Water Management in Regenerative Agriculture

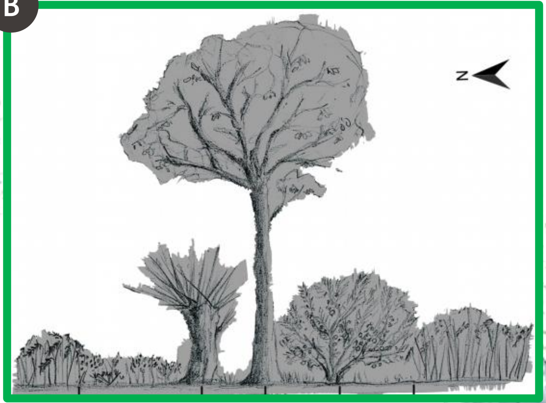
– Soil, Agroforestry & Keyline Design –

Irrigation and Drainage Engineering

ENV-549

A

B



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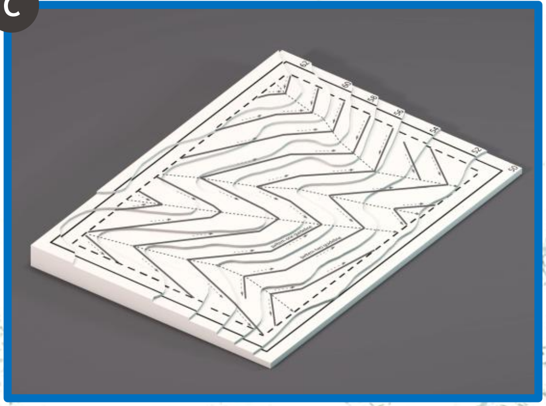

Robin Monard

December 10, 2024

Welcome !

… to today’s guest lecture. Short presentation …

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2020
M.Sc. Environmental engineering (TUM / EPFL)

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Before we start

Extra Info Slide

- Ask questions at any time!
- References on the slides are listed in appendix
- Setting the context – A little reminder

$$\boxed{B_n = ETM - P_e - R}$$

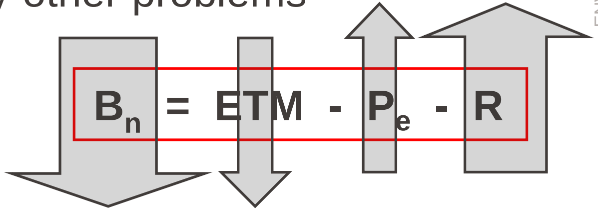
B_n: net irrigation water requirements

ETM: maximum evapotranspiration

P_e: effective precipitation

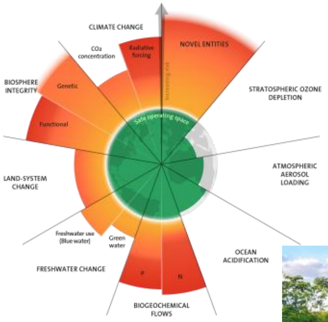
R: reserve available at the start of the calculation period

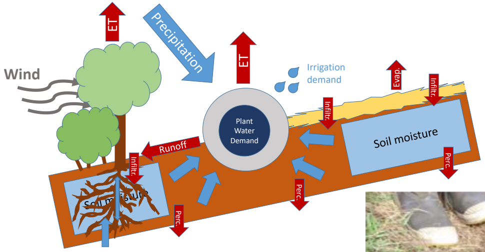
→Today's question: How to reduce the net irrigation water need ?!
… while at the same time discovering solutions to many other problems

