopesticides due to:
- Concern over environmental impact of PPPs
- More stringent rules of PPP safety
- Pressure for zero detectable residues on fresh produce
- PPP resistance
- Lack of new synthetic PPPs coming to market



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Biopesticides

Micro-organisms

Bacteria, fungi, oomycetes & viruses are all used for the biological control of pests, plant pathogens & weeds

Insecticides	Fungicides	Herbicides
The most widely used microbial insecticide is the pathogenic bacterium Bacillus thuringiensis (Bt) which produces an insecticidal protein crystal during bacterial spore formation that can be sprayed against pest targets	Micro-organisms used against plant pathogens include the fungus Trichoderma, an antagonist of Rhizoctonia, Pythium, Fusarium & other soil-borne pathogens	Based on fungi such as Chondrostereum purpureum, have been developed that can infect multiple weed species

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Biopesticides

Botanicals

- Plant extracts. Plants produce a wide variety of secondary metabolites with activity against crop pests and/or disease. One of the most widely used botanicals is neem oil, an insecticide extracted from seeds of the neem tree.
- It repels a wide variety of pests such as aphids, thrips & cabbage worms

Semiochemicals

- Chemical compounds produced by an organism which induce a behavioural change in organisms of the same species or a different species. The most widely used semiochemicals for crop protection are insect sex pheromones, which are deployed in pest monitoring, mating disruption & trapping

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Biopesticides

Benefits

- Little to no toxic residue
- Minimal/no re-entry/handling interval after application
- Can be applied with existing equipment
- Generally low risk to natural crop pest predators/non target species
- Low-risk supplementary treatment to aid predators in high pest pressure situations
- Risk of target resistance considered to be low
- Some microbial biopesticides can become self-replicating, giving potential ongoing control
- Generally lower development costs & simpler route to market: should encourage increasing availability in coming years

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AgriCaptureCO_2

Biopesticides

Drawbacks

- A slower rate of control & often a lower efficacy/shorter persistence vs conventional PPPs
- Greater susceptibility to adverse environmental conditions
- Because biopesticides are not as "robust" as conventional PPPs, they require a greater level of knowledge on behalf of the grower to use them effectively
- Low tolerance for cosmetic pest/disease damage in some sectors, e.g. horticulture
- Generally effective as one strand of comprehensive & robust IPM strategy
- Persistence affected by a range of factors including UV radiation exposure, temperature, rainfall, humidity & the microbiota & chemistry of the plant surface or soil. In general, microbial biopesticides do not persist for long on foliar surfaces, but for longer in soil

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TRAINING & BEST PRACTICE

- Training an important element of IPM to encourage optimised use of PPPs. In the UK:

BASIS Professional Register	City & Guilds NPTC	City & Guilds NRoSO	NSTS
a charitable organisation committed to raising professional standards across land management & food production	provide land-based vocational qualifications, e.g. to enable operation of crop sprayers	use CPD to ensure ongoing training in use of PPPs	the National Sprayer Testing Scheme to ensure correct functioning & operation of PPP application machinery

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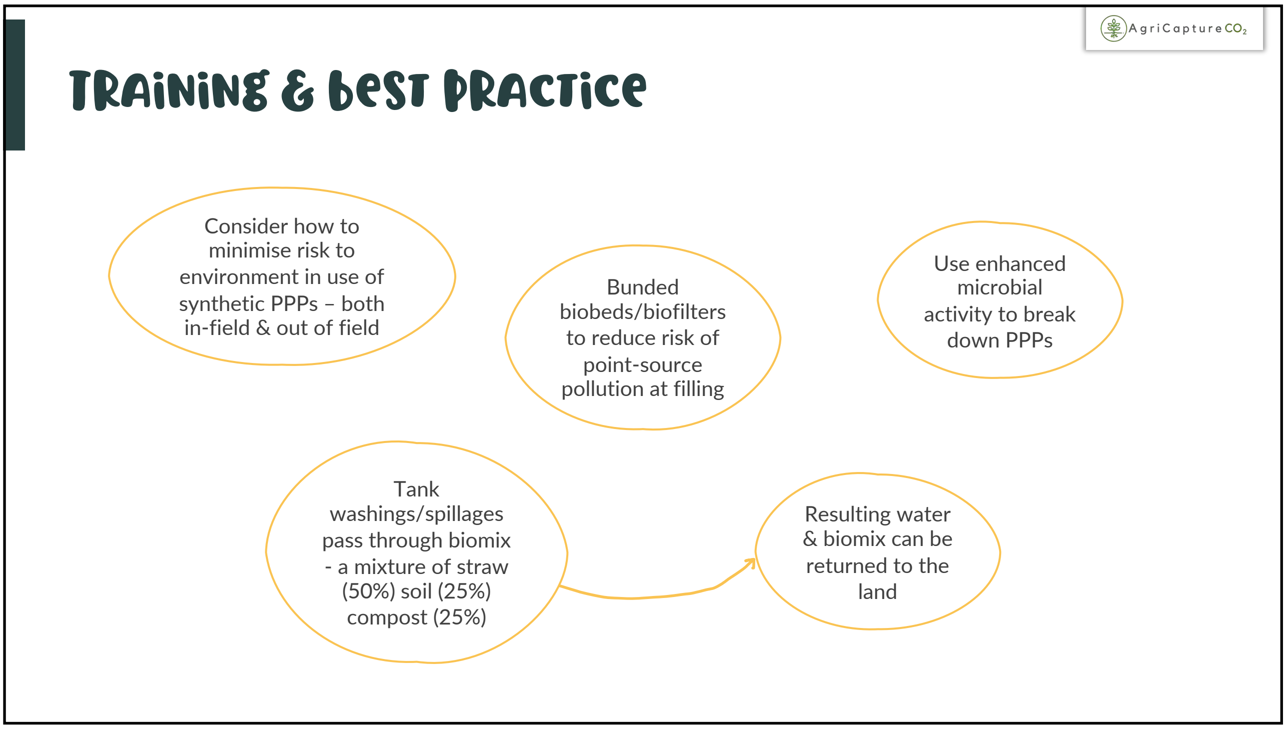
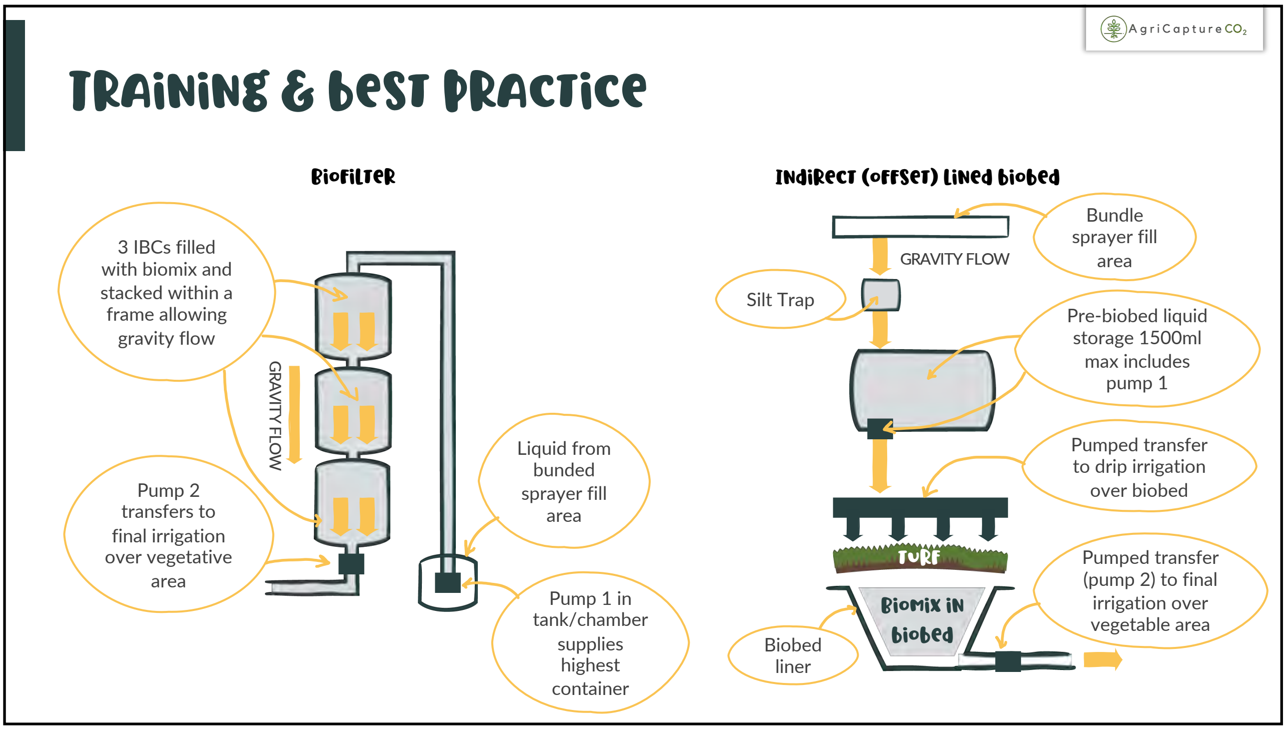
TRAINING & BEST PRACTICE

- UK industry schemes to promote optimised use of both individual active ingredients & PPPs more generally
- Promote better environmental stewardship
- Voluntary Initiative (VI) is an Industry-led programme to promote the responsible use of PPPs via IPM approach to sustainable agriculture in line with the Sustainable Use Directive (SUD)

34


AgriCapture CO2
TRAINING & BEST PRACTICE
Consider how to minimise risk to environment in use of synthetic PPPs – both in-field & out of field
Bunded biobeds/biofilters to reduce risk of point-source pollution at filling
Use enhanced microbial activity to break down PPPs
Tank washings/spillages pass through biomix - a mixture of straw (50%) soil (25%) compost (25%)
Resulting water & biomix can be returned to the land

35


AgriCapture CO2
TRAINING & BEST PRACTICE
BIOFILTER
3 IBCs filled with biomix and stacked within a frame allowing gravity flow
GRAVITY FLOW
Pump 2 transfers to final irrigation over vegetative area
Liquid from bunded sprayer fill area
Pump 1 in tank/chamber supplies highest container
INDIRECT (OFFSET) LINED BIOBED
Bundle sprayer fill area
GRAVITY FLOW
Silt Trap
Pre-biobed liquid storage 1500ml max includes pump 1
Pumped transfer to drip irrigation over biobed
TURF
Biomix in biobed
Biobed liner
Pumped transfer (pump 2) to final irrigation over vegetable area

36

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BEDANKT EFHARISTO POLI

HVALA VAM MERCI

DANKE DZIĘKUJĘ WAM

THANK YOU

gilab SatAgro ONE CARBON WORLD EEB European Environmental Bureau L.E.A.F. GWCT THE ALLERTON PROJECT planet.

ELGO - DIMITRA HELLENIC AGRICULTURAL ORGANIZATION - DIMITRA mellow yellow EnvirometriX Lancashire County Council AGRICULTURAL UNIVERSITY OF ATHENS ARTHUR'S LEGAL Challenge the Status Quo

37

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5 PRINCIPLES OF REGENERATIVE AGRICULTURE

HEALTHY SOIL · HEALTHY CROPS · HEALTHY BUSINESSES

Reduce Soil disturbance

MODULES: SOIL PROTECTION

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1

2

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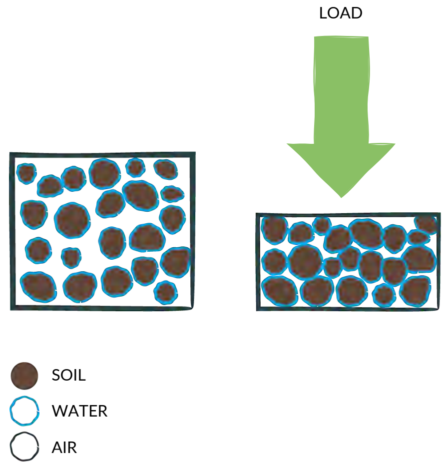
What is Soil Compaction?

- Pressure causing aggregates/individual soil particles closer together
- Soil pore spaces are compressed
- Both shallow & subsoil compaction
- Increased soil bulk density
- More clay, heavier soils at greater risk of compaction – especially when wet
- Best to avoid compaction occurring rather than remedy after the event



Soil Compaction as the result of applied pressure

3

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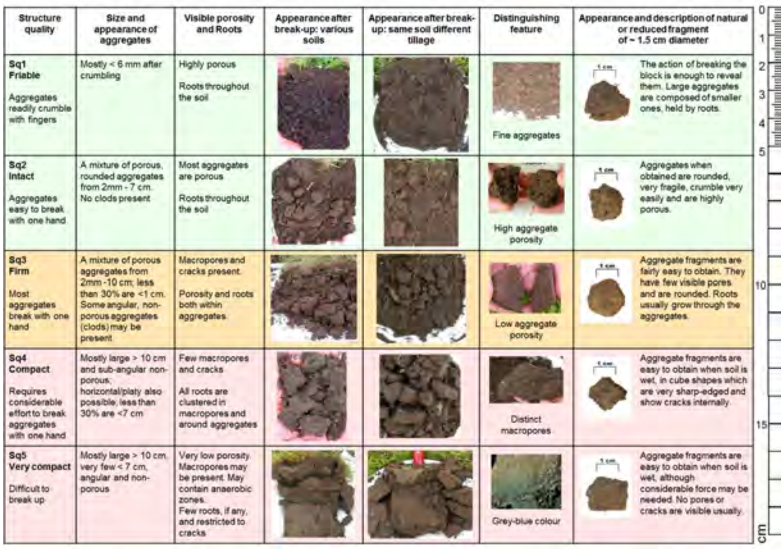
Visual Evaluation of Soil Structure (VESS)



Structure quality	Size and appearance of aggregates	Visible porosity and Roots	Appearance after break-up: various soils	Appearance after break-up: same soil different tillage	Distinguishing feature	Appearance and description of natural or reduced fragment of ~ 1.5 cm diameter
Sq1 Friable Aggregates readily crumble with fingers	Mostly < 6 mm after crumbling	Highly porous. Roots throughout the soil			Fine aggregates	1 cm. The action of breaking the block is enough to reveal them. Large aggregates are composed of smaller ones, held by roots.
Sq2 Intact Aggregates easy to break with one hand	A mixture of porous, rounded aggregates from 2mm - 7 cm. No clods present	Most aggregates are porous. Roots throughout the soil			High aggregate porosity	1 cm. Aggregates when obtained are rounded, very fragile, crumble very easily and are highly porous.
Sq3 Firm Most aggregates break with one hand	A mixture of porous aggregates from 2mm -10 cm; less than 30% are <1 cm. Some angular, non-porous aggregates (clods) may be present	Macropores and cracks present. Porosity and roots both within aggregates.			Low aggregate porosity	1 cm. Aggregate fragments are fairly easy to obtain. They have few visible pores and are rounded. Roots usually grow through the aggregates.
Sq4 Compact Requires considerable effort to break aggregates with one hand	Mostly large > 10 cm and sub-angular non-porous; horizontal/platy also possible; less than 30% are <7 cm	Few macropores and cracks. All roots are clustered in macropores and around aggregates			Distinct macropores	1 cm. Aggregate fragments are easy to obtain when soil is wet, in cube shapes which are very sharp-edged and show cracks internally.
Sq5 Very compact Difficult to break up	Mostly large > 10 cm, very few < 7 cm, angular and non-porous	Very low porosity. Macropores may be present. May contain anaerobic zones. Few roots, if any, and restricted to cracks			Grey-blue colour	1 cm. Aggregate fragments are easy to obtain when soil is wet, although considerable force may be needed. No pores or cracks are visible usually.

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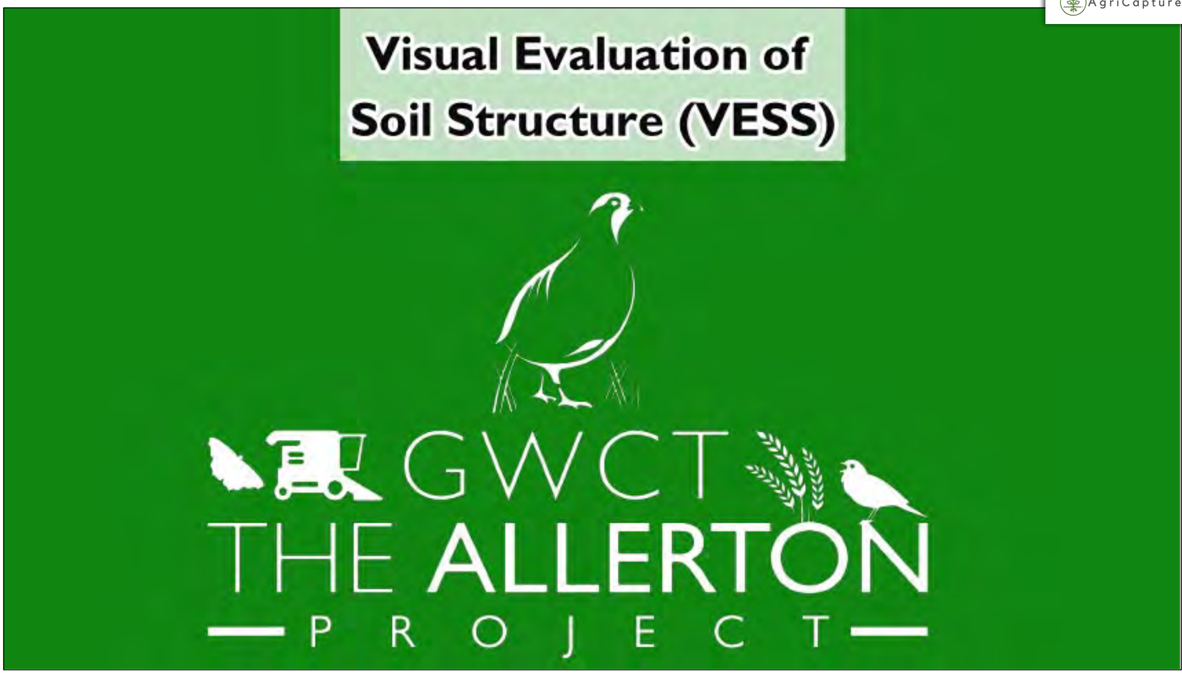

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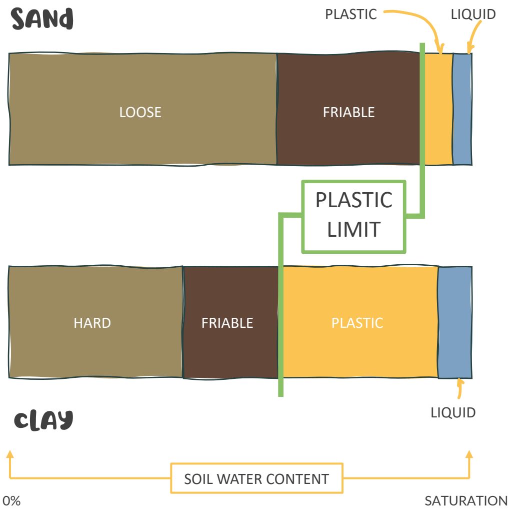
Soil consistency

- Soils can be regarded as **liquid, plastic** or **friable** depending on water content
- Around the **plastic limit** soils may become seriously compacted by heavy machinery & tillage
- Aggregates may be compacted into a smeared, dense mass
- Soil texture has a major influence on soil consistency – clay soils take longer to move from plastic to friable
- When soils are more friable (or frozen) they are more resistant to compaction and damage from machinery & tillage



Soil consistency states for a sand and for a clay soil

6

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WHAT PROBLEMS DOES SOIL COMPACTION CAUSE?