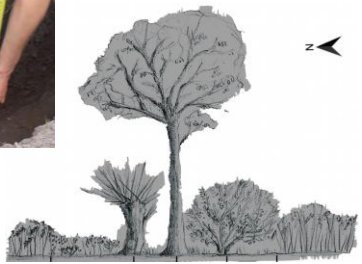


Structure

Introduction	Water Management in Regenerative Agriculture (RA)	Outlook







Why regenerative agriculture (RA) ? – The obvious reasons

Water shortage problems

Water excess damages

Why regenerative agriculture (RA) ? – The obvious reasons

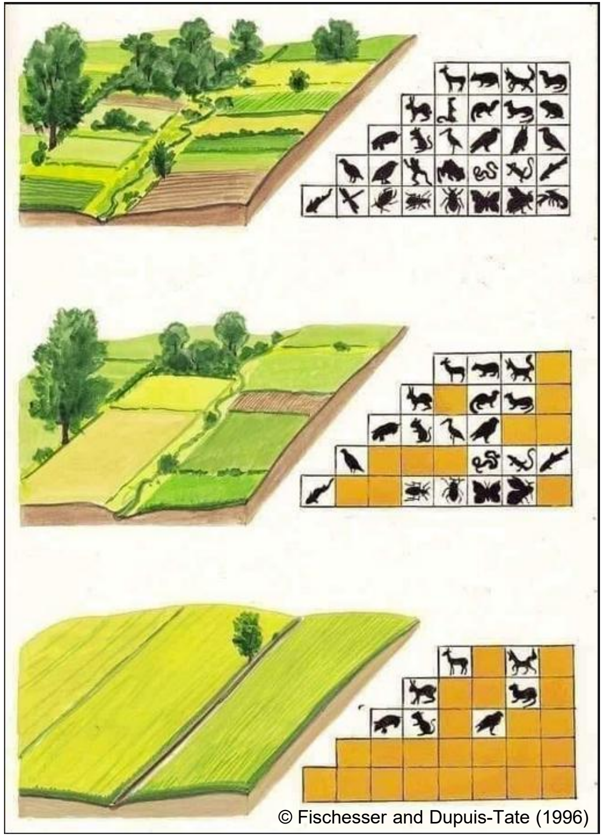
© USDA

© EPA

Water quality problems

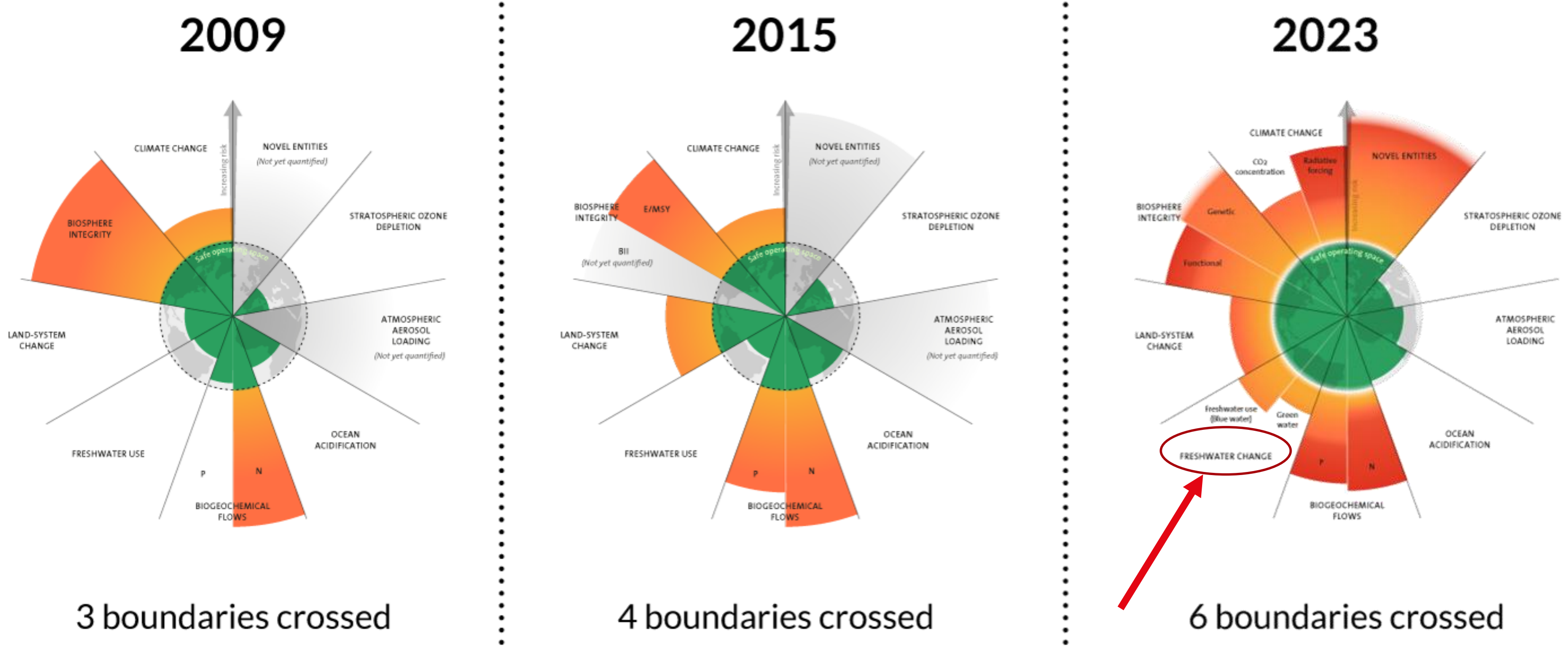
Biodiversity crisis

© Iberdrola



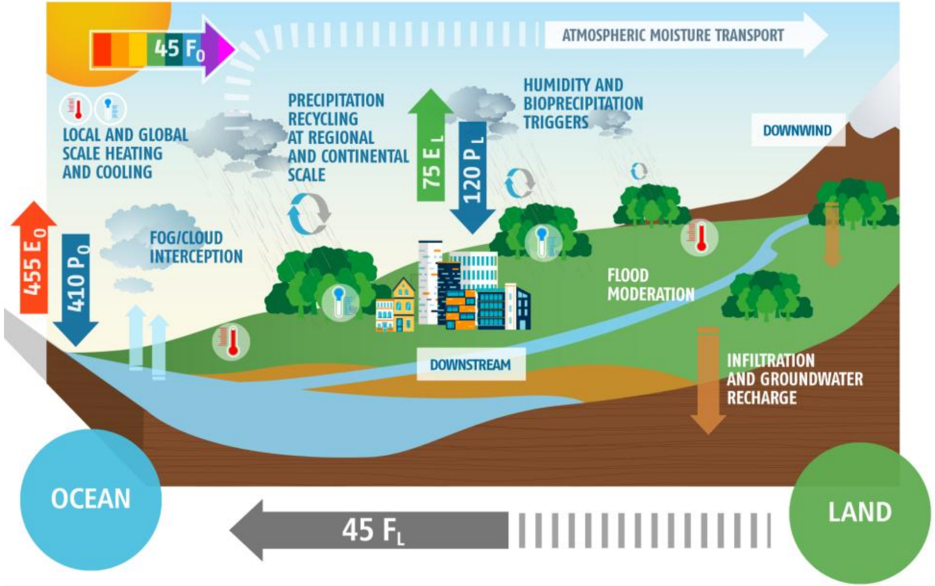
© Fischesser and Dupuis-Tate (1996)

The bigger picture: Planetary boundaries



(Richardson et al. 2023)

Green water and precipitation recycling



The global hydrologic landscape (Ellison et al. 2019)
Quantifications of water flows in 1000km3 per year

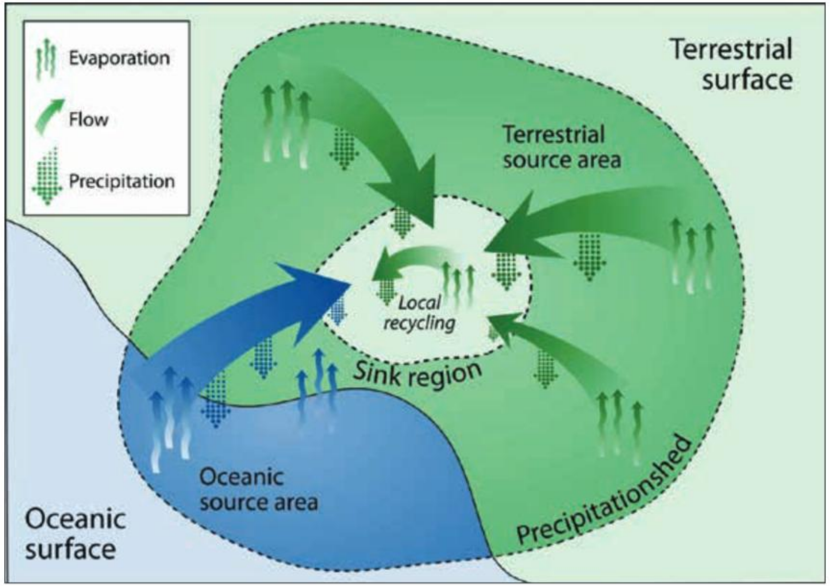
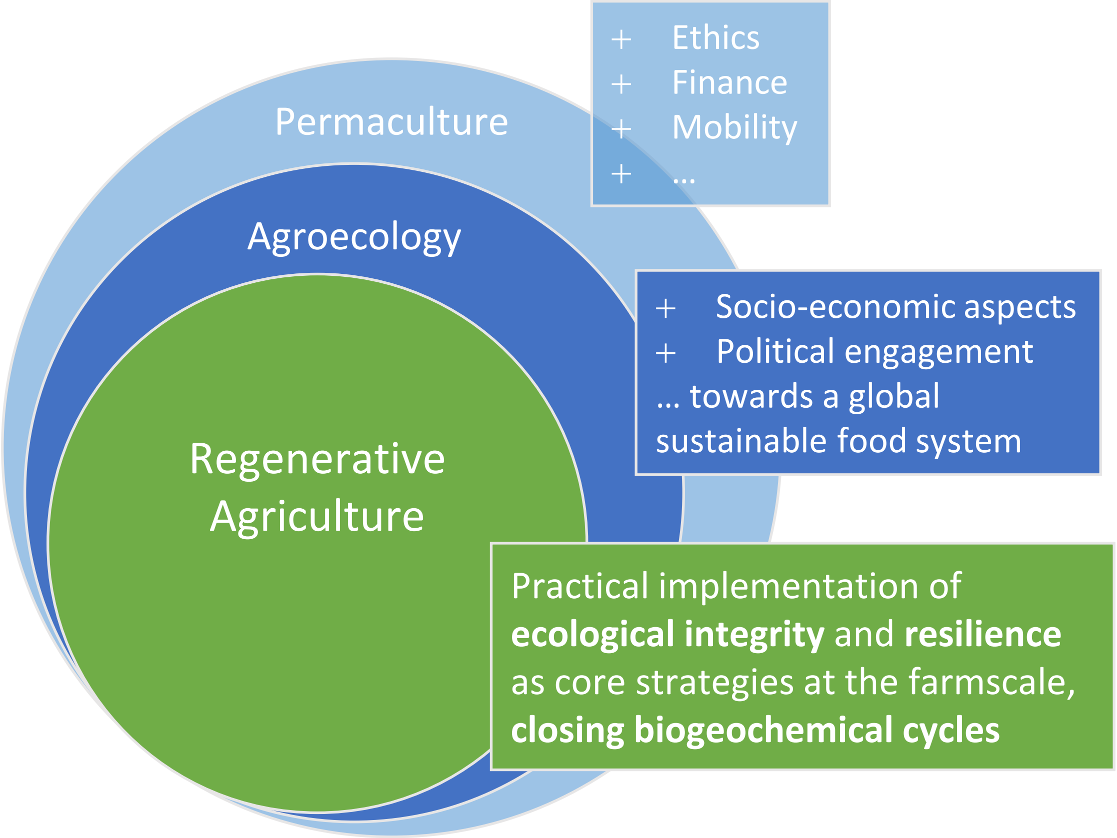


Diagram of a precipitationshed (Keys et al. 2012)

What is regenerative agriculture?



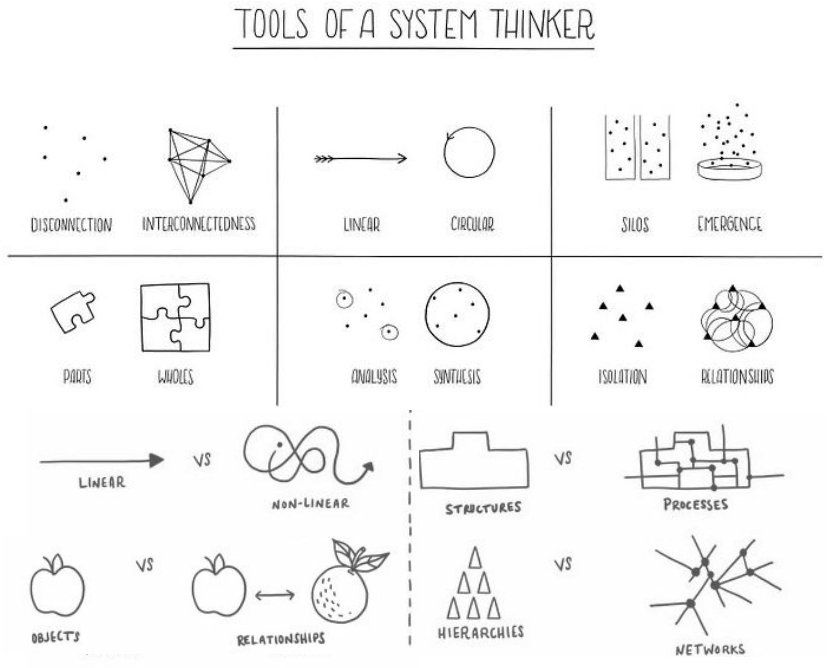
Regenerative Agriculture – Goals

1) Soil
   Contribute to building soils along with soil fertility and health.
2) Water
   Increase water percolation, water retention, and clean and safe water runoff.
3) Biodiversity
   Enhance and conserve biodiversity.
4) Ecosystem health
   Capacity for self-renewal and resiliency.
5) Carbon
   Sequester carbon. (→ Sink instead of source!)

(Elevitch et al. 2018)

Regenerative Agriculture – Core principles

1) Systems thinking



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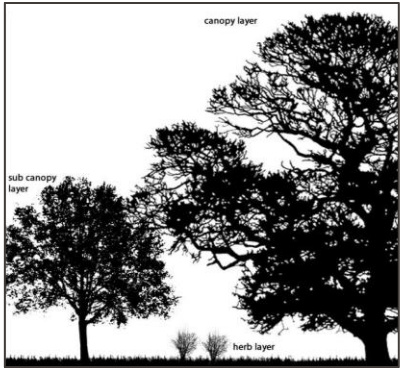
2) Ecosystem mimicry

Layers of the temperate deciduous forest



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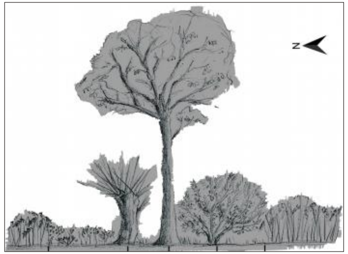
Agroforestry system



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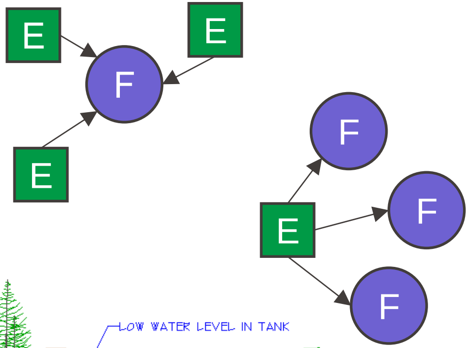
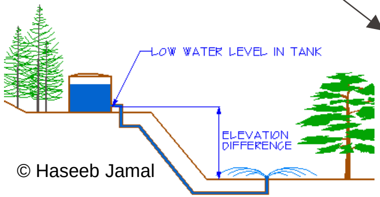
Regenerative Agriculture – Strategies

- Functional redundancy



- Multi-functionality
- Energy conservation



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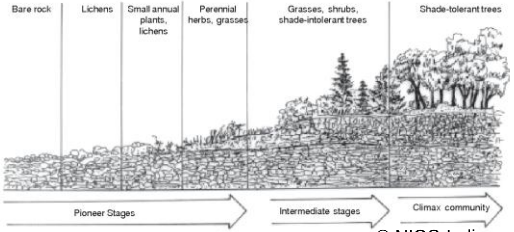
- Maximum diversity

© ILO

- Natural succession



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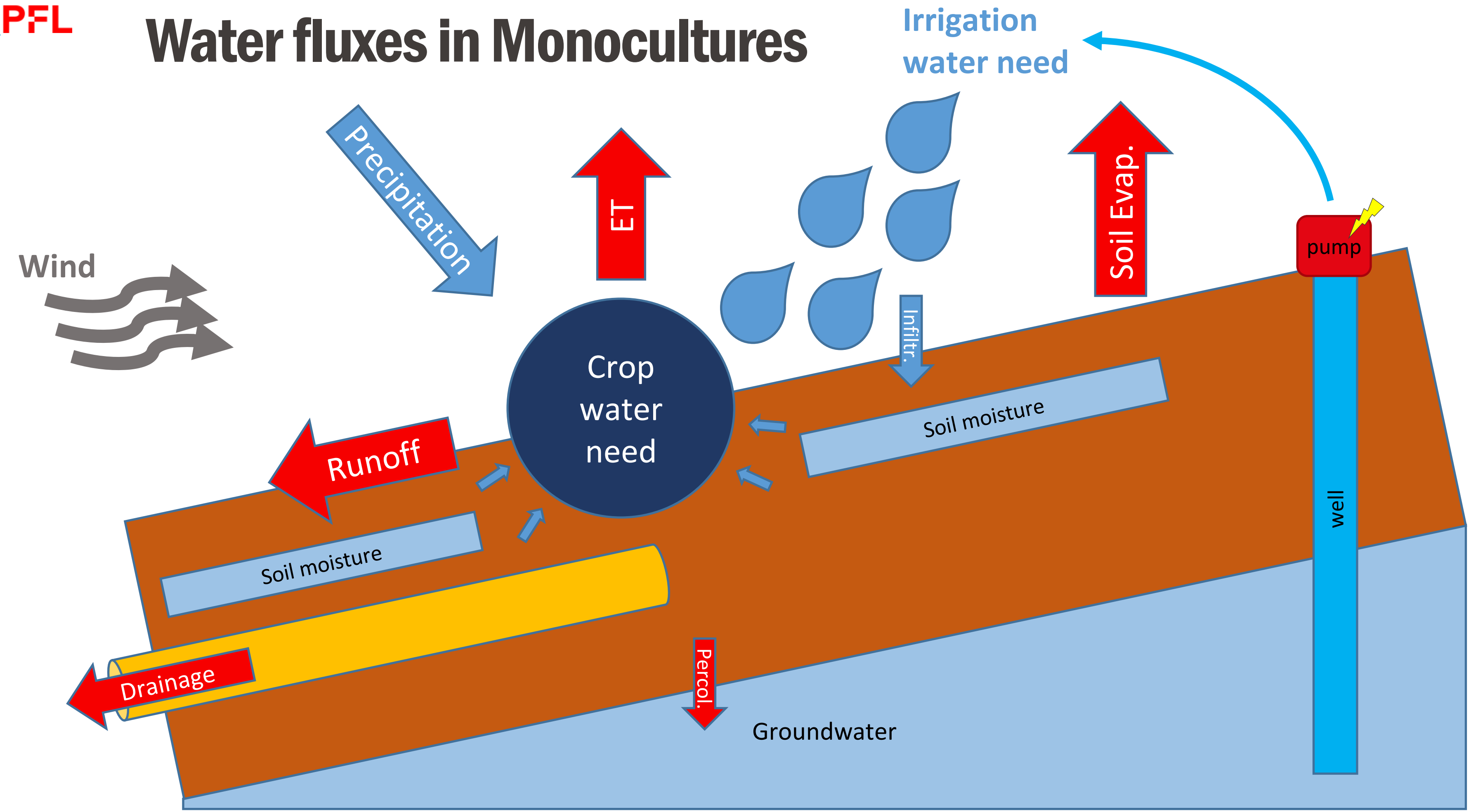
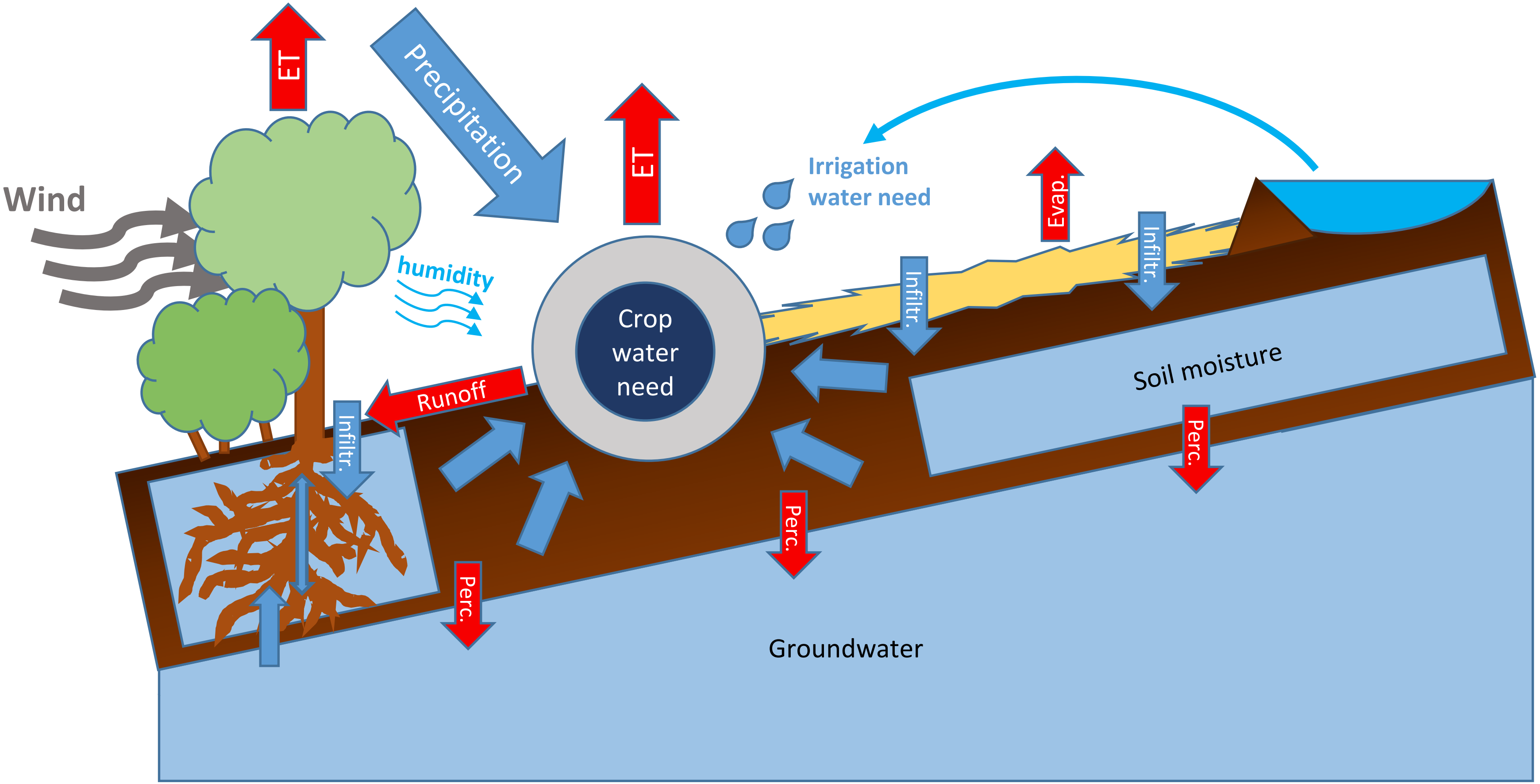
Regenerative Agriculture Practices – An Overview