- Compacted soils have reduced pore spaces for gas & water exchange
- Degraded environment for soil micro-organisms leads to anaerobic soil conditions & release of nitrous oxide
- Soil biota – e.g. earthworms – also restricted in activities
- Reduced water infiltration & water holding capacity (waterlogging)
- Increased surface runoff and erosion – risk of fertiliser runoff increases by up to 60% (AHDB)
- Impeded root growth & reduced productivity
- Requirement for expensive remedial action

7

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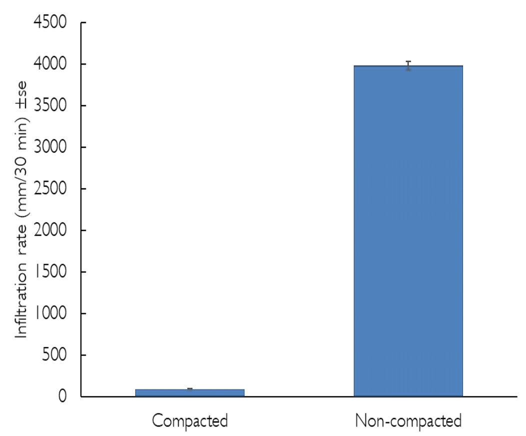
WHAT PROBLEMS DOES SOIL COMPACTION CAUSE? - 2

- Compaction & water infiltration in arable fields
- Data from 14 fields of varying soil types in the Eyebrook catchment, UK
- Significant risk of waterlogging, runoff & erosion



Source: EU H2020 SoilCare

GWCT THE ALLERTON PROJECT
SoilCare SOILCARE FOR PROFITABLE AND SUSTAINABLE CROP PRODUCTION IN EUROPE

8

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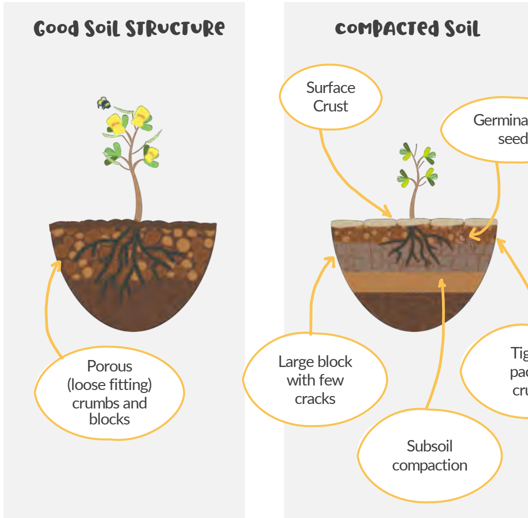
Restricted Rooting

- Compacted soil becomes hard under drying vs a well structured soil with large pores between aggregates
- 300psi threshold at which root growth ceases
- Roots require pore spaces >0.1mm to grow into & anchor
- In compacted soils, plants develop fewer, thicker & shallower roots with less fine hairs
- Inefficient at nutrient & water uptake
- Particular problem in drier climates/rain-fed systems where crops become prone to drought



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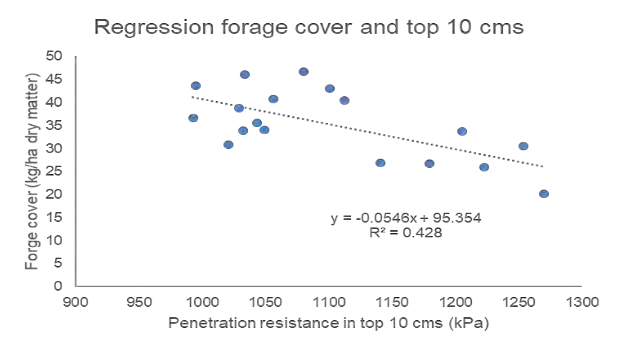
Restricted Rooting - 2

- Data taken from pasture in the Eyebrook catchment, UK
- Strong correlation for decreasing forage cover as compaction increases



Source: EU H2020 SoilCare

10

Shallow compaction

- Loss of soil aggregation from compaction by machinery
- Worsened by impact of reduced soil health by tillage (reduced structure & organic matter levels)
- Compaction most pronounced in wet, plastic soils
- Compacted soils (resulting from poor soil health caused by tillage) may leave a cloddy seedbed, requiring additional secondary tillage to create a fine tilth
- This may lead to surface sealing of the soil by rainfall due to lack of natural soil aggregates – a thin layer of tough compaction which may impede plant growth

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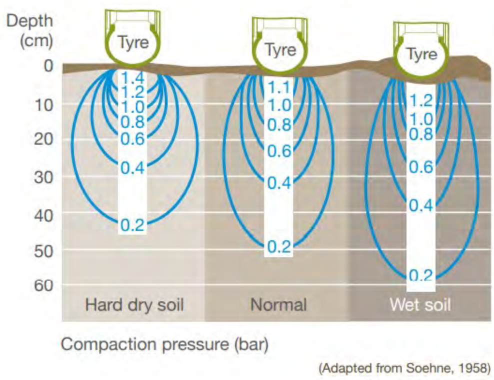
Subsoil compaction

- Subsoil generally wetter, more clay & lower SOM than topsoil: more prone to compaction
- Caused by surface traffic – a cone of compaction which varies depending on:
  - Soil type
  - Weight of machinery
  - Moisture content (plasticity of soil)
- Also caused by cultivation ('plough') pans - weight & shearing force of cultivation equipment can create compaction layers
- Tractor tyre in plough furrow also creates panning & compaction at further depth



Source: AHDB Soil Management for Horticulture (UK)

12

Livestock Poaching

- Surface compaction from livestock also a problem in wet conditions
- Cattle can leave 10-12cm deep depressions which lie in water
- High densities of sheep can create a compaction pan 2-6cm deep over a wide area
- Particularly in areas of greatest activity – around gateways/feeders/troughs
- Rotational/mob grazing at high stocking densities not a major risk factor due to short intensity of paddock rotation & benefits to soil health

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Ground Pressures

- A 4m implement pulled by a tractor with 710mm tyres will traffic 40% of a field – excluding headland turning (AHDB)
- Loads over 10t per axle at greater risk of creating subsoil compaction – keep machinery as light as possible
- Appropriate choice of tyres/tracks can reduce compaction associated with high axle loads
- Determine appropriate ballasted weight for each operation
- Consider use of dual tyres
- Consider use of improved flex/very high flex/hyperflex carcase tyres with lower pressures
- Consider use of Central Tyre Inflation Systems (CTIS)

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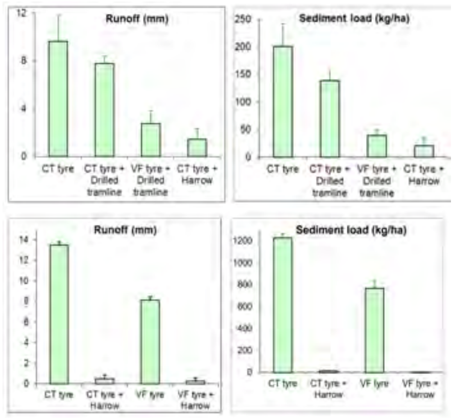
Mitigation measures

- AHDB (UK) study into mitigation measures for tramline management in cereals
- Concluded that Very Flexible (VF) tyres operating at half the pressure of conventional tyres (CT) were effective in reducing runoff & erosion
- Drilled tramlines & GPS operations also an option
- Rotary harrow used behind sprayer wheels very effective in all cases



Source: 'Reducing risks associated with autumn wheeling of combinable crops to mitigate runoff and diffuse pollution', AHDB 2014

15

Controlled traffic farming (CTF)

- Uses GPS guidance & concentrates cultivation, seed drill, harvesting & sprayer passes into dedicated pathways
- Reduces in-field wheelings & reduces soil compaction
- Tillage/drilling/harvesting widths divisible into the sprayer width
- Avoid random field trafficking even outside full CTF systems; retain annual tramlines, unload at field ends, avoid over-using entrances
- Adopting CTF reduces need for cultivations as less remedial work required
- Reduced tillage/direct drilling requires fewer passes to establish a crop

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Low disturbance subsoiling & sward lifting

- Sometimes mechanical alleviation of the soil profile may be necessary, especially in heavy soils
- Consider use of low disturbance implements to achieve vertical fissures through compacted layers with minimal disturbance of profile
- Excessive vertical lift height can rearrange soil profile and healthy structure can be lost
- Only loosen compacted areas & to depth required
- Ensure appropriate soil conditions
- Consider use of deep-rooting cover crops instead of mechanical cultivations, especially in lighter soils

17

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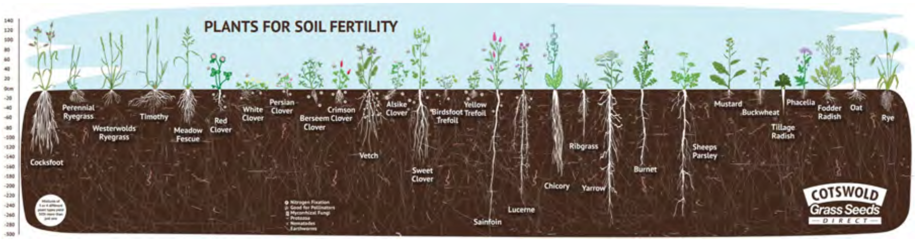
Cover crops to improve soil structure



- Cover crops with a vigorous, active root system can help open up soil structure
- Impacts vary with species, soil type and cropping system
- Shallower rooting species with fibrous roots (such as rye or some clovers) can create a friable surface structure
- Deeper rooting plants (often brassicas/broadleaves) can reduce compaction at depth (>20cm) but may require full-season fallow; ill suited to catch crops
- Finer roots of legumes can feed soil microbes while tap roots grow to depth & break pans

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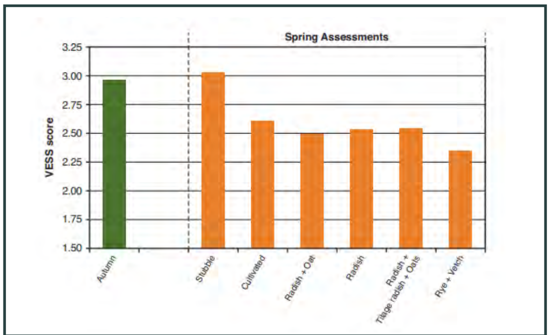
Cover crops to improve soil structure

- Improvements in soil structure allow crop roots to grow more easily and locate nutrients not otherwise available, improve water infiltration & reduce need for cultivations
- Cover crops provide food for soil biota, especially deep burrowing earthworms, to produce virtuous circle of biological soil structuring
- Diversity of organic inputs leads to greater diversity of soil microbial community with more diverse functional groups



The impact of a range of cover crops compared to an autumn. ‘farm standard’ cultivation on VESS (Visual Evaluation of Soil Structure) pre an post winter on Kellogg’s Origins™ site 2014/2014 (a lower VESS score is indicative of a better soil structure).

Source: ‘Cover Crops: a practical guide to soil & system improvement’ NIAB TAG & Kelloggs Origins™

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Reflections

- Compaction a major challenge to soil structure & health, a keystone of regenerative agriculture
- Applying nutrients to compacted soil is inefficient & increases risk of pollution as plants will be unable to utilize them
- Highly dependent on soil type & water content, but also management
- Best to adopt practices to avoid compaction rather than need to remedy
- Consider appropriate rotations, reduced tillage, use of cover crops, stocking system, timeliness of operations, tyre pressures/axle loads/ballasting & CTF before mechanical solutions

20


AgriCapture CO2
Bedankt
Efharisto poli
Hvala vam
Merci
Danke
Dziękuję wam
Thank you
gilab
SatAgro
One Carbon World
EEB European Environmental Bureau
GWCT The Allerton Project
planet.
ELGO - DIMITRA Hellenic Agricultural Organization - Dimitra
mellow yellow
EnvirometriX
Lancashire County Council
Agricultural University of Athens
Arthur's Legal

21

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5 PRINCIPLES OF REGENERATIVE AGRICULTURE

HEALTHY SOIL HEALTHY CROPS HEALTHY BUSINESSES

Reduced Tillage/No Till

Optimisation of Soil Management

MODULES: BIOLOGICAL DIVERSITY, SOIL PROTECTION, REDUCED SOIL DISTURBANCE

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1

2

Cultivations/Tillage

Any mechanical act to prepare or work soil to raise crops

3

Tillage options

Conventional:
Frequently involves inversion ploughing with the purpose of loosening the soil and burying weeds and residues from previous crop. Often followed by secondary tillage before drilling

Non-inversion tillage:
Often with discs or tines to prepare land for drilling, some definitions specify maximum cultivation depths (e.g. 100mm) and/or a particular percentage cover, usually 30% residues left on the surface

Strip tillage:
Strips covering less than 1/3 soil surface are tilled with residue moved onto untilled strips. Most frequently carried out by single-pass drill

Zero/No-till/direct drilling:
Seed drilled into the stubble of previous crop with very low soil disturbance

4

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Why Reduced Tillage?

- Reduces soil erosion
- Improves soil structure
- Builds soil organic matter/soil organic carbon
- Increases crop residue retention & soil cover
- Improves soil water infiltration & storage, reduces evaporative loss
- Reduces damage to soil biome
- Increases farmland biodiversity
- Reduces fuel usage & increases work rate

5

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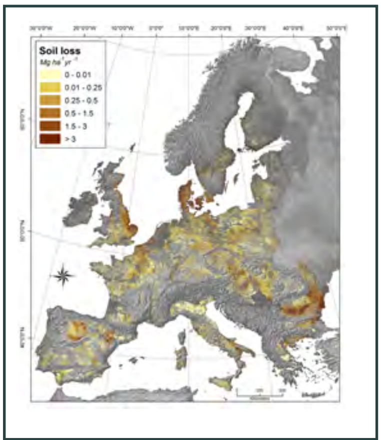
Benefits: Reduces Soil Erosion - 1

- The mean soil loss rate in the European Union's erosion-prone lands (agricultural, forests and semi-natural areas) is approximately 2.46t/ha/yr
- Any soil loss >1t/ha/year considered irreversible over 50-100 years
- Losses of 20-40t/ha in individual storms are recorded in Europe every 2-3 years
- 970 million tonnes soil lost annually
- Erosion is sensitive to climate, terrain & land use, plus management practices (e.g. tillage)
- Mediterranean soils particularly at risk: long dry periods followed by heavy rains on steep slopes

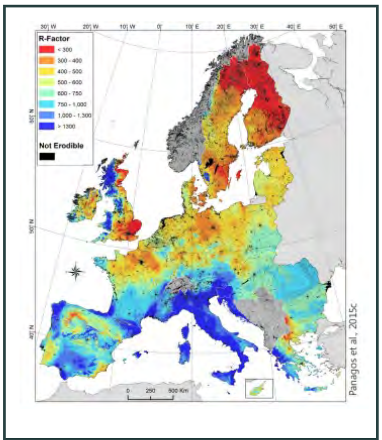
6

Benefits: Reduce Soil Erosion - 2



Soil loss from wind in the EU/UK

Soil loss from water in the EU/UK



Rainfall erosivity in Europe

Source: European Soil Data Centre

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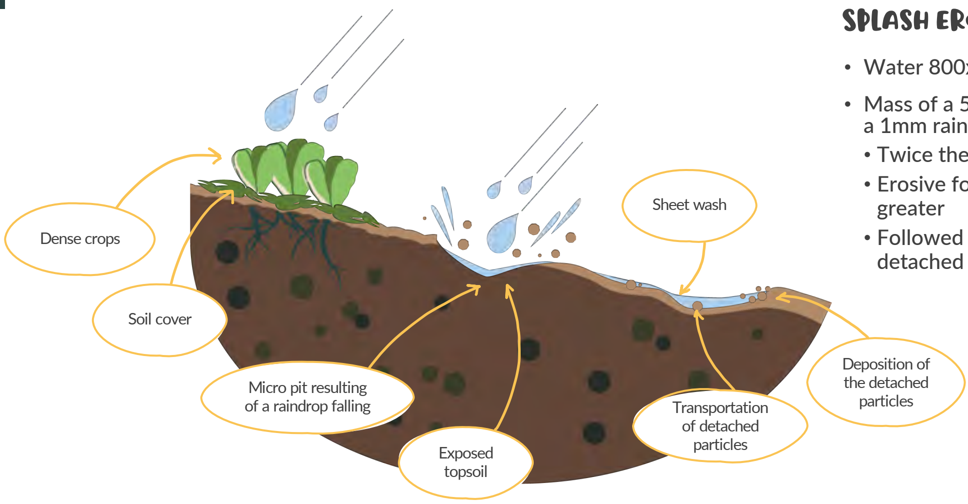
Benefits: Reduce Soil Erosion - 3



Splash Erosion

- Water 800x heavier than air
- Mass of a 5mm raindrop 125x that of a 1mm raindrop
  - Twice the terminal speed
  - Erosive force on impact 500x greater
  - Followed by transportation of detached particles

8

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Benefits: Reduce Soil Erosion - 4

- Water sheet, rill & gully erosion across the field surface
- Erosive capacity of water determined by volume, speed and gradient
- Bare, cultivated & compacted soil most at risk
- Tractor tramlines greatest source of erosion/runoff in arable situations

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Benefits: Reduce Soil Erosion - 5

- Wind erosion – achieved at wind speeds over 20kph
- Suspension of finer particles into dust clouds
- Saltation of coarser materials into dunes
- Dry, cultivated, bare soils most at risk

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Benefits: Reduce Soil Erosion - 4

- Wind erosion most likely in summer on dry cultivated land (catch crops)
- Water erosion most likely in autumn/winter when rainfall levels are high on cultivated, fallow land (cover crops)
- Sloping land most at risk
- Loss of fertile topsoil contributes to watercourse sedimentation and nutrient/pesticide pollution, impacting on water quality and biodiversity

11

Benefits: Reduce Soil Erosion - 7

12

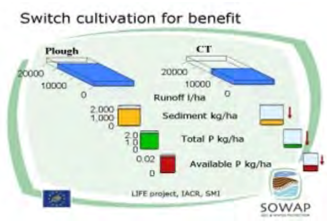
Benefits: Reduce Soil Erosion - 8

- **SO**il & **WA**ter **P**rotection (SOWAP)

SOWAP
SOIL & WATER PROTECTION


SOWAP research at GWCT Allerton Project, UK, 2009

- Direct drilling vs inversion tillage can reduce runoff by as much as 90%
- Reduce soil erosion by as much as 95%
- Nutrient runoff also decreased



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Benefits: Reduce Soil Erosion - 9

14

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Benefits: Reduce Soil Erosion - 10

- Erosion can be reduced by reducing the shear forces of wind & rain on soil, or improving the ability of the soil to resist them
  - Keep soil covered
  - Increase aggregation & infiltration
  - Do not disturb the soil more than necessary
  - Implement mitigation measures such as buffer strips and margins
  - Avoid high-risk actions at high-risk times of year, e.g. overwintered cultivated fallow
  - Build soil health

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Benefits: Improves Soil Structure - 1

- Soil structure - the arrangement of the solid parts of the soil & the pore spaces between them
- Different to soil texture – the relative proportions of primary particles of sand/silt/clay/organic matter in the soil
- Aggregates – the building blocks of soil - are formed from these primary particles and modified by chemical, biological & physical factors
- Aggregate stability plays a major role in soil structure & soil health
- Lighter soils have lower aggregate stability & more likely to slump – especially under excess cultivation

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Benefits: Improves Soil Structure - 2

Why is soil structure important?