Ground cover management		
Soil building		
Integration of trees and shrubs	Agroforestry Systems (AFS)	
Water harvesting and Regen. hydrology	**Rainwater harvest and redistribution**: Keyline Design	**Atmospheric water harvest**: *Dew collection; Fog collection*
Crop diversity and Crop choice	**Adaptive crop choice**: *Crops adapted to (a changing) regional climate and to local site conditions* **Genetic diversity**: *Robust varieties; Composite-Cross-Population (CCP) seeds* **Crop diversity in time and space***: Crop rotation; Synergistic cropping, Intercropping, Polycultures*	
Local nutrient cycling	**Composting | Residue retention** **Integration of crops and livestock** **Natural nutrient supply**: *Biological N-fixation; Microorganism supported P-supply; Compost tea*	
Natural pest and weed management	**Preventive measures**: *Support of beneficial organisms; Soil health; Crop diversity and crop selection* **Natural plant strengthening agents**: *Compost tea; Liquid plant manures* **Mechanical weed control | Biopesticides** (last resort)	

Water fluxes in Monocultures

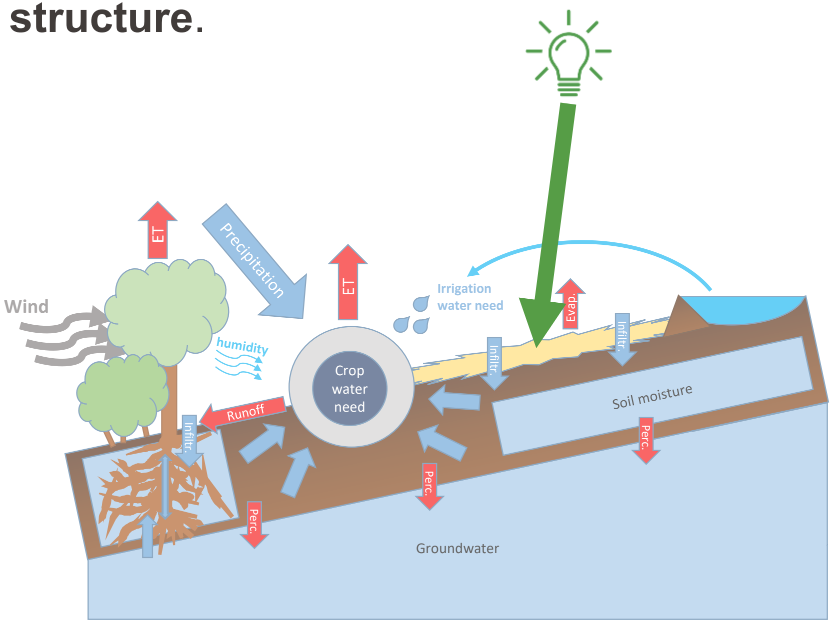


Water fluxes in Agro-ecosystems



Ground cover practices

- No bare soils to
  - **keep the moisture** in the topsoil,
  - **protect it from UV** radiation
  - and thus preserve **soil life** and **crumb structure**.
- Examples
  - **Mulching**
  - **Cover crops** and **catch crops**
  - **Understory crops**



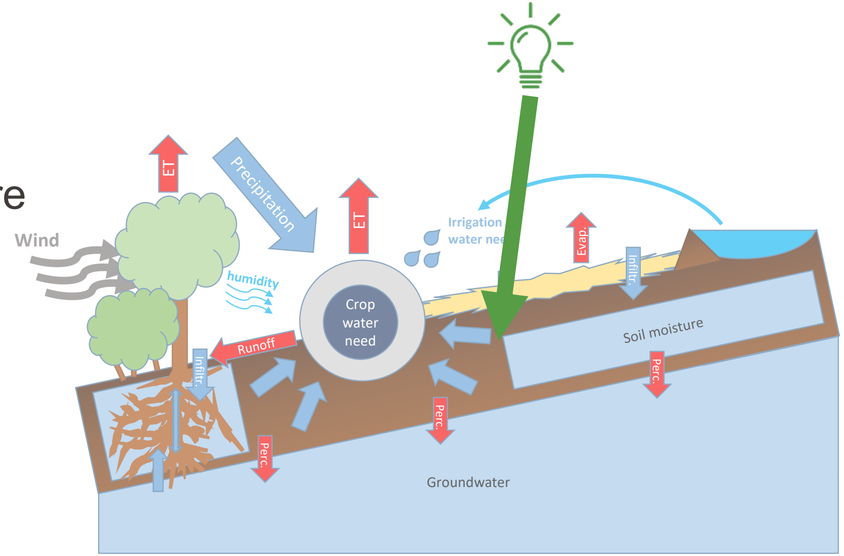
Soil building – Soil organic matter and water retention

- Goal: Increase **soil water retention** (SWR)
  - → increased soil moisture
  - → decreased irrigation water need
  - → less runoff and erosion
- Key characteristics to **improve SWR**
  - Increased **soil organic matter** (SOM)
  - Increased **pore space**
  - Depth of the **root system** / rhizosphere

1% SOM in the top 15cm of soil
can hold about
250000 L/ha = **250 m3/ha** = 25 L/m2 = 25mm
of water

(USDA 2014)

Note: Different studies find different values, but the message is the same

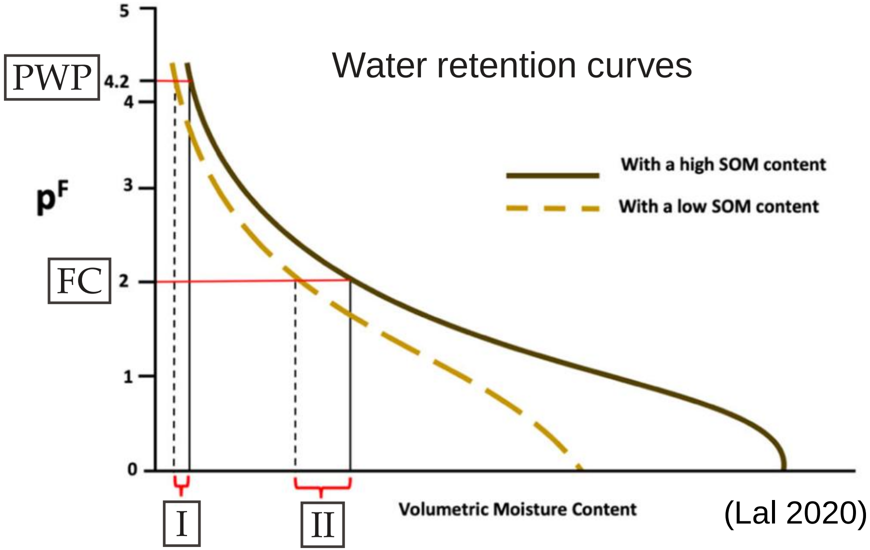


Soil building – Plant available water capacity (PAWC)

Increase in Soil organic matter (SOM) content

- increases SWR more at field capacity (FC) than at the permanent wilting point (PWP)
- **increases Plant available water capacity (PAWC)** for all soils (sand, silt, and clayey texture)
- increases **drought resilience** also for degraded and depleted soils

PWP	Permanent Wilting Point
FC	Field Capacity
I	SWR increase @ PWP
II	SWR increase @ FC
II – I	PAWC increase with high SOM content



(Lal 2020)

Soil microorganisms – Example of mycorrhizal fungi (MF)

Fungi trading networks

- **Water transport** by mycorrhizal fungi (MF) to host plants
  - → MF can access **micropores** not available to plant roots
- **Nutrient exchange** between MF and host plants
  - → C (sugar) ←→ P/N/…

© Emmanuel Lattes / Alamy Stock Photo

EPFL

Soil building practices

Table 2. The summary on effects of agricultural practices on soil and water conservation and on other variables. The effects are compared to conventional tillage and use of agrichemicals. (Effect indicators: ↑ positive, / neutral, ↓ negative).

Practice	Soil Conservation	Water Conservation	Other
Cover/catch crops	↑ soil structure ↑ soil erosion ↑ soil organic matter (SOM)	↑ soil moisture ↑ soil water capacity ↑ runoff ↑ water quality downstream	↑/↓ crop yield ↑ nutrient regulation ↓ weeds ↑ biodiversity
Residue retention/mulch	↑ soil erosion ↑ SOM	↑ soil moisture ↑ evapotranspiration ↑ runoff	↑↓ crop yield ↑ weeds ↑ fungus
No-till/direct seeding	↑ soil erosion ↑↓ SOM	↑ soil moisture ↑ soil water capacity ↑ runoff ↑ water quality downstream	↓/↑ crop yield ↑ nutrient regulation ↑ weeds ↑/ pests
Minimum tillage	↑ SOM	↑ soil moisture ↑ soil water capacity	↓ crop yield ↑ weeds
Crop rotation	↑ soil structure ↑/ SOM	↑ soil water capacity	↓↑ crop yield ↑ nutrient regulation ↑ weeds ↑ crop diversity
Intercropping	↑ soil structure ↑/ SOM	↑ soil water capacity	↓↑ crop yield ↑ nutrient regulation ↓ weeds ↑ crop diversity
Organic agriculture	↑ soil structure ↑/ SOM	↑ soil water capacity	↓/ crop yield ↑ nutrient regulation ↓↑ weeds ↑ crop diversity
Agroforestry	↑ soil structure ↑ soil erosion ↑ SOM	↑ soil water capacity ↑ evapotranspiration	↑ crop yield ↑ nutrient regulation ↑weeds ↑ crop diversity ↑ micro-climate ↑ carbon sequestration

RA farming approaches
Minimum mechanical soil disturbance
Maintaining a living root system
Organic material supply
Soil life stimulation

- Subsoiling
- Rotational grazing / holistic-planned grazing
- Biochar and Terra preta
- Composting
- …
- …

(Choden & Ghaley 2021)

Agroforestry systems (AFS) – Definition and effects

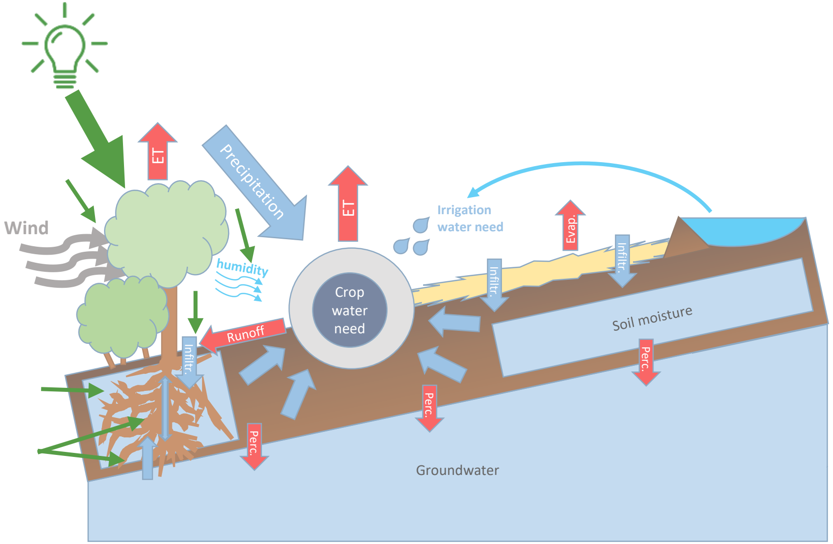
Effects on water fluxes

- **Windbreak** → Protection from drying winds
- **Runoff barrier** → Water interception and infiltration
- Increased **Soil water holding capacity**
- Biological irrigation by **Hydraulic redistribution**
  - → Deep-rooting (woody) plants vertically redistribute soil moisture
  - → **Hydraulic lift**: Water supply from deeper soil layers to shallow-rooting crops
  - → Reverse hydraulic lift: Accelerated draining of upper layers following strong precipitation
  - → Hydraulic redistribution enhanced by microorganisms and **mycorrhizal networks**
- **Microclimate** (Temperature buffering, humidity, …)
  - → Reduced heat stress, improved crop quality/yields

Definition

«Land-use systems where woody perennials (trees, shrubs, etc.) are used on the same land as agricultural crops and/or animals»

(FAO, short version)

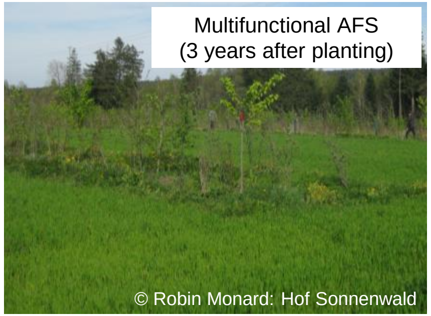


Agroforestry systems (AFS) – Further benefits

- **Aesthetics**
- **Nutrient lift**
- **Shelter for livestock**
- **Fodder** for livestock
- **Erosion control** → soil stability
- Build-up of **soil organic matter**
- Wood and **tree products** → timber yields
- Introduction of **mycorrhizal fungi** and networks
  → soil health, water and nutrient availability
- **Crop diversification** → resilience and productivity
- Wildlife **habitat** → biodiversity and pollinators
- **Wildlife corridors** → ecological habitat connectivity