- Pore spaces allow water & air flow
- Compacted, anaerobic soil provides difficult habitat for plant roots & soil fauna & can emit nitrous oxide
- Compacted soil increases surface run off & erosion, as well as loss of nutrients & plant protection products
- Poor soil structure impacts soil health, productivity & profitability

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Sq5 Very compact Difficult to break up	Mostly large > 10 cm, very few < 7 cm, angular and non-porous	Very low porosity. Macropores may be present. May contain anaerobic zones. Few roots, if any, and restricted to cracks			Grey-blue colour	Aggregate fragments are easy to obtain when soil is wet, although considerable force may be needed. No pores or cracks are visible usually.

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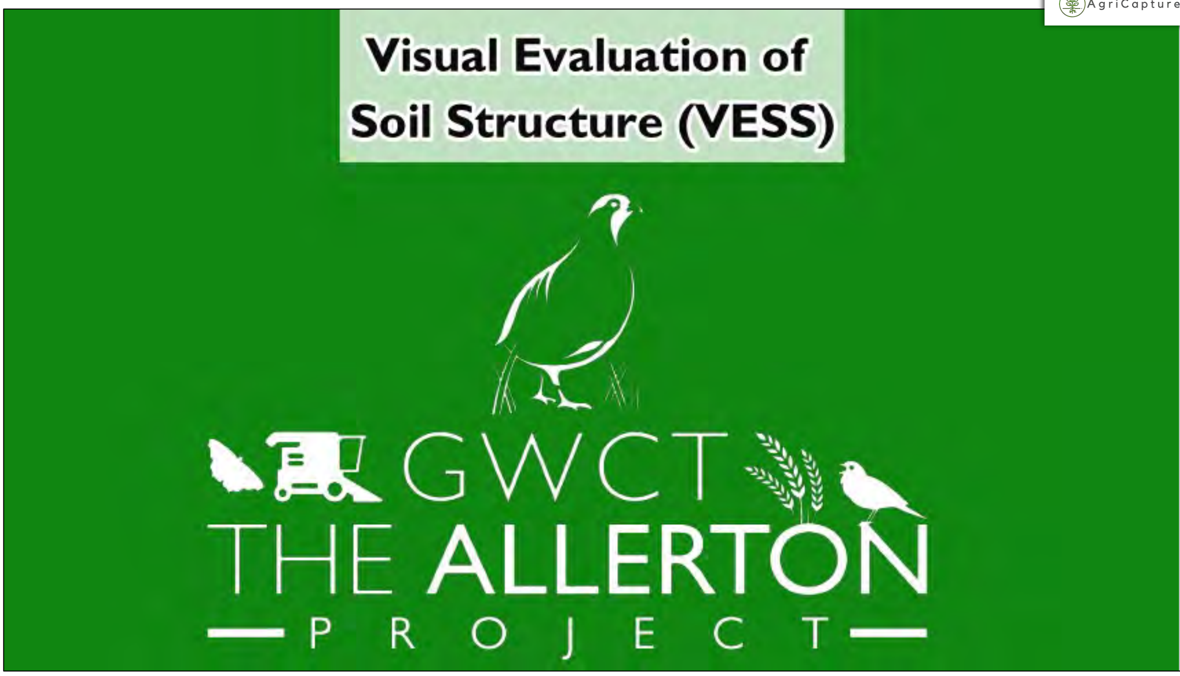

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Benefits: Improves Soil Structure - 3

- Soil with a good structure for crop growth needs to have:
  - A mixture of aggregate sizes which remain stable when wet (slake test)
  - A mixture of large (>75µm diameter) and small (<30µm diameter) pores (pores should make up c.50% of soil volume)
  - Connectivity of pore space is also important for air and water movement within the soil.
  - Micro-aggregates formed by chemical attractions; macro-aggregates by fungal hyphae/biological adhesives, soil profile stabilised by plant root systems

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Benefits: Improves Soil Structure - 4

- Tillage disrupts natural soil structure & aggregates created by biological processes such as earthworms & rooting systems which exude biological adhesives
- Disrupts & reduces soil biome such as earthworms & fungal mycorrhizal networks which improve aggregation, structure and pore spaces
- Can create compaction, panning, capping & downhill soil movement
- Overcultivation can lead to poorly structured soils which are vulnerable to erosion with low levels of biological activity
- Reduced tillage, especially combined with continual crop cover, can lead to significant improvements in natural structure & aggregates

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Benefits: builds SOM/SOC - 1

- Soil organic matter (SOM) consists of approximately 58% soil organic carbon (SOC) by mass
- SOC is the measurable component of SOM & refers to the carbon component of organic compounds
- SOM is the dead & decaying fraction of the soil consisting of:
  - Roots & living microbial biomass [the living]
  - Active SOM (detritus) [the dead]
  - Stable SOM (humus) [the very dead!]
- Detritus (fresh & partially decomposed residue) provides short-term fertility (N,P,K) & is easy to decompose
- Humus is the stable, hard to decompose fraction of SOM & the final product of decomposition. Consists of molecules bound tightly to clay particles, particles inside micro-aggregates and inert compounds

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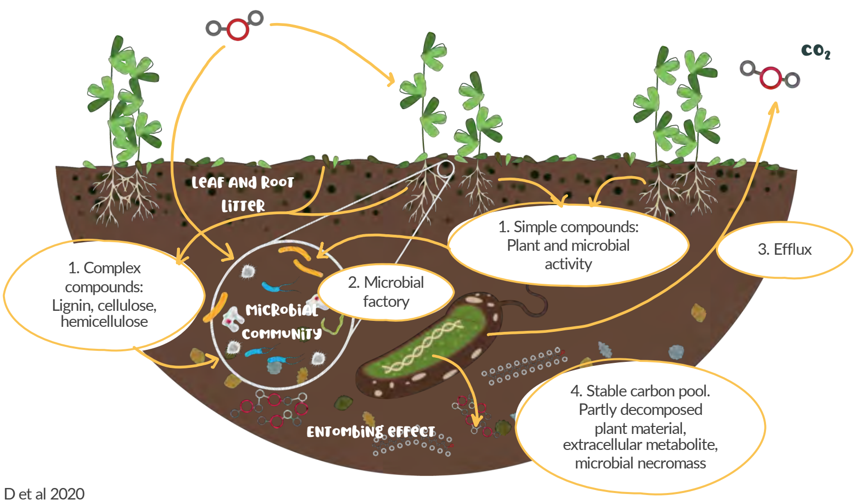
Benefits: builds SOM/SOC - 1



Adapted from Naylor, D et al 2020
Annu. Rev. Environ. Resour. 45:25-59

22

Benefits: builds SOM/SOC - 2

Benefits of stable SOM:

- Physical: enhances aggregate stability, improves water infiltration/soil aeration, reduces runoff & improves water holding capacity
- Chemical: Increases soil cation exchange capacity (CEC), improves pH buffering capacity, accelerates decomposition of soil minerals, making them available for crop uptake
- Biological: Provides food for soil biome, enhances soil microbial biodiversity & activity thus boosting soil resilience, enhances pore space via action of soil microorganisms thus increasing infiltration and reducing runoff

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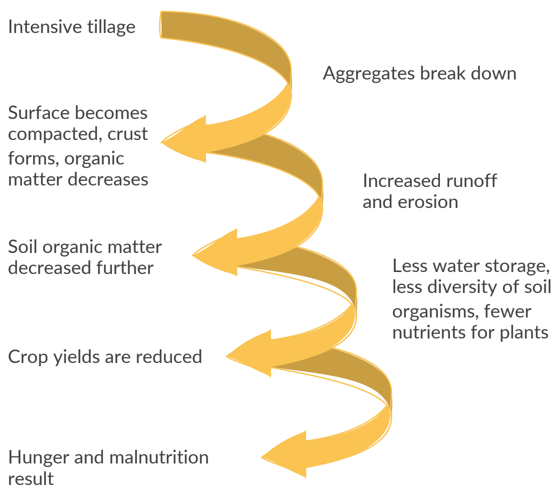
Benefits: builds SOM/SOC - 3

- Tillage increases the rate of decomposition of both active SOM (mineralisation) and stable humus fraction, reducing SOC levels over decades
- Tillage breaks down aggregates & allows SOM within to become more readily available to soil organisms & introduces oxygen to allow more rapid oxidation via microbial respiration & release of CO2 back into the atmosphere
- As SOM drops, soil becomes more susceptible to erosion with a lower water holding capacity, creating a negative cycle of declining productivity



The downward spiral of soil degradation. Modified from Topp et al.

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Benefits: builds SOM/SOC -4

Tillage buries surface residue, reducing food source for fertility/SOM building worms

Undisturbed root systems contribute a higher % of their weight to stable organic carbon than above-ground plant biomass

SOC of 2% considered to be the minimum for sustainable functioning of productive soils

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Benefits: builds SOM/SOC -5

Natural factors that influence SOM levels

Temperature	Rainfall	Soil Texture	Type of vegetation
SOM tends to be lower in hotter regions due to higher levels of microbial activity and faster decomposition of organic matter	Soils in arid regions generally experience low OM due to low levels of vegetation and low microbial activity. Soils in areas of high rainfall may also have low OM due to saturation and waterlogging restricting aeration	Fine-textured soils (clay/silt) tend to have higher OM levels due to strong OM/soil particle chemical bonds which protect OM from microbial decomposition, plus reduced decomposition from smaller soil aeration pores	Grassland soils contain more & deeper levels of OM than forest land due to deep & extensive root systems with high turnover rates. Forest soils may have a thin surface layer of high OM (up to 50%) but much poorer mineral layer beneath

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Benefits: increase crop residue retention - 1

Reduced tillage increases surface residue

Provides vital food source for soil biome such as worms & increases SOM levels

Residue acts as 'soil armor' & protects it from erosion/excessive evaporation especially in hot climates

Increases field travelability

Crop residues slow surface runoff & aid water infiltration

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Benefits: increase crop residue retention - 2

- Inversion tillage may leave <5% surface cover vs >90% in no-till systems
- Reduced tillage (e.g. discing) can leave >30% surface cover, reducing erosion by as much as 70%
- 100% surface cover virtually eliminate surface runoff & erosicanon
- Drilling directly into cover crops can be a highly effective soil management technique

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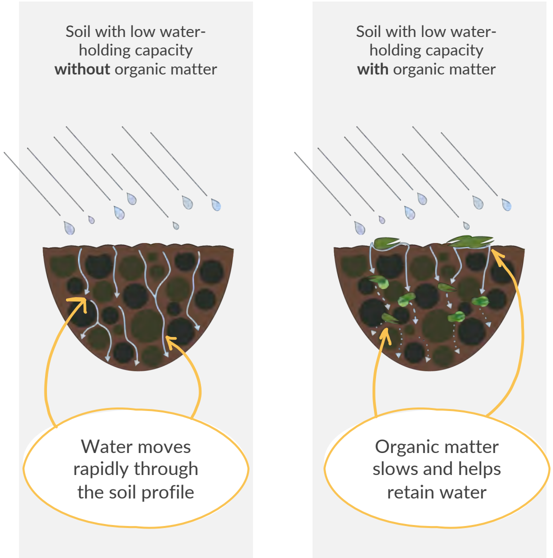
Benefit: improves Soil water capacity - 1

- Water holding capacity (WHC) a fundamental aspect of soil (capillary action)
- Water held in soil macropores & available to plants
- Water also slowly dissolves soil minerals in healthy soils, building a pool of stored organic nutrients
- Degraded & compacted soils have reduced water infiltration & WHC, plus poorer aeration and root growth
- Poor infiltration leads to increased surface runoff & erosion, increased soil degradation
- Increasing SOM can improve the WHC of soils by improving soil aggregation & structure



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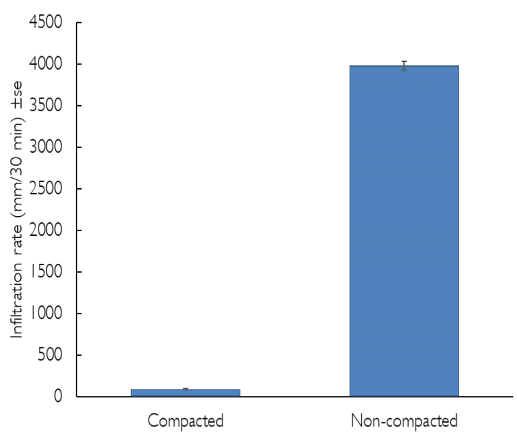
Benefit: improves Soil water capacity - 2

- Water infiltration rates, compacted vs non-compacted arable soils
- Data from 14 fields in the Eyebrook Catchment (primarily clay) UK SoilCare, H2020



Source: EU H2020 SoilCare

GWCT THE ALLERTON PROJECT
SoilCare SOILCARE FOR PROFITABLE AND SUSTAINABLE CROP PRODUCTION IN EUROPE

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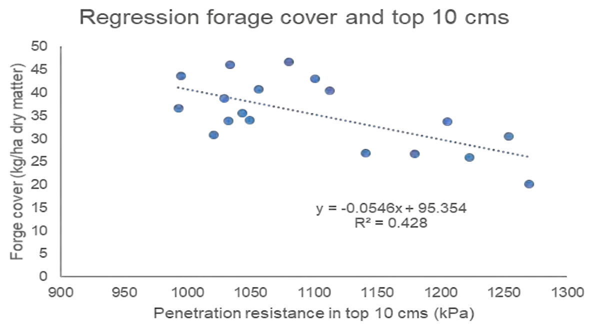
Benefit: improves soil water capacity – 3

- Soil organic matter vs water infiltration rates in arable soils, UK



Source: EU H2020 SoilCare

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Benefit: improves soil water capacity – 2

- Infiltration capacity largely governed by soil type & texture – larger pore spaces = higher infiltration (and exfiltration) rates (e.g. lighter, sandier soils)
- BUT: soil heath & structure created by management are important: finer textured soils (clays) can also develop larger pore spaces and higher infiltration rates/WHC through aggregation built by reduced tillage & increased SOM
- SOM can retain up to 10x its weight of water
- WHC of a silt loam containing 4% organic matter more than double that of a silt loam containing 1% (Hudson 1994)

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Benefit: improves soil water capacity - 3

- Influence of soil fauna – e.g. deep-burrowing earthworms which aid infiltration & aggregation but are disrupted by tillage
- Influence of living roots (e.g. cover crops) create channels to aid infiltration
- Influence of crop residue/soil cover to reduce evaporative water loss
- Increasing infiltration & WHC boosts soil & crop resilience, especially in areas of low rainfall. It can also reduce need for irrigation
- Particularly important in face of climate change – more infrequent, heavy rains/longer droughts

Every 1% increase in organic matter can result in up to 20,000 gallons of available soil water per acre*

Healthy soils with high organic matter will equate to higher water holding capacity
*USDA-NRCS

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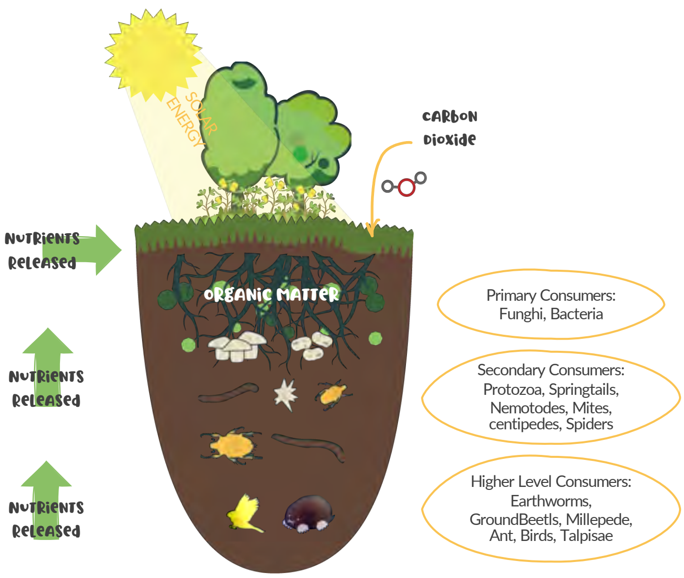
Benefit: Reduces damage to soil biome - 1

- Soil organisms have a critical role in breaking down & incorporating organic residues
- They influence decomposition, nutrient availability & soil structure – e.g. by the release of exudates or growth of fugal hyphal networks
- Soil organisms more abundant & diverse in systems with complex rotations
- Organisms form a soil food web as energy moves down the trophic levels
- Key organisms: bacteria, fungi, algae, protozoa, nematodes, earthworms, insects (e.g. springtails, ants, beetles)
- Effective functioning of soil biome requires:
  - The supply of food for the soil trophic network
  - Maintenance of a suitable habitat for soil organisms