© Wilson et al. 2018

AFS classifications – Distinction by …



… Dominant land-use

1) **Silvoarable** AFS → field crops
2) **Silvopasture** AFS → pasture
3) **Agrosilvopastoral** AFS
4) **Plantation** AFS → orchards, vineyards, or other perennials

… Complexity (Lovell et al. 2018)

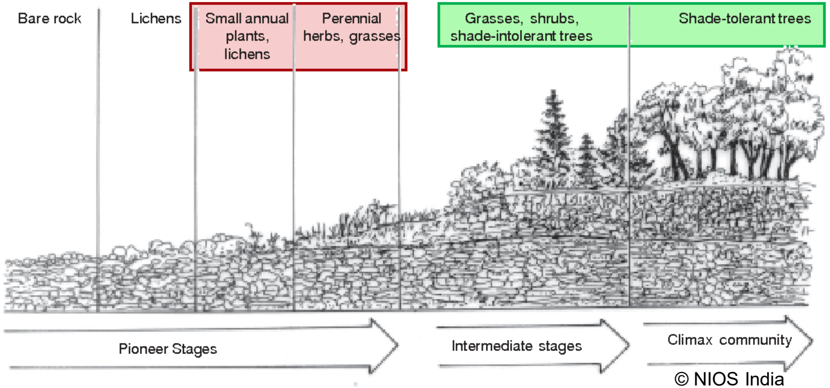
1) **Integration** of woody plants in agriculture, e.g. fodder hedges, wind breaks
2) Woody plants as **productive components** (nuts, fruits, timber, …), e.g. alley cropping
3) **Multifunctional AFS**, i.e. stratified species assemblages

… Spatio-temporal evolution (Siminski et al. 2016)

1) **Static AFS**
   Active management to preserve a more or less static composition and structure
2) **Dynamic or Successional AFS** (SAFS)
   Multi-stratum AFS, designed and dynamically managed based on ecological succession

Successional Agroforestry Systems (SAFS)

- Concept of SAFS
  - Conventional agriculture artificially fixes natural succession at early stage, traditionally by plowing → working 'against' natural processes
  - SAFS **mimic ecological succession processes** to capture carbon, water, nutrients → working 'along with' natural processes
  - Succession processes are **artificially accelerated** by targeted intervention → planting, pruning, thinning, harvest
  - **Disturbance events** occur **naturally** (e.g. end of life of fruit tree) **or** are **intentionally** caused (e.g. timber harvest)
- Well-designed SAFS
  - are subject to **continuous change** → "Succession of cultivated plants"
  - have a **similar structure to native forests**
  - are **multifunctional**



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Ecological succession (= Natural succession)
- **Process of change in the ecological community** in a certain environment over time
- Locally and periodically **reinitiated** following a severe **disturbance event**
- In natural ecosystems, the successive phases are **distributed in time and space**

Agroforestry design considerations

- General considerations
  - Regional and local **climate** (P, T, Wind)
  - **Site conditions** (Topography, Geology, Soil)
  - **System dynamics** (Initial VS. Projected conditions)
  - **Legal restrictions**
  - Socio-economic context
- Band pattern: Geometry and orientation based on
  - **Topography** (Keyline Pattern, Contour lines)
  - **Climatic considerations** (Wind direction, Shadowing effects)
  - **Farm characteristics** (Machinery dimensions, Land parcel shape)
- Tree crop selection based on
  - **Farmer's aims**, maturation and other management considerations
  - **Species compatibility and synergistic interplays**
- Design principles for multifunctional AFS
  - High density and **high diversity** (structural and functional)
  - Promotion of complementary plant associations


© Volterra


© Forest research UK


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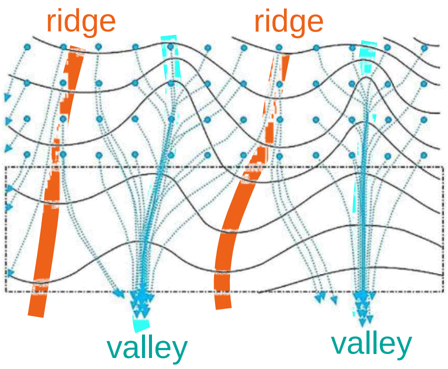
The concept of Keyline

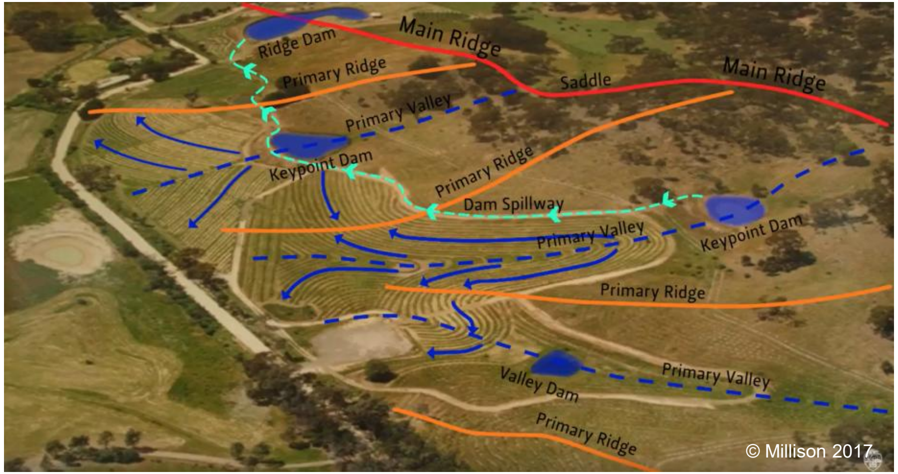


Keyline Design

- Methodology for **holistic farm design** and management ("Scale of Permanence")
- Analysis of where, how and when water can be harnessed
- Drainage and irrigation as interwoven disciplines
- "Let nature assist the farmer by **making use of landscape topography and hydrology**"

Concept

- Observation:
  Dry ridges and waterlogging in valleys
- **Capture water as high in elevation as possible and** use gravity to **guide it from wetter** (water excess) zones **to dryer** (water limited) **zones**
  - By developing landscape-specific **machining and cultivation patterns**
  - As well as **water collection, transport and storage structures**, if needed



Keyline Design – Effects and Principles

Keyline Design

Contour Farming

a) Local sedimentation of soil particles
b) Reducing runoff concentration
c) Increasing infiltration
d) Soil building practices
e) Guiding surface runoff and interflow
f) Storing and redistributing excess rainwater
g) Parallel line cultivation patterns

Erosion control (a, b)

Water retention (b, c, d)

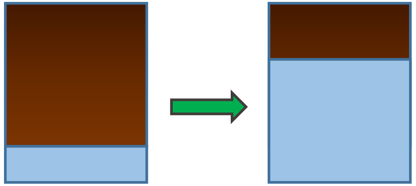
Water re-distribution (e, f)

Equidistance (g)

Principles			
	Soil	S4	Slow it Spread it Store it Sink it
	Reservoirs	R4	Receive Recharge Retain Release

Keyline Design – Further benefits

- **Groundwater recharge**



- **Surface water protection**
(drastically reduced nutrient and sediment loadings)

- Non-structural / Nature-based **flood mitigation**

- Landscape **aesthetics**

Flow control – Cultivation patterns and Subsoiling

Flow control through
Cultivation AND/OR Agroforestry bands AND/OR Subsoiling
along Keyline patterns!