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Benefits: Reduces damage to Soil biome - 2

- Plant residues provide energy for soil micro-organisms
- Soil structure impacts on microbiology affecting colonisation & gas/water exchange
- Tillage impacts the biomass & community structure of soil micro-organisms
- Intensive tillage accelerates carbon oxidation, reducing soil OM & impacting microbial biomass
- Mineralised nutrients may impact on biome diversity, favouring denitrifying bacteria
- Plant residues remain near the surface under reduced tillage to be naturally incorporated to benefit of soil health

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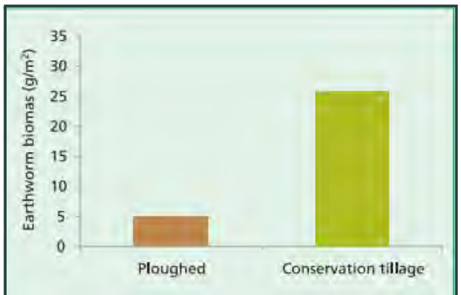
Benefits: Reduces damage to Soil biome - 3

- Majority of soil biology exists in the cultivation layer
- Tillage physically disrupts the soil biome, e.g. damaging beneficial fungal hyphal networks in the rhizosphere & earthworm burrows
- Tillage physically harms/exposes soil biota – e.g. earthworms
- Tillage buries/reduces surface residues – food source for soil organisms
- Bare soil can be an inhospitable environment for soil organisms – exposed to sunlight/ wind/ rain/ temperature extremes
- Soil compaction/damage to soil structure creates inhospitable environment for soil biology – loss of pore spaces/aggregates leading to anaerobic conditions



Conservation tillage trial, Hungary
SOil & WAter Protection Project (SOWAP)

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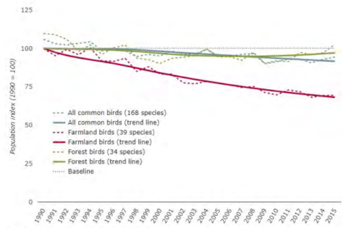
Benefits: increases farmland biodiversity - 1

- Biodiversity: the number, variety & variability of living organisms and how these change from one location to another & over time
- Sharp declines in farmland biodiversity across Europe in recent decades – e.g. EU Farmland Bird Index has declined by 30% since 1990
- Within agriculture, multiple causes including:
  - **More & earlier winter sowing** with loss of overwintered stubbles & the food they contain
  - **Tillage** reducing the availability of cover & diversity of food sources for birds, invertebrates & mammals
  - **Simplified crop rotations** reducing habitat diversity at farm & landscape scale
  - **Increased inputs** leading to increased crop density and reduced nesting opportunities & floral diversity



Source: European Environment Agency.

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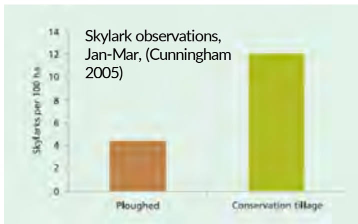
Benefits: increases farmland biodiversity - 2

- Reduced tillage benefits farmland birds by providing a greater range of habitat & food sources over winter
- Ground nesting Skylarks shown to respond positively to reduced tillage in UK (Cunningham 2005)
- Inversion tillage typically buries seeds below 10cm; non-inversion tillage to 5cm or less
- Reduced tillage also has a beneficial impact on field invertebrate & worm numbers, an important part of many diets

Skylark



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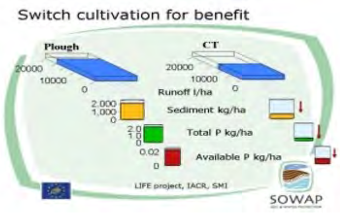
Benefits: increases farmland biodiversity - 3

- Benefits for aquatic biodiversity via reductions in soil erosion & runoff leading to reduced watercourse sedimentation which is harmful to spawning fish

SOWAP
SOIL & WATER PROTECTION

- Reductions in nitrogen, phosphorous & pesticide leaching/runoff leading to improved water quality



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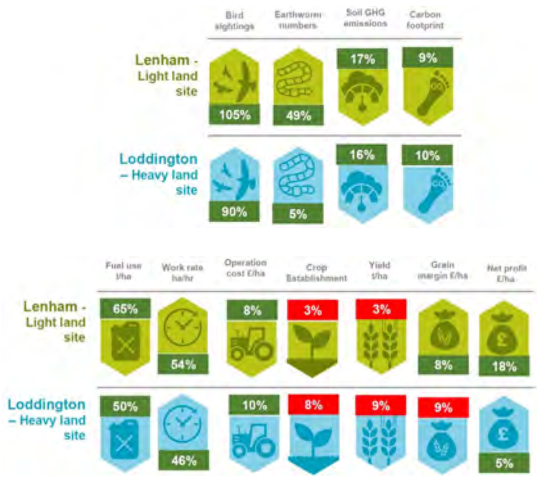
And finally…

- Syngenta-led conservation agriculture (CA) trials carried out on heavy land at GWCT Allerton Project UK & light land at Lenham, UK

syngenta NIAB THE ALLERTON PROJECT

- Interim 3-year results of a 5-year rotation
  - (W Barley, W OSR, W Wheat, Sp Beans, W Wheat)
- Results demonstrate plough vs direct-drill comparison



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Bedankt
Efharisto poli
Hvala vam
Merci
Danke
Dziękuję wam
Thank you

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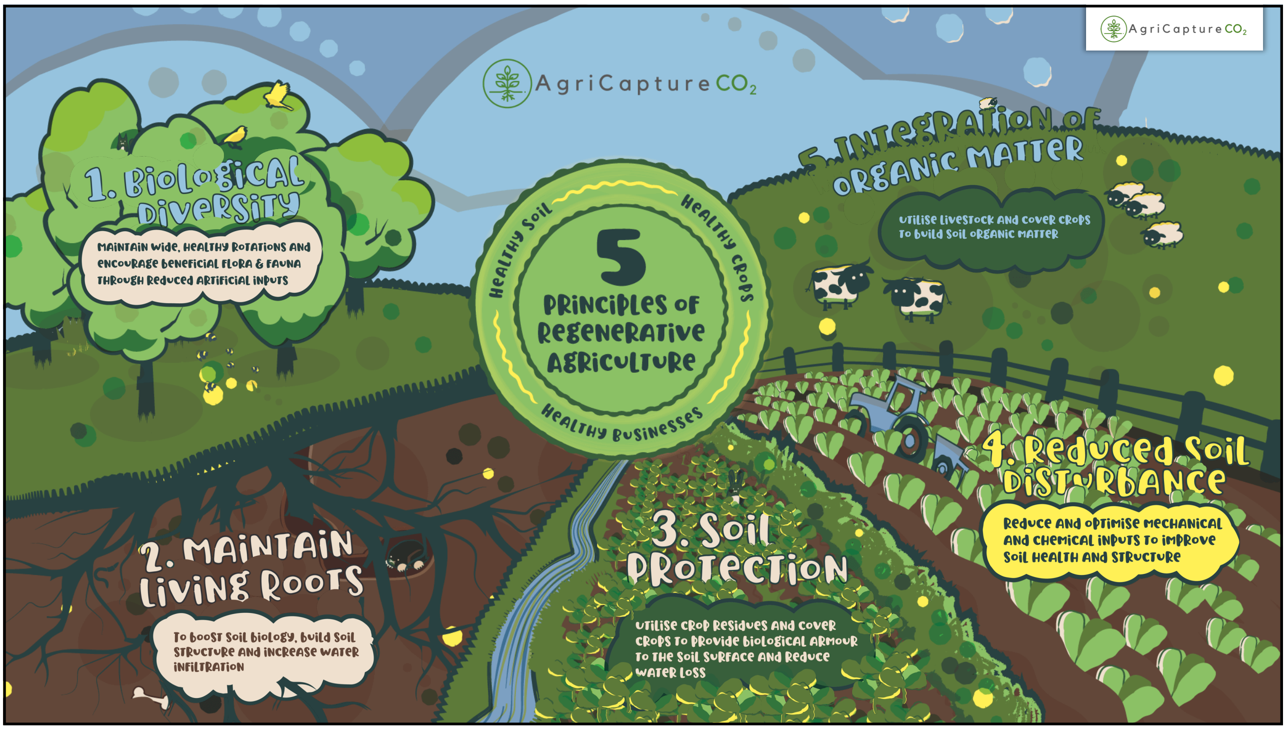
5 Principles of Regenerative Agriculture

Healthy Soil · Healthy Crops · Healthy Businesses

The Soil

AgriCapture CO_2 · GWCT THE ALLERTON PROJECT

1



2

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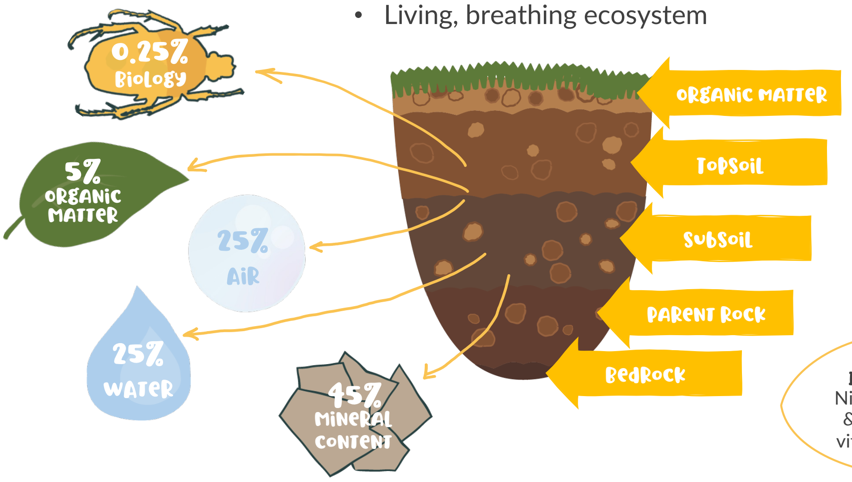
WHAT IS SOIL?

AN IDEAL SOIL!

- A mixture of minerals, gasses, liquids & biology
- Living, breathing ecosystem



IT'S ALIVE
One spoonful of heathy soil can contain 1 billion bacteria & other organisms

IT'S POROUS
Pore spaces in soil absorb air & water, and deliver nutrients to plants

IT'S NUTRIENT-RICH
Nitrogen, phosphorous & other nutrients are vital for plant nutrition

3

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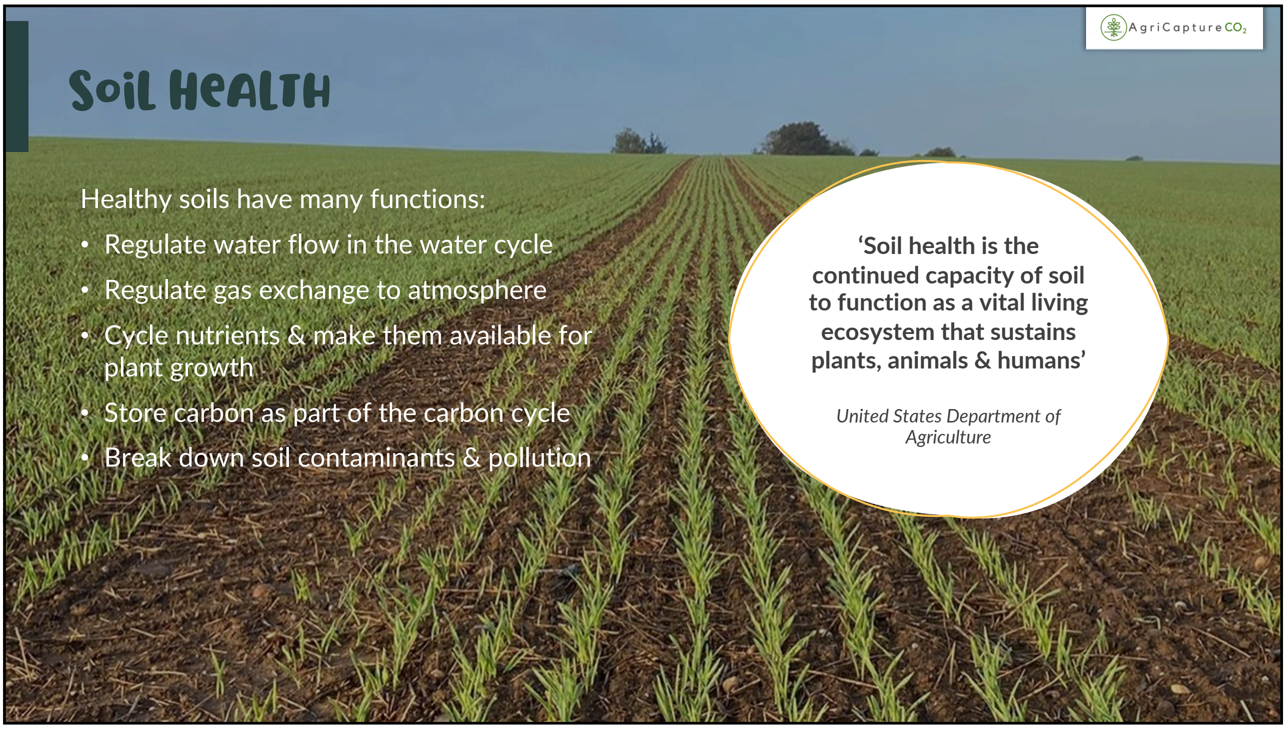
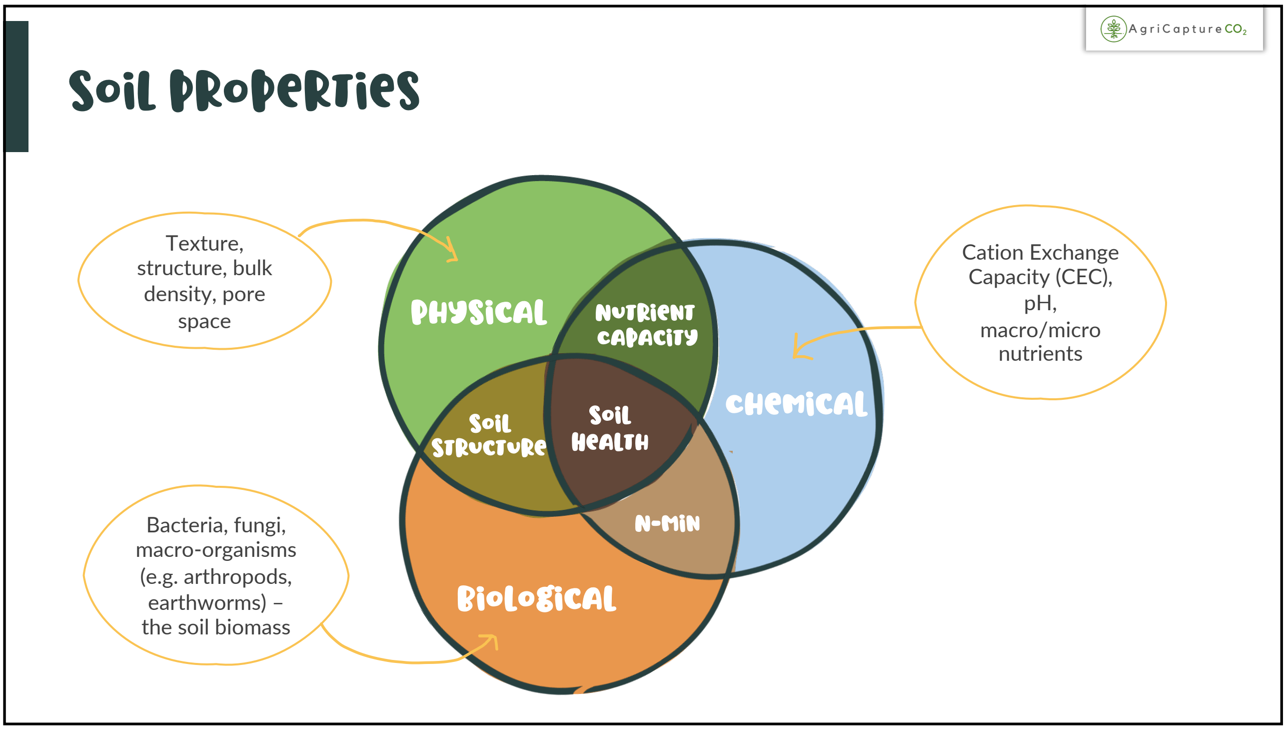
WHAT IS SOIL?

- A mixture of minerals, dead & living organisms (organic materials), air & water
- Formed from interactions between parent materials, soil organisms, climate & relief
- 'The unconsolidated mineral or organic material on the immediate surface of the earth that serves as a natural medium for the growth of land plants' – The Soil Society of America
- Soils form over long timescales: by natural weathering by 0.01-0.1mm/year
- 0.1mm soil layer has a mass of 1t/ha

4


AgriCapture CO2
Soil Health
Healthy soils have many functions:
• Regulate water flow in the water cycle
• Regulate gas exchange to atmosphere
• Cycle nutrients & make them available for plant growth
• Store carbon as part of the carbon cycle
• Break down soil contaminants & pollution
'Soil health is the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals & humans'
United States Department of Agriculture

5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Soil Properties
Texture, structure, bulk density, pore space
Physical
Nutrient capacity
Chemical
Cation Exchange Capacity (CEC), pH, macro/micro nutrients
Soil structure
Soil health
N-min
Biological
Bacteria, fungi, macro-organisms (e.g. arthropods, earthworms) – the soil biomass

6

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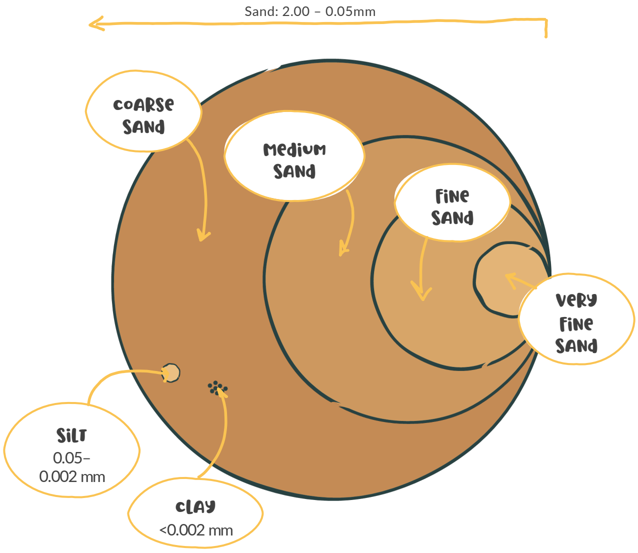
Soil Texture

- Primary mineral components combine to dictate soil texture
- Texture = a fundamental, unchanging soil property
- Mineral components of soil derive from parent material: coarse, sandy soils from sandstones & granites to fine textured soils from mudstones & slates
- Texture influences:
  - Water holding capacity
  - Soil water infiltration
  - Workability
  - Fertility (inc. cation exchange capacity)



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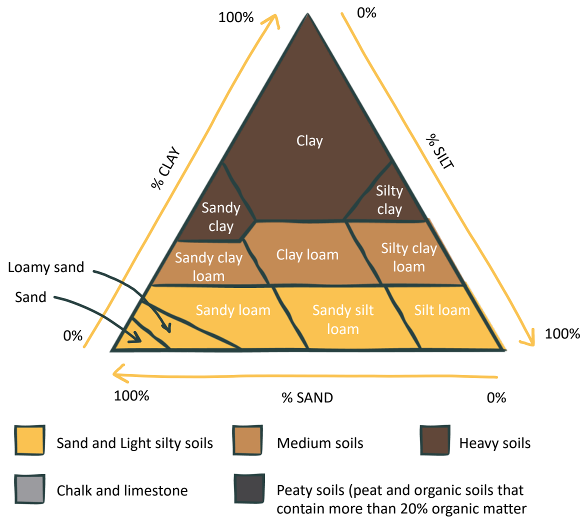
Soil Texture - Mineral Soils

- **Sandy soil:** very loose with low OM; few to no aggregates
- **Loamy soil:** a broad mixture of sand, clay, intermediate mineral particles & a heavy dose of organic material. Texture can range from very porous (sandy) to extremely dense and resistant to water movement (clay)
- **Clay soil:** comprised of very fine mineral particles & not much organic material. The resulting soil is quite sticky since there is not much space between the mineral particles, often poorly draining



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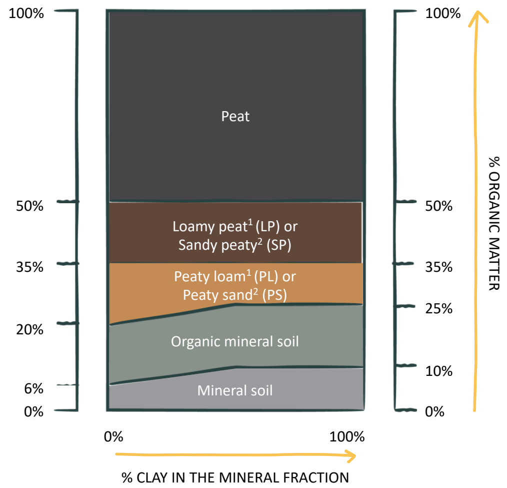
Soil Texture - Peats

- Peat soils unusual in being organic, not mineral based
- Either lowland or upland environment
- Lowland: develop in wet, marshy conditions at sea level. Neutral/alkaline pH and productive when drained
- Upland: form where high rainfall prevents organic matter decomposition. Invariable acidic due to influence of climate on formation
- Risk of rapid soil erosion & loss in dried peat soils – plus attendant CO_2 loss



[1] less than 50% sand in mineral fraction
[2] more than 50% sand in the mineral fraction

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Soil Structure

- The 'architecture' of the soil
- The combination of primary mineral components (sand, silt, clay) with **organic matter**
- Unlike texture, can be modified by agricultural practices
- Soil structure affects water & air movement through soil via pore spaces, influencing its ability to sustain life & perform other vital functions
- **Aggregates:** the building blocks of soil, formed from primary particles & modified by chemical, biological & physical factors
- Organic matter a major element in aggregate formation, from micro- to macro aggregation
- Aggregate stability plays a major role in soil structure & soil health

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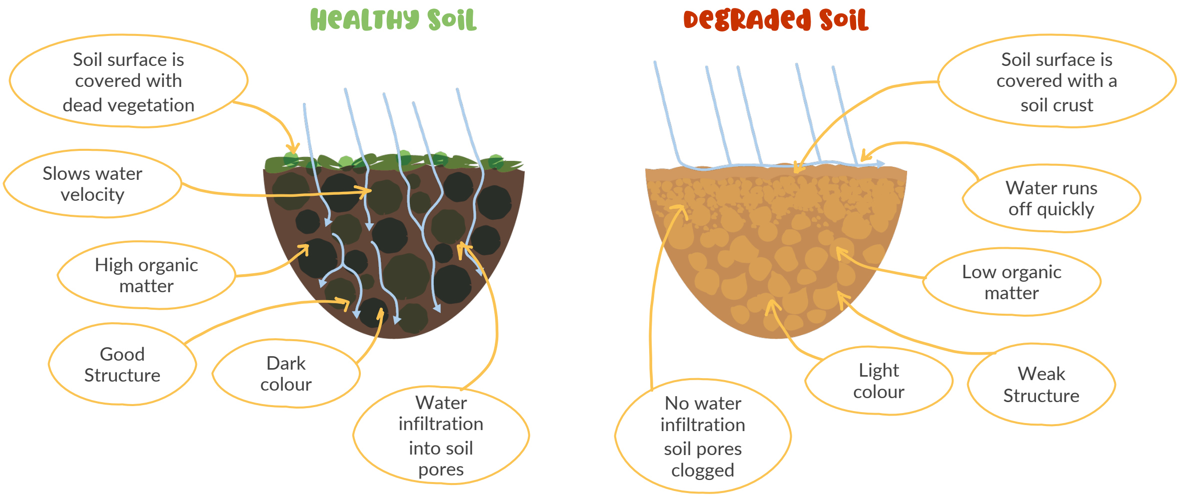
Soil Structure



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Soil Aggregates

Small aggregates are bound together mostly by organic & chemical bonds, so are influenced heavily by soil texture, pH & organic matter content.

- Sandy soils form very lose soils with few to no aggregates
- Clay has a big impact on soil structure: just 5% clay will help aggregate formation
- Fine clay particles can stick together (flocculation), dependent on soil pH & organic matter content. Liming adds calcium ions giving clay particles something to 'flock' around
- During heavy rainfall events less stable clay particles can fall apart & the fine particles can be washed away or block soil pores leading to capping

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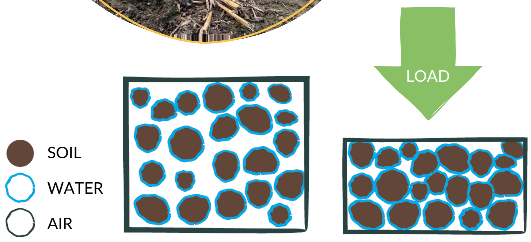
Soil Structure

Why is good soil structure important?

- Pore spaces allow water & air flow
- Compacted, anaerobic soil provides difficult habitat for plant roots & soil fauna & can emit nitrous oxide (N_2O)
- Compacted soil increases surface run off & erosion, as well as loss of nutrients & plant protection products
- Poor soil structure impacts soil health, productivity & profitability
- Poor structure reduces efficient nutrient take up
- Good structure increases the number of field grazing/working days & reduces the horsepower/fuel requirements/number of passes required



Soil Compaction as the result of applied pressure

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Topsoil Structure

Well structured topsoil:

- Small, rounded aggregates
- Network of differing pore shapes & sizes
- Allows good aeration, root growth & drainage
- Aggregates of 1-10mm which remain stable when wetted
- Roots & macrofauna help structure soils: role for cover crops & diverse grass leys in arable systems
- Biological interactions important in creating/stabilising soil structure
- Organic matter & clay vital in creating strong aggregation

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Subsoil Structure

Well structured subsoil:

- Vertically orientated, often continuous, pores & fissures
- Formed by physical shrink-swell processes & maintained by root/earthworm action
- Soil forms column-like structures
- These columns give the overall soil profile strength
- Strong soils = more resilient & can better resist compaction
- Avoid weakening column strength via tillage
- Clay/clay-loam textures can self-structure via swelling/shrinking with wetting/drying
- Increase in SOM can aid self-structuring

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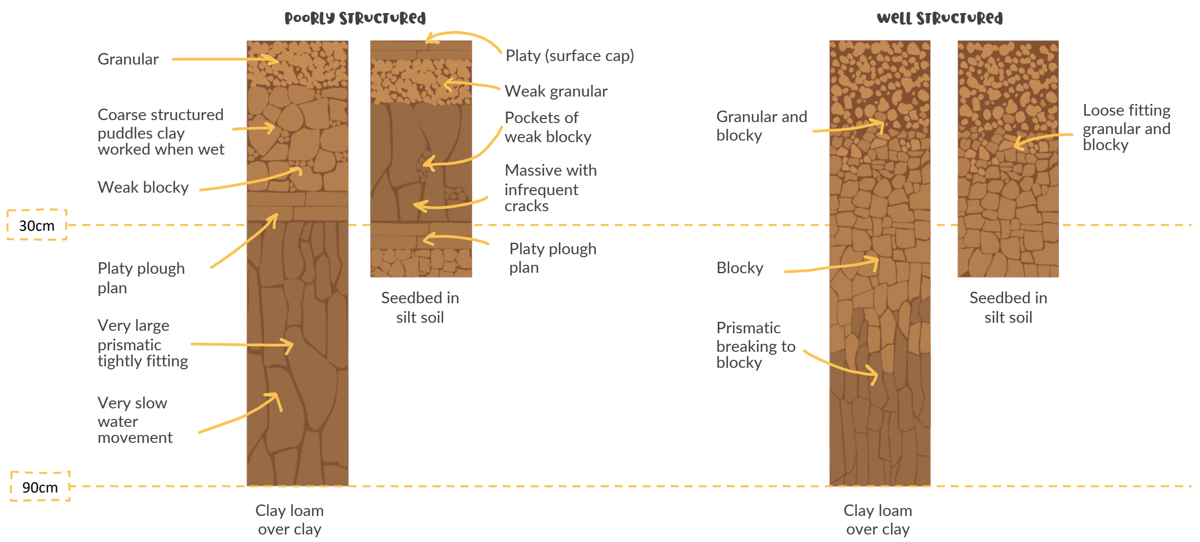
Examples of soil structures under contrasting textures & managements



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Soil structure - issues

Compaction
Primarily machinery/livestock in wet conditions, especially in heavy soils

Capping
Soil surface forms a crust, especially fine tilth & heavy rain. Over-cultivation & disaggregation in fine soils

Panning
Smearing of wet soils causes sub-surface compaction, e.g. plough pan

Slumping
Common on silty soils with low OM & poor natural structure

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Soil density & pore space

- Bulk density = mass of oven dry soil per unit of volume
- Pore space = volume of pores as a fraction of total soil volume (requires knowledge of soil particle density)
- Compaction = increase in bulk density, reduction in pore space & reduction in crop rooting ability
- Pore space occupied by both air & water
- Macropores (>150µm) allow excess water to drain from the soil under gravity
- The capillary forces in micropores allow water to be retained in the soil for plant uptake: plant roots can access micropores as small as 0.2µm
- When macropore volume <10% risk of insufficient air for root respiration

BULK DENSITY	PORE SPACE (%)	DESCRIPTION
0.5-0.8	>70	Loose, uncompacted topsoils. Peats & organic soils
≈1.0	60-75	Permanent pasture, woodland soils
≈1.5	45	Compacted, root penetration difficult
≈2	25	Dense; no root growth

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Soil & water

- Soil continuously wets (precipitation, irrigation) & dries (evaporation, transpiration, runoff & drainage)
- Soil moisture highly influenced by texture: moves slowly through clay, quickly through sand

Infiltration	Hydraulic conductivity	Soil permeability
rate at which water enters soil surface	how easily water moves through a soil layer	(pore size/ fissures/compaction) & moisture content dictate conductivity

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Soil & water

- Cracks & macropores allow rapid infiltration & movement between layers. Smaller pores take longer to fill & movement of water into them relies on capillary forces
- Drainage rates a combination of infiltration & hydraulic conductivity. In most soils, the subsoil drainage rate controls drainage across the profile
- Water moves from wet areas to dry areas by capillary action: water can move up, sideways & down
- Smaller pores hold water with more force: water moves more slowly in the very small pores of clay soils
- Soils with larger pores, e.g. sands, drain more quickly & retain less water

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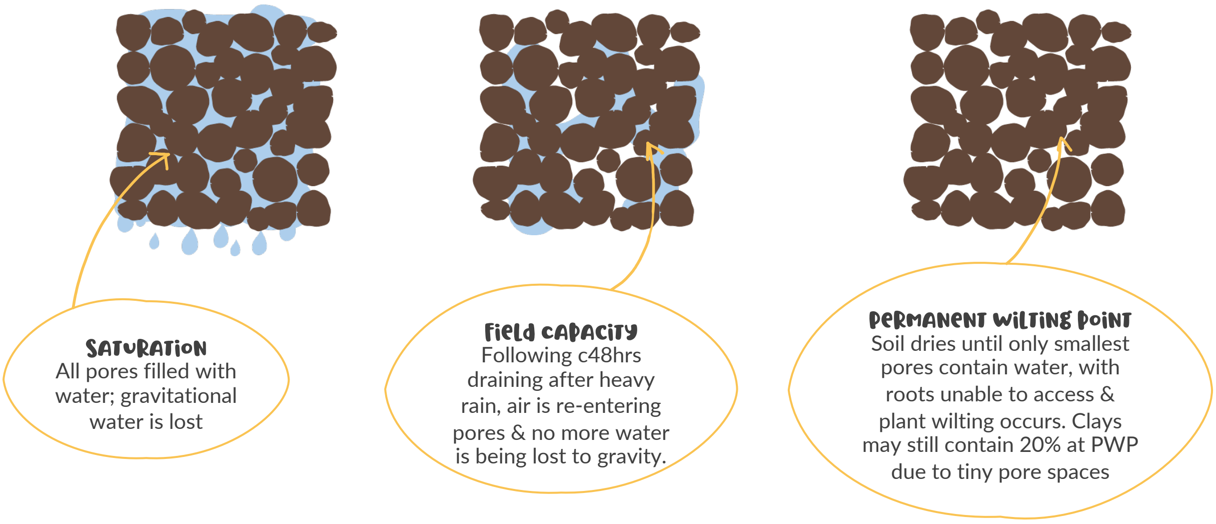
Soil & water



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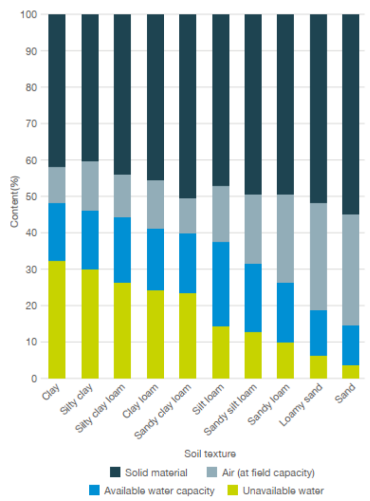
Soil & water

- **Soil moisture deficit** – when water loss via evapotranspiration exceeds water inputs
- **Available water capacity (AWC)** – the volume of plant available water in a soil
- Soil type (therefore pore type) dictates AWC
- Water content % across different soil types will give different outcomes – e.g. the AWC of a clay soil is lower at a given water % than in a sand soil
- Soil health & structure also important
- Improving soil structure & increasing SOM can increase the AWC of a soil
- High-yielding or shallow rooted crops increase risk of soil moisture deficit



Soil texture affects the available water capacity (AWC)

Source: Principles of soil management, AHDB UK

22

Soil Chemistry

- Crops require 16-19 vital elements for growth, both macro- & micro-nutrients
- Retention & release of nutrients to crops depends on variety of soil & environmental factors
- Soil pH an important influence on nutrient availability & uptake
  - Nutrients stored in organic sources (e.g. N) are released when soil organisms mineralise the organic materials
  - Soil biome is pH dependent, with max mineralisation at pH 6-7
  - Importance of soil liming
- Rainfall has a naturally acidifying effect
- Low CEC soils acidify most rapidly
- Organic peat soils can be either acidic (upland/moorland) or neutral/alkaline (lowland)

23

Soil Chemistry

Factors affecting soil pH:

- Deposition of atmospheric pollutants in rainfall
- Use of acidifying N fertilisers
- Offtake of basic cations in crops
- Oxidation of OM, which generates free hydrogen ions in soil

- Soils become more acid as calcium, magnesium, potassium & sodium are displaced from cation exchange sites by hydrogen ions in rainwater & leached from the soil
- Liming reduces soil acidity
- Increases soil biological activity
- Improves soil structure/workability
- Soil pH therefore an important element for healthy, biologically active & productive soils

SOIL TYPE	pH RANGE
Sandy heathland	3.5-5.0
Calcareous brown soil	6.5-8.0
Upland peat	3.5-4.5
Cultivated, non-calcareous soil	5.0-7.0
Cultivated, calcareous soil	7.0-8.0
Permanent pasture, lowland	5.0-6.0
Permanent pasture, upland	4.5-5.5
Lowland peat	4.0-7.0

Typical soil pH ranges, from Soffe & Lobley, 'The Agricultural Notebook', 21st Edition

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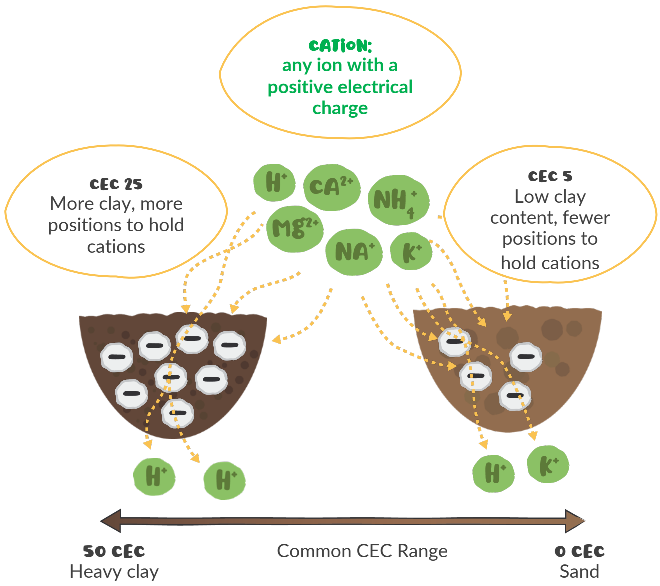
Soil chemistry