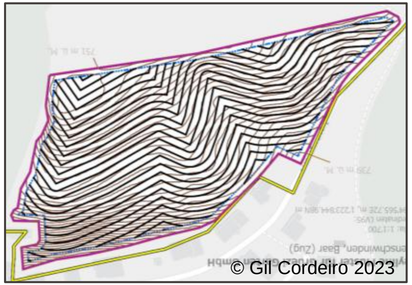

© VillaTierradelSol


© VillaTierradelSol

Subsoiling for

- Guiding of interflow along Keyline pattern
- Breaking up compacted layers
- Deep root development
- Improved soil water regime
- Improved soil aerobic conditions


© Perkins 2019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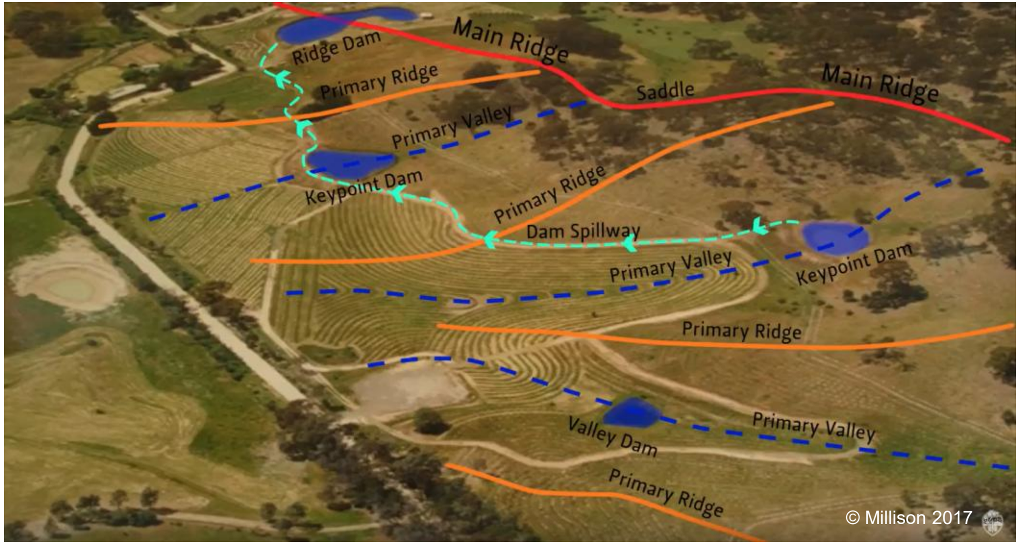
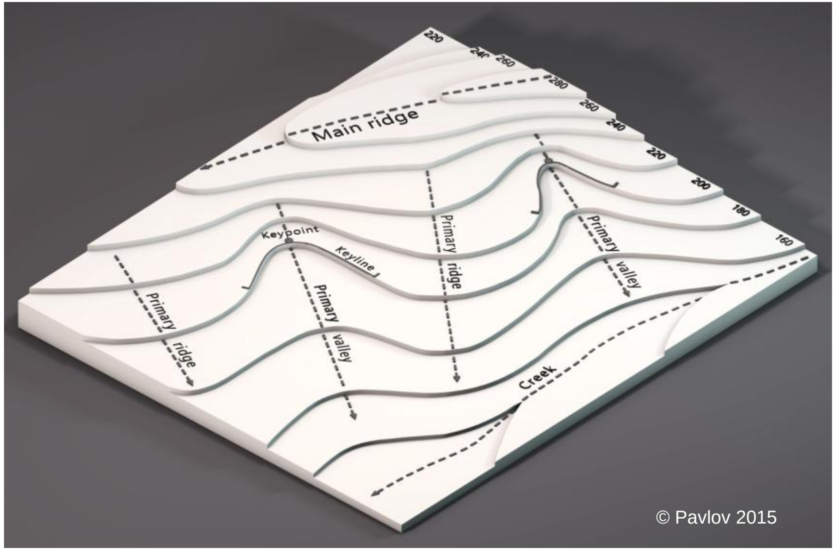
Timing	Not too wet soil (smearing), Not too dry soil (breaking), Moderate temperatures
Frequency	Depends on site conditions
Depth	Stepwise increase from year to year
Tools	Subsoiler / Flat lifter, e.g. Yeomans plow

Reading the landscape – Major landshapes



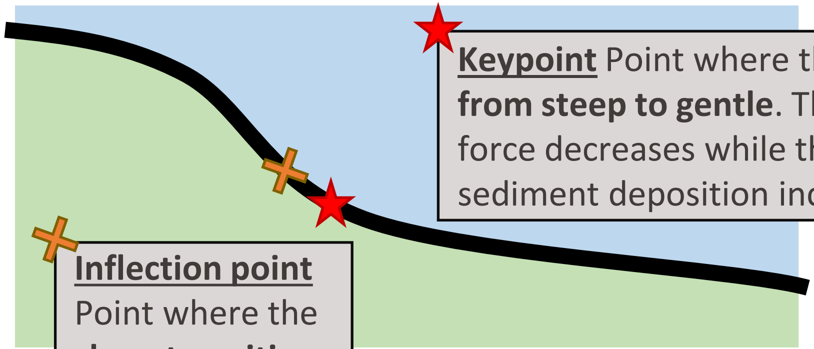
Main ridge
→ Watershed limit
→ Drainage divide



Primary ridge
→ centerline = downslope crestline

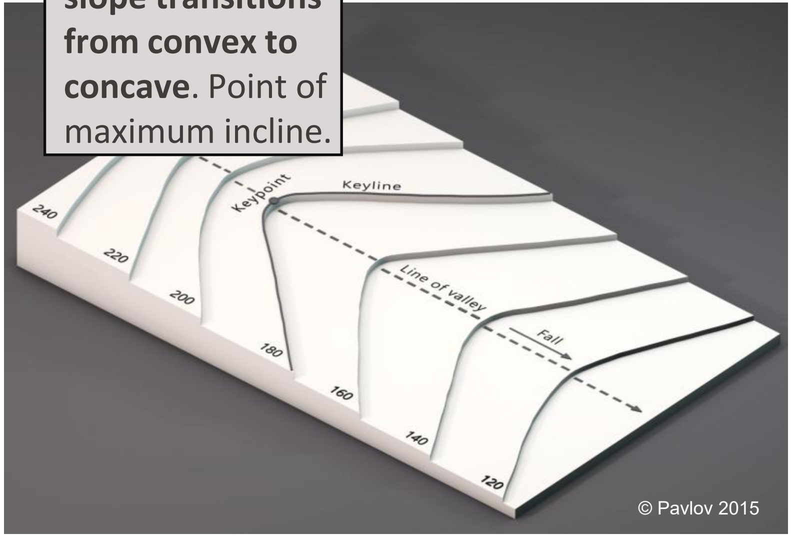
Primary valley
→ centerline = downslope thalweg

Contour maps and Keypoint



Keypoint Point where the **slope transitions from steep to gentle**. The hydraulic erosive force decreases while the tendency to sediment deposition increases.

Inflection point
Point where the **slope transitions from convex to concave**. Point of maximum incline.



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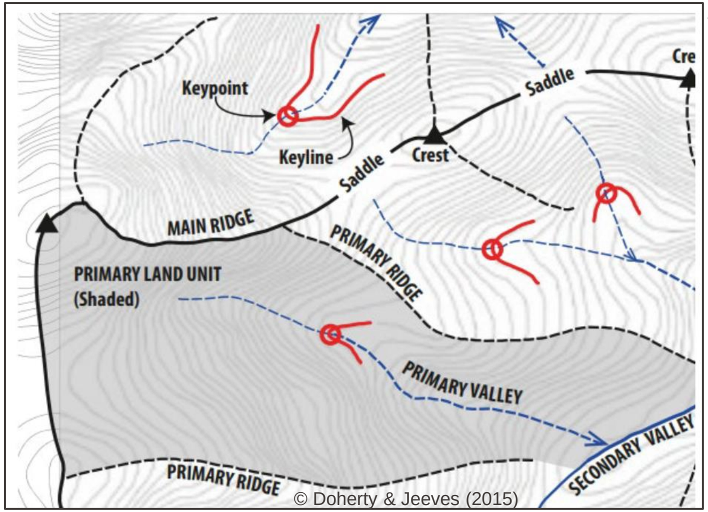


© Doherty & Jeeves (2015)

Keypoint

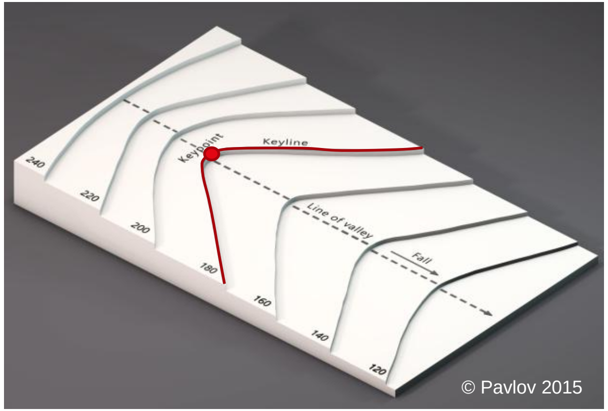
- Natural point of **runoff concentration***
- Often **high clay content**, natural deposition area
- Important for placement of dams and swales
- Nowadays less relevant for cultivation pattern development thanks to modern-day GIS technology and RTK-GNSS surveying