Cation exchange capacity (CEC) & nutrient availability

- Soils are highly dynamic: clay mineral, iron oxides & organic matter components of soil act in a chemically active manner due to electrical charges on their surfaces
- -ve charge sites adsorb & hold +ve charge cations by weak electrostatic force
- Critical to supply of plant nutrients as many exist as cations (Mg, P, Ca, Na, NH4)
- Soils with large –ve charge (e.g. clays) tend to be more fertile as they retain more cations (higher CEC) vs leaching in low CEC (sandier) soil
- The lower the CEC, the faster pH will decline due to leaching



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Soil chemistry

SOIL TYPE	CATION EXCHANGE CAPACITY (MILLIEQUIVALENTS/100G SOIL)
Sandy loam	5-15
Sandy clay loam	10-20
Clay loam	20-40
Clay	30-50
Lowland peat	150-200
Upland peat	40-60

CEC of example mineral & organic soils, from Soffe & Lobley, 'The Agricultural Notebook', 21st Edition

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Soil biology

- Living soil distinguished from inert geological material by biological activity & organic matter
- Agricultural practices can modify soil biology & local environmental conditions
- A teaspoon of soil contains
  - >1bn bacteria (1000s of species)
  - >1m other single-celled microbes
  - >1m fungi
  - 100s of meso (e.g. nematodes, mites) & macro (e.g. earthworms) fauna
- Soil biology cycles SOM & nutrients within: SOM essential for soil life

ENCHYTRAEIDAE

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Soil biology

- Biodiversity crucial to soil functionality
- Drives productivity through nutrient cycling, stabilising soil structure & regulating organic matter content
- Biodiversity improves soil resilience: provides more pathways along which soil processes can occur under stress without loss of productivity

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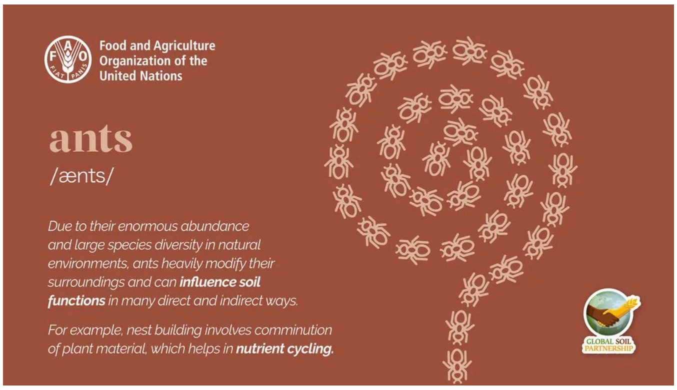
Soil biological organisms

MACROFAUNA

- >2mm in size (from invertebrates to burrowing mammals)
- Moles, earthworms, ants, millipedes, spiders, beetles
- 'Structural engineers' of the soil: e.g. earthworms restructure & generate new stable aggregates with worm casts. This creates new microhabitats for other soil organisms & plant roots



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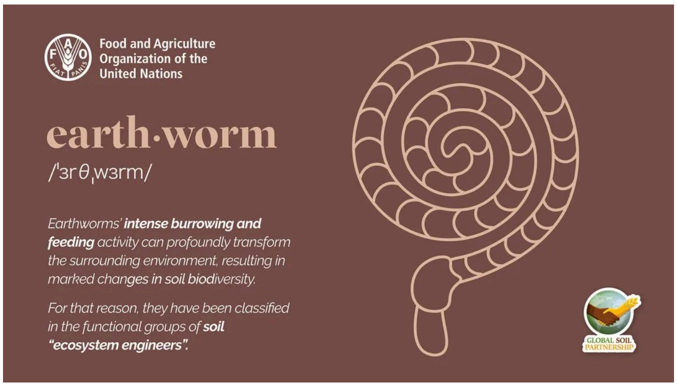
Soil biological organisms

MACROFAUNA

- Earthworms consume more plant litter materials than all other invertebrates combined
- Earthworm biomass varies from <20kg/ha - >500kg/ha depending on soil conditions
- Feed on dead OM & incorporate into soil, mixing organic & mineral material & excreting bacteria in mucilage
- Ingest & excrete up to 100t/ha/year
- Key in aerating soil & aiding water infiltration



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Soil biological organisms

MESOFAUNA

- 0.1-2mm in size
- Arthropods such as mites, springtails & enchytraeids
- Graze on bacteria & fungi, but may also ingest organic material
- Up to 200,000 arthropod mesofauna/m^2
- Some mesofauna are predatory, some are herbivores; most scavenge degraded organic matter
- Aid nutrient cycling, stimulation of microorganisms & deposition of faeces which increase soil fertility/provide food for next trophic level

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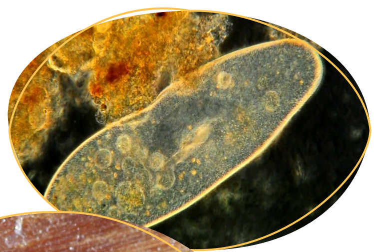
Soil biological organisms

MICROFAUNA

- Protists – feed on soil bacteria
- Nematodes - a diverse group, including plant parasites & predators that feed on bacteria, fungi or other nematodes
- Microfauna release plant-available nutrients



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Soil biological organisms

Micro-organisms

- Bacteria, fungi, viruses
- Microorganisms that interact directly with roots can affect plant health and/or productivity in either a positive, neutral, or negative way
- Contribute to:
  - soil stability (aggregate formation)
  - decomposition of organic matter
  - nutrient cycling & uptake by plants
  - disease suppression & induced systemic resistance
  - plant growth promotion
  - production of antibiotics & hormones
  - toxin breakdown (pesticides, pollutants)

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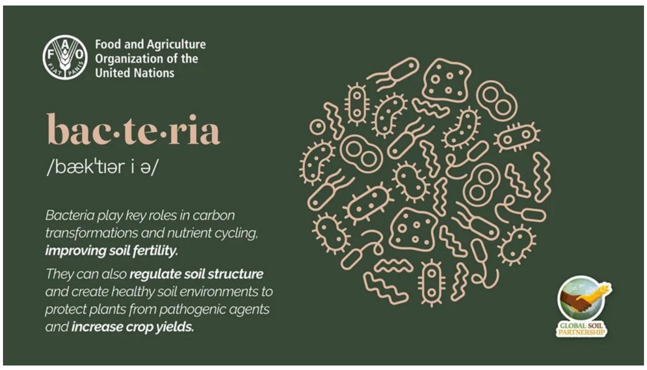
Bacteria

- Live in water films around soil particles
- Rapidly reproducing (24hrs?)
- Approx 1% of SOM
- Wide diversity, able to decompose diverse substrates
- Secrete enzymes which break down complex molecules into simple soluble compounds, e.g. glucose, which can be easily absorbed
- Both aerobic & anaerobic species
- Include N fixing, nitrifying & denitrifying bacteria
- Includes actinomycetes – larger in size and especially important in degrading resistant OM, e.g. lignins



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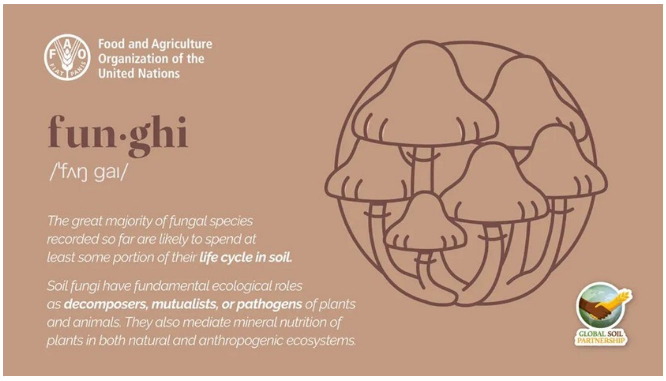
Fungi

- Less numerous than bacteria but larger in mass
- Up to approx. 0.5% of SOM
- Associated with initial breakdown of OM
- Tolerate wider range of soil conditions & some better able to degrade resistant materials such as lignin
- Mycorrhizal fungi of particular value in P deficient soils due to symbiotic plant root relationships in rhizosphere which increase P cycling & absorption in return for carbon-rich root exudate
- Excrete protein-rich glomalin which acts as organic glue to bind aggregates



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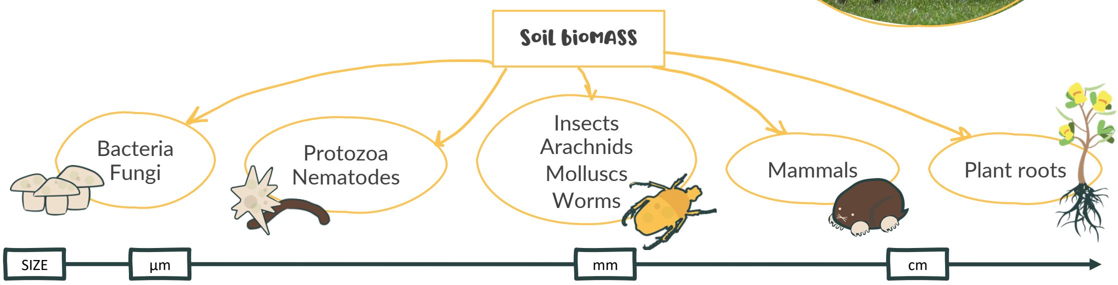
Soil biodiversity

- In 200g of arable soil there is c.0.5g of living matter
- 5 tonnes/ha! (c.100 sheep...)
- On grassland c10g of living matter
- 100 tonnes/ha! (c2000 sheep...)

(Source: European Commission)



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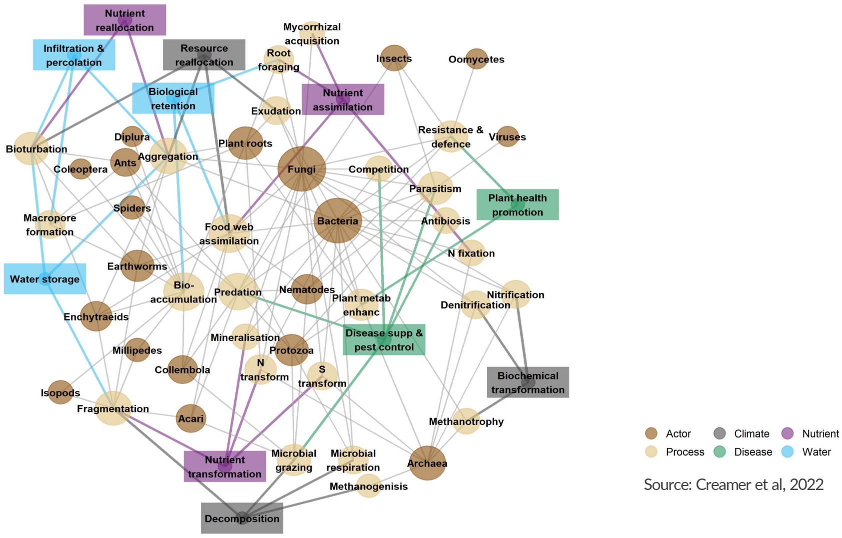
Soil biology – A 'Simplified' Soil Network!



Source: Creamer et al, 2022

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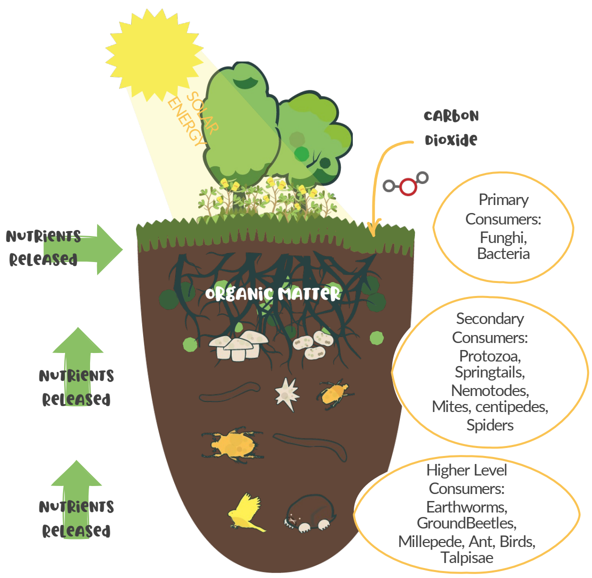
Soil biology

- Soil organisms have a critical role in breaking down & incorporating organic residues
- They influence decomposition, nutrient availability & soil structure – e.g. by the release of exudates or growth of fugal hyphal networks
- Soil organisms more abundant & diverse in systems with complex rotations
- Organisms form a soil food web as energy moves down the trophic levels
- Key organisms: bacteria, fungi, algae, protozoa, nematodes, earthworms, insects (e.g. springtails, ants, beetles)
- Effective functioning of soil biome requires:
    - The supply of food for the soil trophic network
    - Maintenance of a suitable habitat for soil organisms



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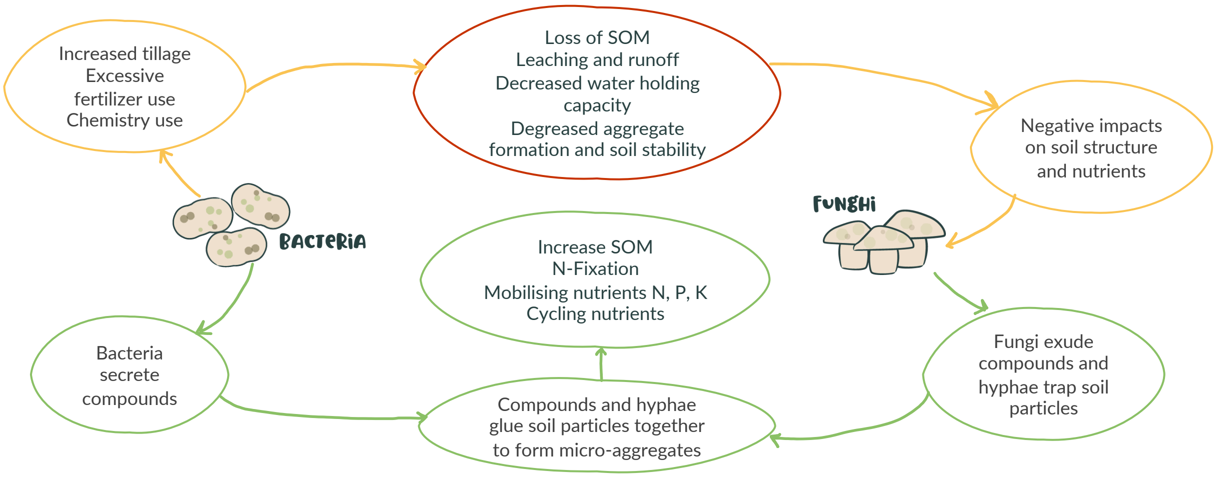
Microbial Activity

Bacteria and fungi promote nutrient acquisition & improve structure in soils



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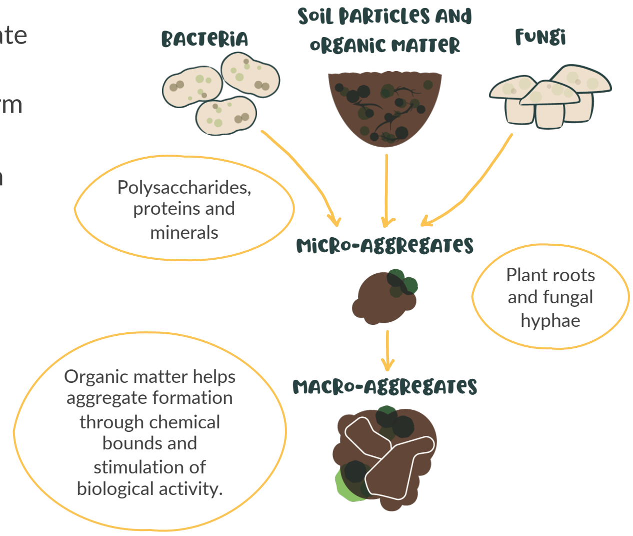
Soil Aggregation & Biology

- Bacteria & fungi also important in aggregate formation
- Chemical bonds between soil particles form micro-aggregates
- Proteins & polysaccharide secretions such as mucilage from soil microbiome help amalgamate micro-aggregates, and then stable macro-aggregates
- Macro-aggregation in combination with plant roots & fungal hyphae
- Roots & fungi also help stabilise the soil profile like a net & prevent erosion



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Soil aggregation & biology

- Soil habitat space defined by size, organisation & connectivity of pores
- Pore size distribution controls the balance of oxygen & water available to organisms at any given soil moisture potential
- Regulates access of soil organisms to one another & to resources
- Larger pores drain freely, but water is held on particle surfaces & in smaller soil pores
- The dung & organic compounds excreted by soil organisms highly efficient at storing water in soil, & acts as a sponge for many plant nutrients, retaining them in a plant-available form
- Soil structure influences the nature & activity of soil organisms, but soil organisms also help build & stabilise the soil structure
- Soil organisms produce a range of sticky compounds that help bind soil particles into microaggregates. Roots & fungi help bind these into larger aggregates or push tightly bound clay particles apart
- Bacteria can form protective biofilms over aggregate surfaces. Plant roots also have a central role in structure development, through drying and compression as they grow

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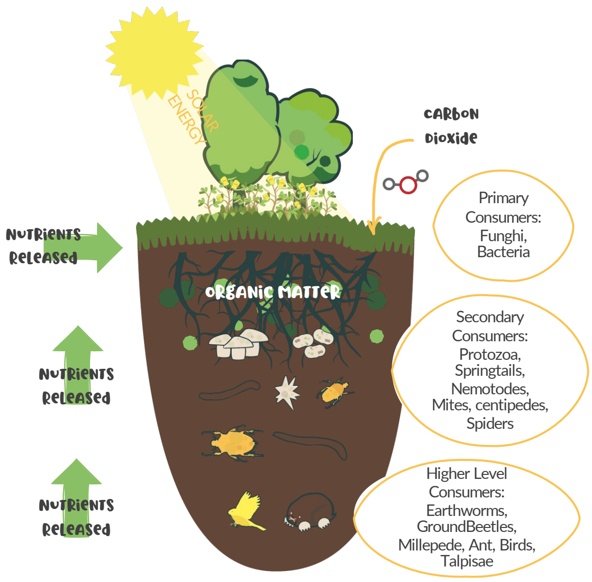
Biological Nutrient Cycling

- When organisms feed, waste nutrients are excreted which are more accessible to plants
- The rhizosphere (root zone) is a key biological region for biological activity & plant uptake: leads to additional plant growth, return of OM & root exudates to soil & recycling of nutrients
- Healthy rhizosphere supports plant pest predators & beneficial microbes that help produce plant growth compounds & fight disease
- Soil fauna can account for 30–40% of net nitrogen released into plant-available forms. The remaining nutrient is released by microbes or the enzymes they produce



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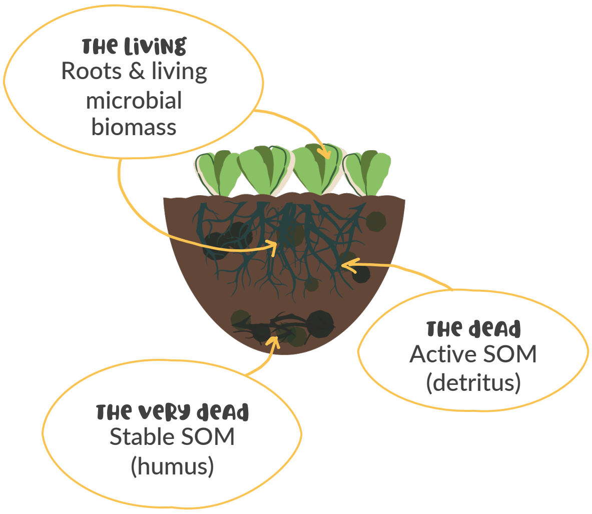
Soil organic matter - 1

- The fraction of soil consisting of any organic material (living or dead) & in all stages of breakdown/decomposition
  - Plants, microbial & faunal biomass (the living/recently living)
  - Detritus, i.e. dead, actively cycling particulate organic material (the dead)
  - Humus & highly carbonised organic matter (charcoal) , i.e. inert, stable OM (the very dead)
- Turnover of soil organic matter can range from <1 year to >2500 years depending on stability of the fraction/level of decomposition



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Soil organic matter - 2

- Microbial biomass includes microorganisms responsible for decomposition of both plant residues & detritus
- Humus is the stable fraction of SOM formed from decomposed organic material – the final product of decomposition
- Living biomass, plant residues & detritus contribute to soil fertility
- Their decomposition releases nutrients, e.g. N, P, K
- Humus/charcoal less important for fertility as it’s the final product of decomposition (very stable)
- However, it does contribute to soil structure, cation exchange capacity (CEC) & carbon sequestration

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Soil organic matter - 3

Fractions of soil organic matter based on Baldock and Skemstad (1999) and use for soil carbon models (Six and Jastrow 2022)

		Composition	Amount in soil	Fractions for models
Non-living organic matter	Dissolved organic matter		< 0.1%	Labile soil carbon Active pool Decomposable plant materials (low C:N ratio, low lignin) Resistant plant material (high C:N ratio, high lignin)
	Particulate organic matter	Litter Macro-organic material Light fraction	5 to 20%	
	Humus	Non-humic biomolecules Humic substances	65 to 80%	Slow soil carbon
	Inert organic matter	Charcoal/char	1 to 5%	Passive soil carbon Inert organic materials
Living organic matter	Phytomass	Plant roots, litter	1%	Labile soil carbon Active pool Decomposable plant materials (low C:N ratio, low lignin) Resistant plant material (high C:N ratio, high lignin)
	Microbial biomass	Bacteria Fungal	2 to 5%	
	Faunal biomass		<1%	

Source: Soil Organic Matter & Soil Function, Murphy, 2014

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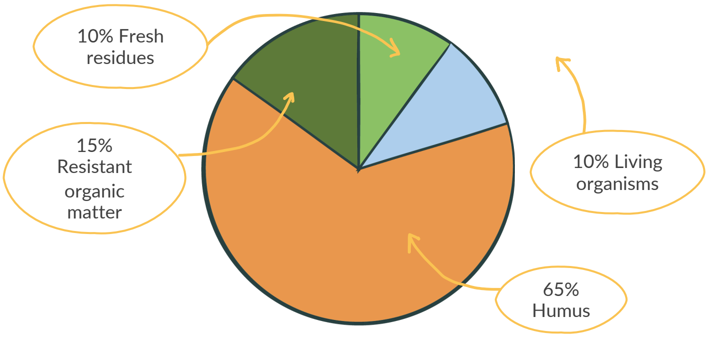
Soil organic matter - 4

Dead and decaying organic matter



Most soil organic matter is dead or decaying, with living organisms making up about 10% of the soil organic matter pool

Adapted from: 'What is soil organic carbon?', Government of Western Australia

Fraction	Size micrometres (μm) and millimetres (mm)	Turnover time	Composition
Dissolved organic matter	<45 μm (in solution)	Minutes to days	Soluble root exudates, simple sugars and decomposition by-products. It generally makes up less than 5% of total soil organic matter.
Particulate organic matter	53 μm – 2 mm	2–50 years	Fresh or decomposing plant and animal matter with identifiable cell structure. Makes up 2–25% of total soil organic matter.
Humus	<53 μm	Decadal (10s to 100s of years)	Older, decayed organic compounds that have resisted decomposition. Can make up more than 50% of total soil organic matter.
Resistant organic matter	<53 μm – 2 mm	100s to 1000s of years	Relatively inert material, such as chemically resistant materials or organic remnants (e.g. charcoal). Can be up to 10% of soil organic matter.

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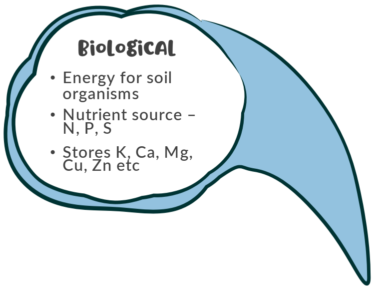
WHY IS SOIL ORGANIC MATTER IMPORTANT?

BIOLOGICAL

- Provides food source for soil microorganisms: large, diverse populations are vital to a well-functioning soil
- Regular OM additions therefore important even if only contributing to active C stocks
- SOM contains vital macro- & micro-nutrients in complex organic molecules made available in simpler, inorganic (mineral) forms via mineralisation by soil microbes
- Chelates can fix and retain certain soil nutrients, and are organic molecules resulting from the decomposition of SOM (or can be secreted from plant roots)



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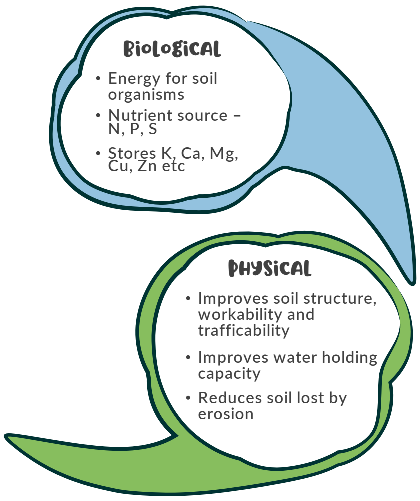
WHY IS SOIL ORGANIC MATTER IMPORTANT?

PHYSICAL

- SOM improves soil aggregation, structure & aeration
- Improves rooting & plant growth
- Increases water infiltration & water holding capacity
- Decreases risk of waterlogging, runoff & erosion
- Increases number of field working days
- SOM difficult to build in coarse, sandy soils due to low aggregation (which protects OM from microbial exploitation) & limited protective bonds with fine materials



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WHY IS SOIL ORGANIC MATTER IMPORTANT?

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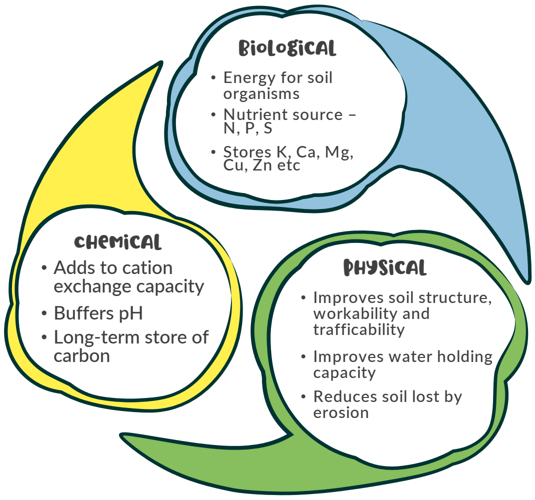
CHEMICAL

- Humus has a high cation exchange capacity (CEC) and keeps many nutrients from leaching by binding them tightly to the soil
- SOM buffers changes in pH by taking free hydrogen out of solution as acids are produced or releasing it as bases are produced
- SOM binds harmful soil minerals (such as aluminium at low pH) & reduces harm to plants, but also some pesticide residues, reducing leaching & pollution



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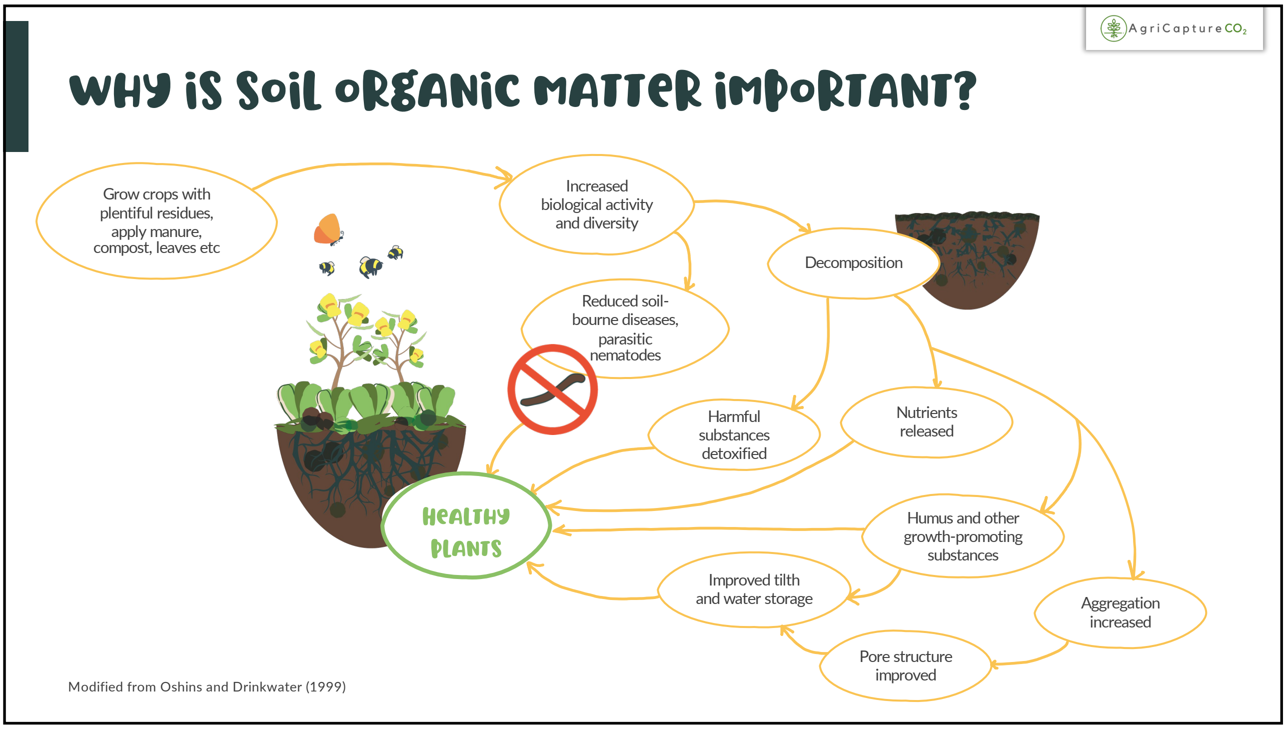
AgriCapture CO2
WHY IS SOIL ORGANIC MATTER IMPORTANT?
Grow crops with plentiful residues, apply manure, compost, leaves etc
Increased biological activity and diversity
Decomposition
Reduced soil-bourne diseases, parasitic nematodes
Harmful substances detoxified
Nutrients released
HEALTHY PLANTS
Humus and other growth-promoting substances
Improved tilth and water storage
Aggregation increased
Pore structure improved
Modified from Oshins and Drinkwater (1999)

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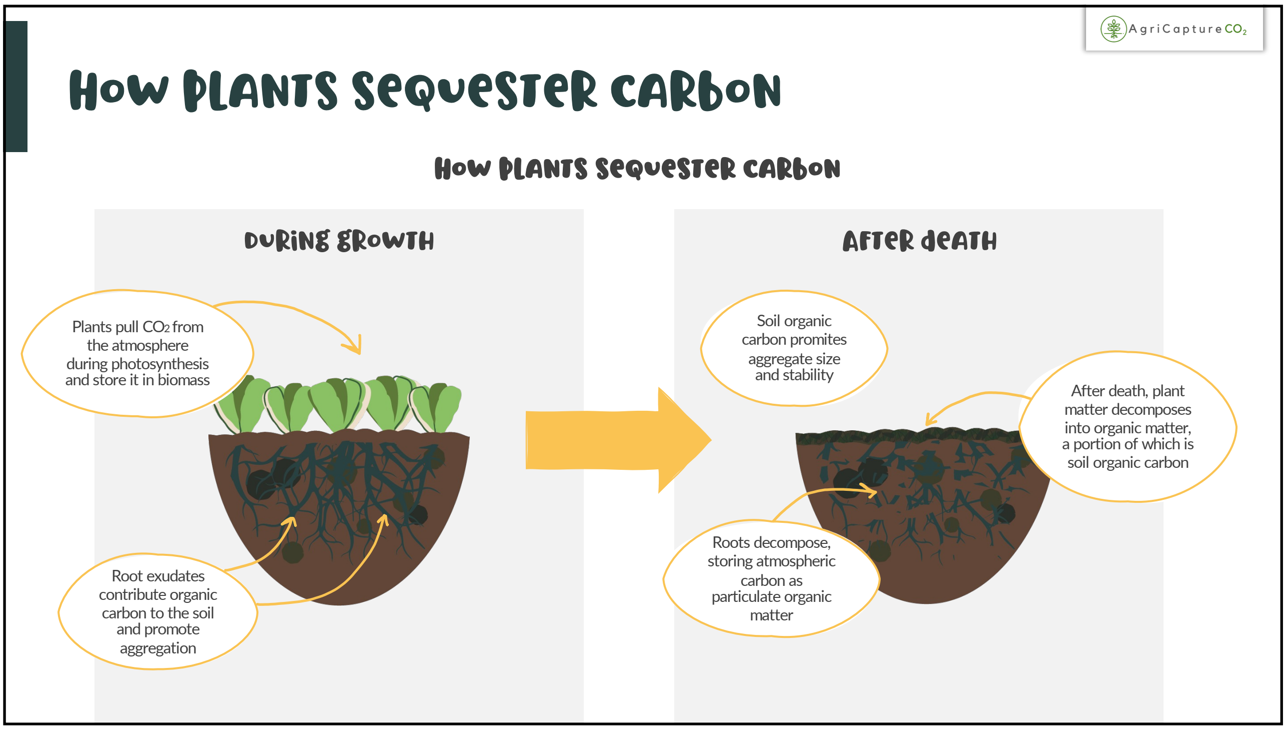
AgriCapture CO2
HOW PLANTS SEQUESTER CARBON
HOW PLANTS SEQUESTER CARBON
DURING GROWTH
Plants pull CO2 from the atmosphere during photosynthesis and store it in biomass
Root exudates contribute organic carbon to the soil and promote aggregation
AFTER DEATH
Soil organic carbon promites aggregate size and stability
After death, plant matter decomposes into organic matter, a portion of which is soil organic carbon
Roots decompose, storing atmospheric carbon as particulate organic matter

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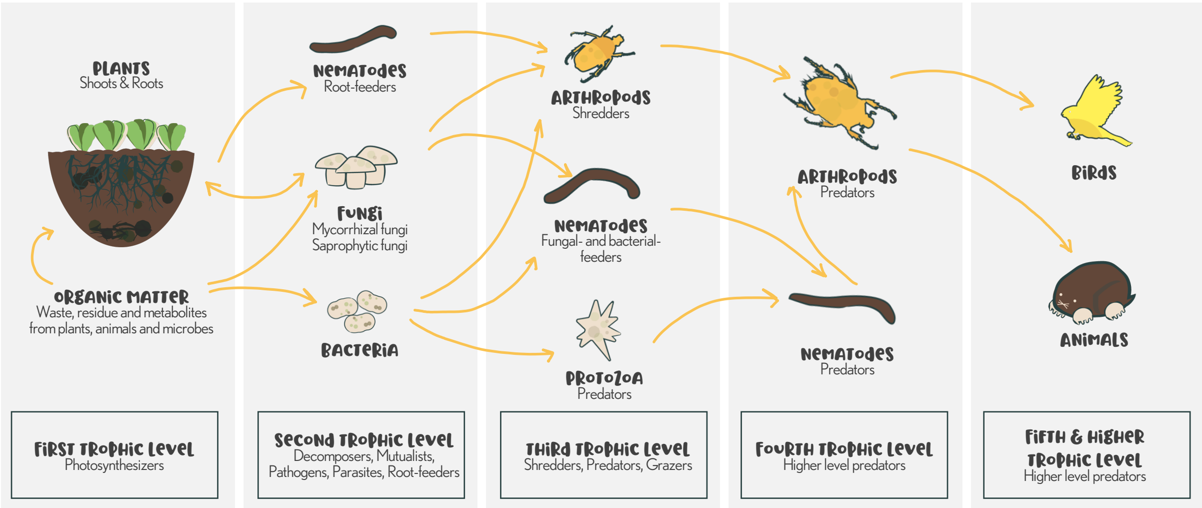
SOM & THE Soil Food web



Trophic levels: refer to the type of food consumed by soil organisms; reflects the flow of energy through the system

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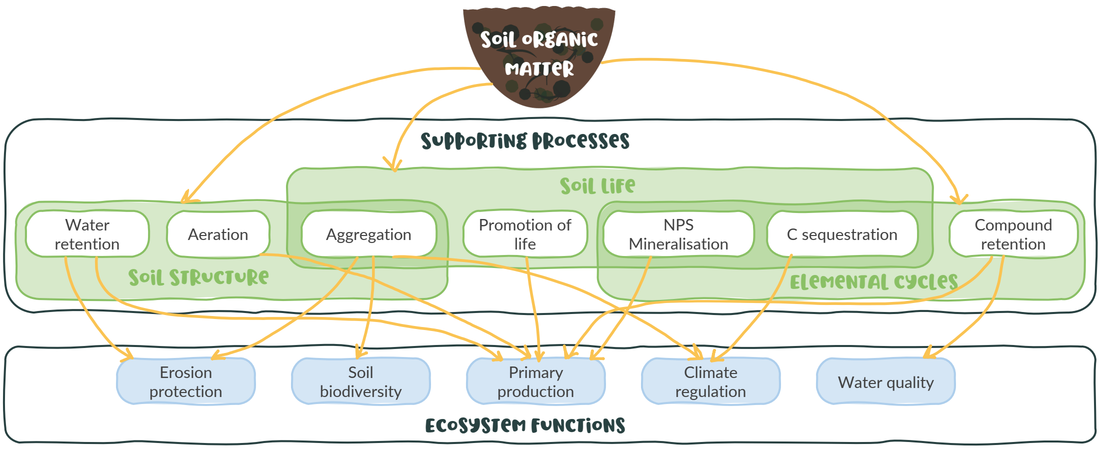
SOM & Soil FUNCTION

Ecosystem functions of a soil organic matter and the processes supporting them



Adapted from source: 'Eco-functionality of organic matter in soils', Hoffland et al, 2020

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NATURAL FACTORS THAT INFLUENCE SOM

Temperature	Rainfall	Soil Texture	Type of vegetation
SOM tends to be lower in hotter regions due to higher levels of microbial activity and faster decomposition of organic matter	Soils in arid regions generally experience low OM due to low levels of vegetation and low microbial activity. Soils in areas of high rainfall may also have low OM due to saturation and waterlogging restricting aeration	Fine-textured soils (clay/silt) tend to have higher OM levels due to strong OM/soil particle chemical bonds which protect OM from microbial decomposition, plus reduced decomposition from smaller soil aeration pores	Grassland soils contain more & deeper levels of OM than forest land due to deep & extensive root systems with high turnover rates. Forest soils may have a thin surface layer of high OM (up to 50%) but much poorer mineral layer beneath

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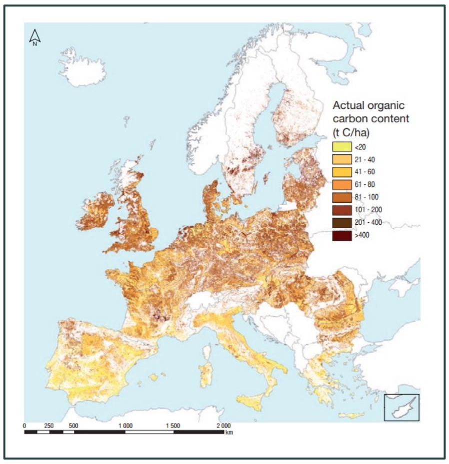
Soil organic carbon (SOC)

- 'The living & dead components of organisms, including fine plant roots, root exudates, fungi, microbes & decomposing organic matter from plant litter or animal products such as manure' – British Society of Soil Science
- SOC can be increased/decreased via management change – but on timescales of years to decades
- SOC highly variable from <1% in arid soils to >50% in peatlands
- Typically <5% in most agricultural soils
- 40-60% SOC lost from many arable soils across the EU in recent decades



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Soil organic carbon (SOC)

Carbon sequestration	Carbon store	Carbon sink	Carbon source
A net transfer of carbon from the atmosphere to land (either into soil or vegetation)	A medium that stores carbon. In a given period, the amount of C may be increasing, decreasing or static	Any reservoir or medium that accumulates & stores more C than it loses over a reference period	Any reservoir or medium that loses more C than it accumulates over a reference period

Source: British Society of Soil Science

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Soil organic carbon (SOC)

- Carbon is the forth most abundant element
- When organisms die & decompose, their remains form organic matter of which c.58% is carbon
- On land this combines with weathered minerals to form soil
- Soil is the second largest carbon store (after oceans) holding 80% of terrestrial carbon (3x that in atmosphere)
- 2.3gt soil carbon (2.3trn t) to 3m depth; 1.5gt in top 1m.
- 1t SOC = c3.6t atmospheric CO_2

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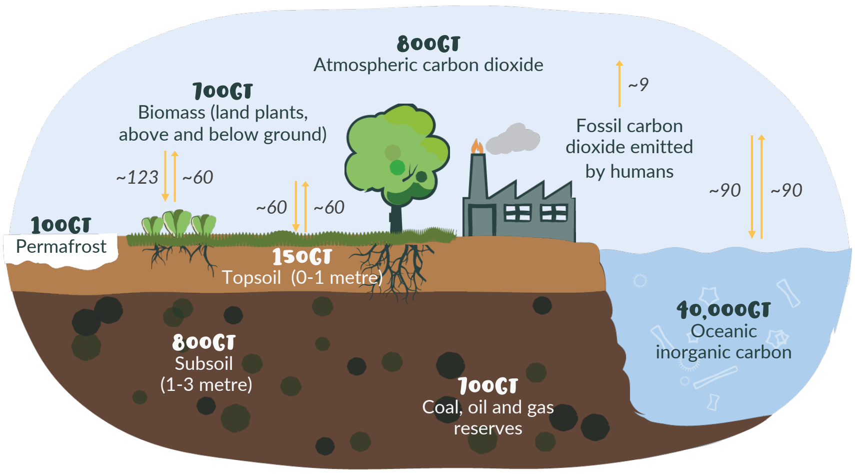
Soil organic carbon (SOC)

Carbon stock and flows on land and in the oceans

- Numbers in **bold** are stocks in Gigatonnes (Gt)
- Numbers in *italic* are flows in GT C per year.



Adapted from British Society of Soil Science – Soil Carbon science note

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Soil organic carbon (SOC)

- CO_2 absorbed by plants via photosynthesis creating biomass
- Biomass enters soil as leaf litter, exudates, root material etc
- In aerated soils, most of this C is converted back into CO_2 via soil organisms & respiration
- A smaller, stable fraction is retained
- Soil carbon cycling integrated with nutrient cycling: soil organisms mineralise OM to make key nutrients ‘plant available’
- Soil type important: soil C turnover reduced in highly acidic/dry/wet conditions, e.g. peat bogs

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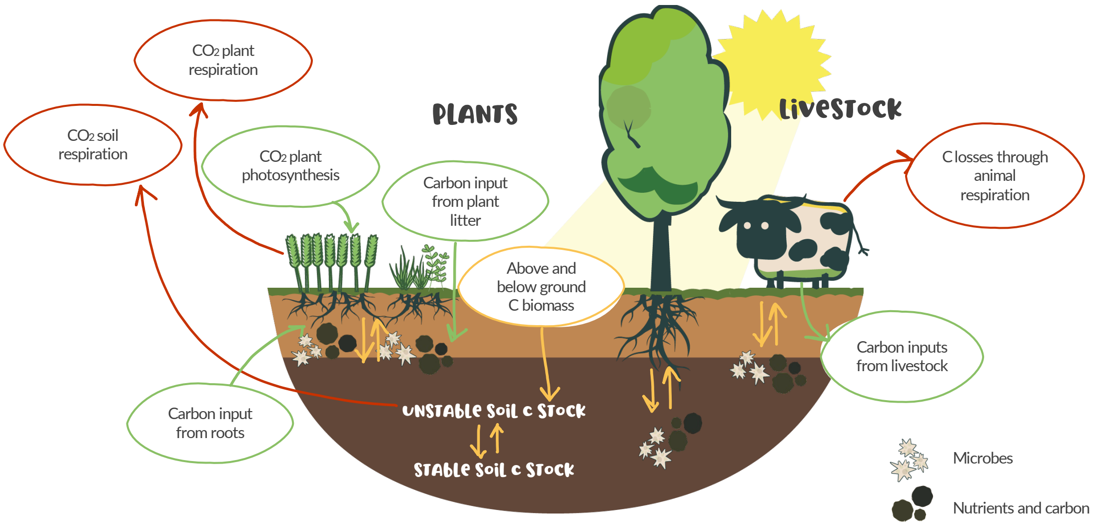
Soil organic carbon (SOC)



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Soil organic carbon (SOC)

- In stable ecosystems, photosynthesis (carbon gain) & plant/microbial respiration (carbon loss) are in balance = no net effect on atmospheric CO_2
- In agricultural systems, additional carbon lost via removal of outputs (crops, livestock) and via livestock respiration
- Additional carbon also gained from green manures, organic manures & other amendments (e.g. biochar)
- In many agricultural settings, the rate of carbon loss via respiration (from cultivation & bare soil) exceeds the rate of photosynthesis = depletion of SOC

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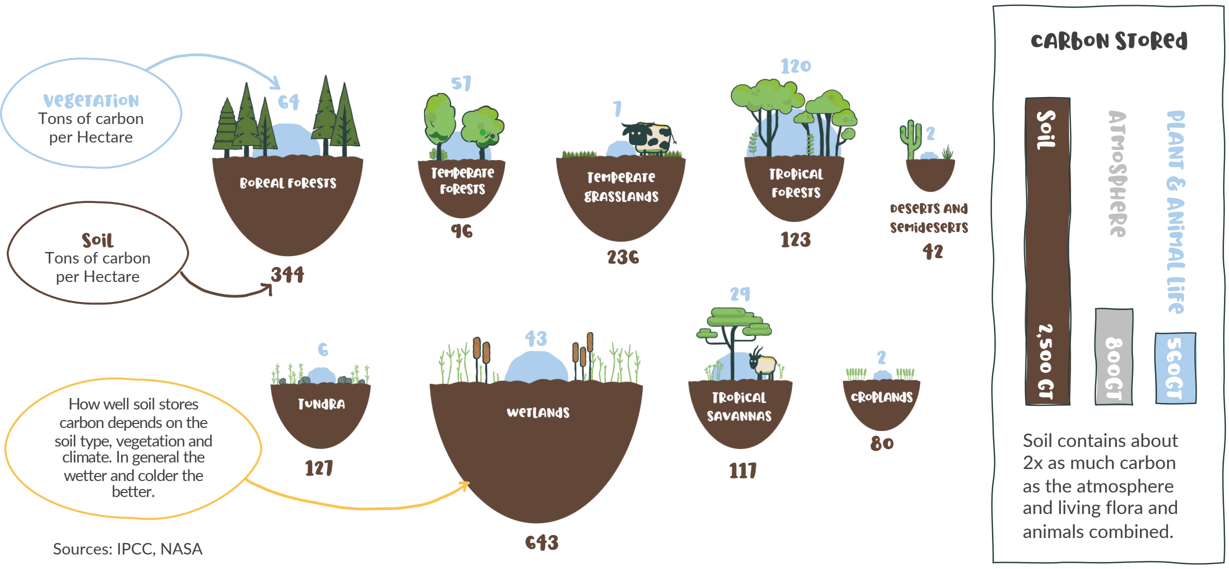
CARBON STORAGE



Soil contains about 2x as much carbon as the atmosphere and living flora and animals combined.

Sources: IPCC, NASA

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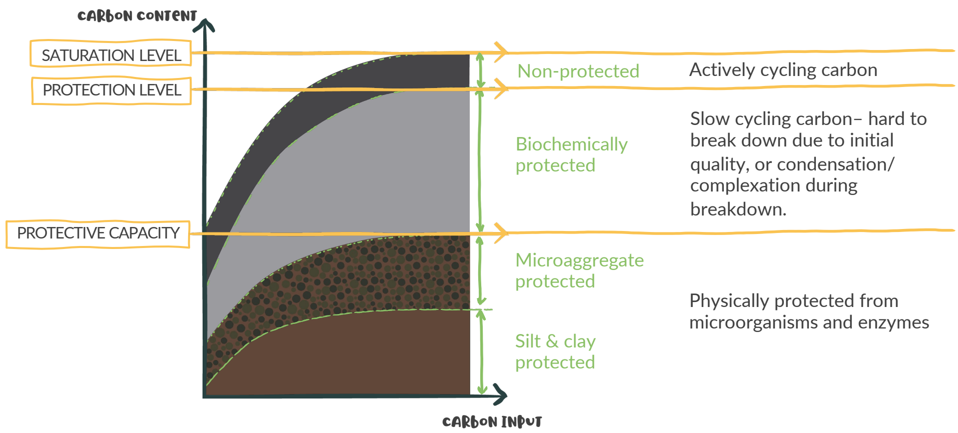
FAST & SLOW CYCLING SOC



Source: Six et al. 2002, Stabilization mechanisms of soil organic matter: implications for C-saturation of soils

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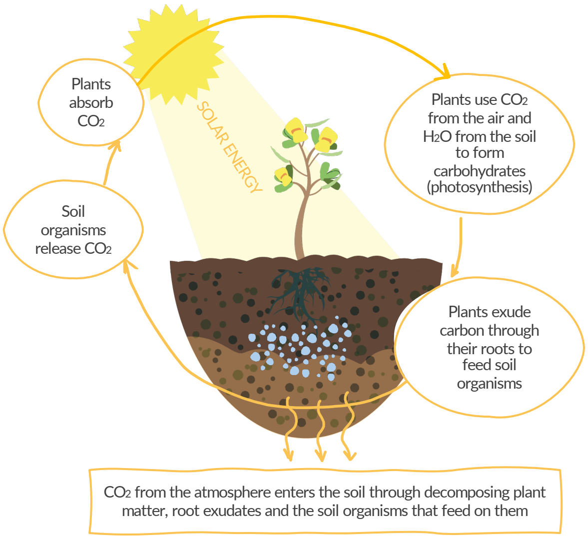
Soil organic carbon (SOC)

- Biochemically protected carbon generally unpalatable to microbes, potentially woody materials high in tannin & biochemically unavailable
- Also potentially in anaerobic conditions which reduce microbial activity
- Soil carbon sequestration requires keeping slow cycling carbon in the soil & converting a % of the active cycling carbon
- Heavy, wet, cold soils will see more actively cycling carbon converted than warm, loamier soils where more will be respired & lost
- Mineral soils have a carbon saturation point, but degraded soils can be built more rapidly. Thin/sandy soils have a low saturation point



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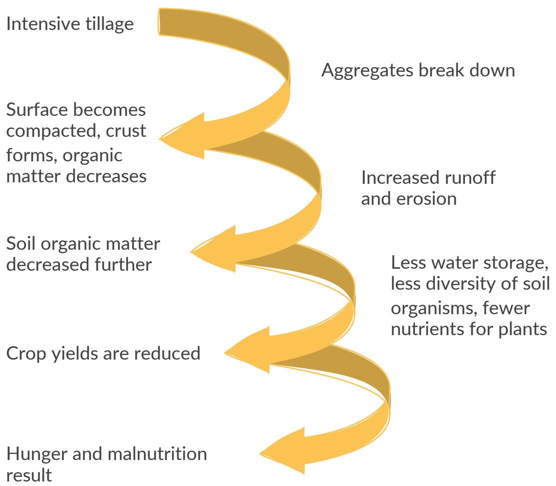
SOM/SOC degradation

- Since 1750 global carbon emissions estimated at:
  - **270bn tonnes** (±30bn tonnes) from fossil fuel combustion
  - **136bn tonnes** (±55bn tonnes) from land use change & soil cultivation
  - Of which depletion of SOC = **78bn tonnes** (± 12bn tonnes)
- Some cultivated soils have lost 50-65% of SOC
- Cumulative loss of 30-40t carbon/ha

Source – Lal, 2004



The downward spiral of soil degradation. Modified from Topp et al.

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Soil Inorganic Carbon (SIC)

- Significant amounts of inorganic carbon can occur in soils – especially, e.g. in chalk/limestone regions via weathering of those rocks
- Generally more stable than SOC & accounts for c.38% of total soil carbon pool
- More abundant in low rainfall regions vs temperate zones
- SIC not included in measurements of soil organic carbon
- SIC does not contribute to soil organic matter
- Techniques such as Enhanced Rock Weathering (ERW) may increase the volume of carbon locked in soils as SIC

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Soil as a Natural Capital Resource

Natural capital: the world's stock of natural resources (air, water, geology, soil, living organisms) which provide ecosystem services & underpin society & the economy

Soil natural capital services:

- supplying a suitable environment and conditions to grow food
- reducing the risk of flooding by absorbing water
- filtering water
- absorbing and reducing pollutants
- regulating our climate and gases in the atmosphere
- providing habitat for soil dwelling organisms and their associated services such as pest control and pollination
- protecting cultural heritage
- providing a stable platform for buildings
- providing raw materials
- the potential for new life saving medicines

(Natural Capital Committee, UK)

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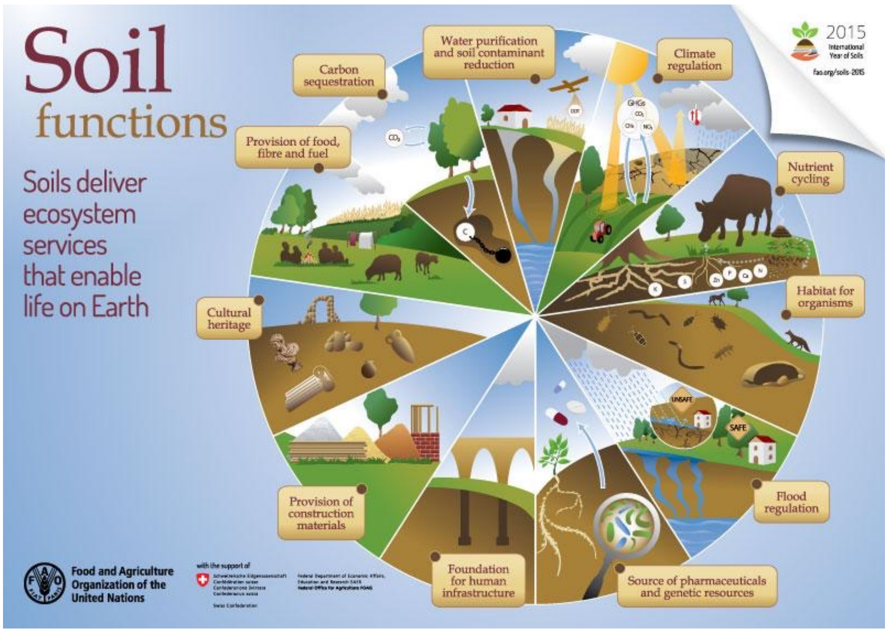

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Impact of Soil Carbon Sequestration

Summary of the impact of soil carbon sequestration on soil function, ecosystem services & United Nations Sustainable Development Goals

- Environmental, natural capital & climate benefits
- Productivity & resilience benefits
- Economic benefits
- Health & community benefits

Source: Smith et al, 2019

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CONCLUSIONS
• Agricultural practices can modify soil properties, including biology & organic matter
• Long-term degradation of soil health linked to agriculture impacts productivity but also, via carbon loss, the health of global ecosystems.
• Effective soil management must enhance soil health to:
• Build soil resilience
• Store/sequester carbon
• Minimise risk of soil degradation & environmental pollution

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