*might be determined via a GIS based surface runoff simulation

Traditional pattern design – The keyline

General goal (Reminder)

- Equidistant cultivation pattern
- Water flow from valleys to ridges



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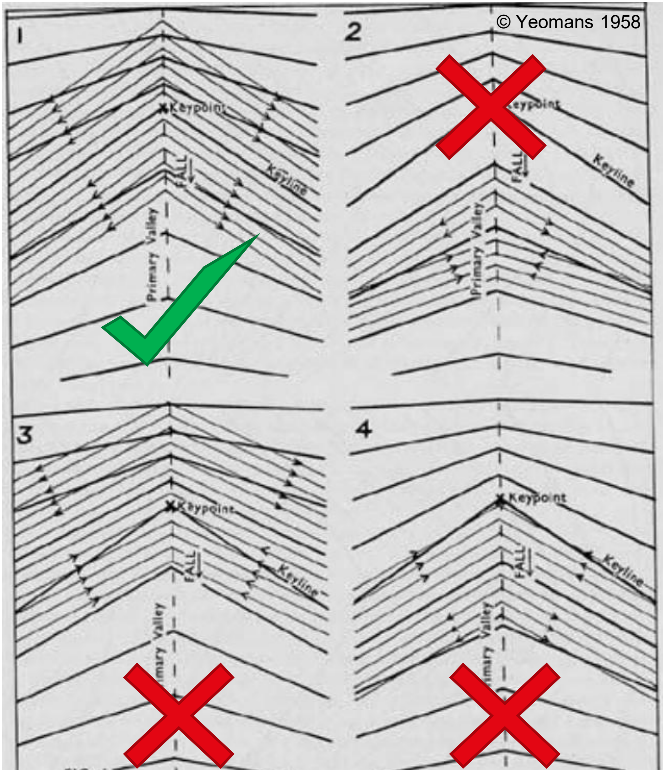
The keyline

- A **line through the keypoint** of a primary valley **on a true contour** or, in actual practice, at a slight gradient, is called the "Keyline of the Valley" (Holmes 1960)
- The uphill and downhill **parallel offset lines** from the keyline are naturally **sloped towards the ridges**



© Yeomans 1958

FIG. 6
Formalised contour diagrams of a primary valley illustrating: (1) Keyline cultivation: lines paralleling the keyline both up and down the slope of the land. (2) Contour cultivation: cutting out the area between contours marked on the land by working parallel upwards from the lower and downwards from the higher one. (3) Effect of cultivating parallel to a contour above the keyline. (4) Effect of working parallel to a contour below the keyline.

Pattern design with major landshapes

1) Determine **Keypoints and** mark the **Keylines** to the edges of the Primary Valleys

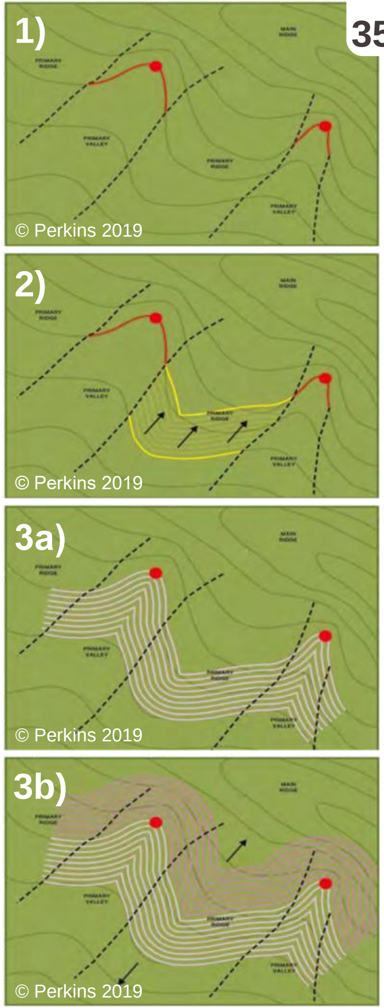
2) **Connect the Keylines** of adjacent valleys by offsetting the lowest contour on the Primary Ridge in uphill direction
→ **Guideline** for pattern development

3a) **Parallel offsetting** of the guideline in downhill direction until the guideline completing Primary Ridge contour line is met

3b) Continue the offsetting both in uphill and downhill direction as far as appropriate
→ **Equidistant cultivation pattern**

(Perkins 2019)

This traditional procedure is only applicable to landscapes defined by «primary ridges» and «primary valleys»
→ Rarely found in practice in continental Europe!



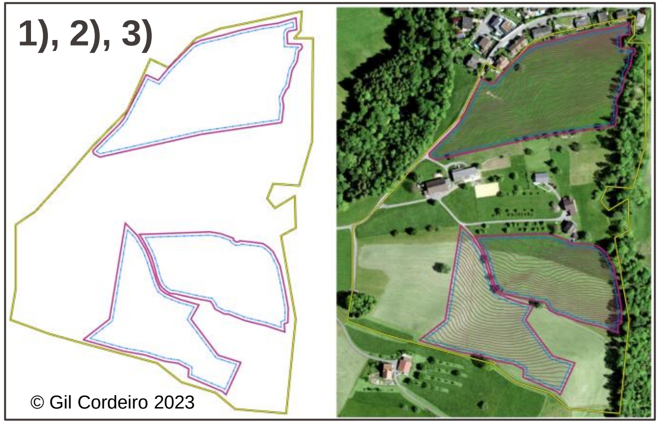
Modern approach: An iterative process! – [1/4]

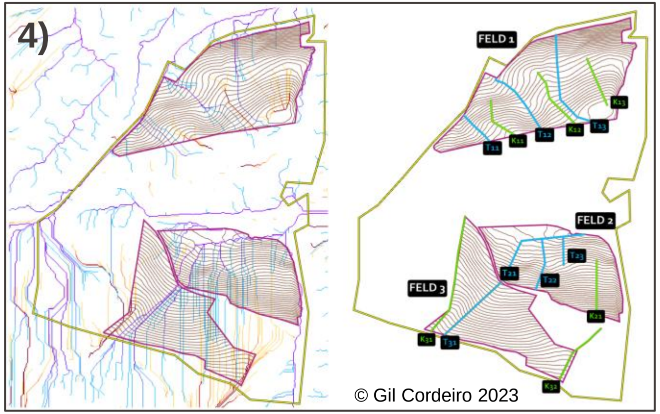
1) GIS data: **Orthoimagery, DEM, Cadastral map, Land-use map**, Erosion risk map (if available)

2) Contour map from DEM with appropriate intervals
   Recommendations for different area slopes (Doherty et al. 2015)
   → 10cm (0-5° slope); 50cm (5-20°); 1-2m (20-45°); 3-5m (35-45°)

3) Defining the Area of interest
   a) Delineate **access routes**, forestry strips, wilderness zones, **areas too steep or narrow** for machines, swamps and wetlands, narrow working widths, …
   b) Decide on water catchment **earthworks**
   c) Reserve space for **headlands**

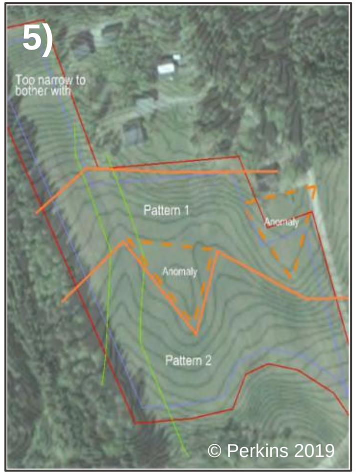
4) Basic Topographic analysis
   a) Valleys, ridges, **centerlines**
   b) Surface runoff simulation / **Flow path analysis** + Determination of keypoints (optional)





Modern approach: An iterative process! – [2/4]

5) <u>Subdivision</u> of area of interest <u>into homogeneous pattern zones</u>
- **Pattern anticipation** and identification of homogeneous pattern zones
- A new pattern might be required, when encountering **major land-shape anomalies or significant shifts** in direction or form of a ridge or valley
- Small-scale anomalies (e.g. runnels, indentations) are usually disregarded



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6) <u>Designing the guideline</u>
→ A **simplified contour line** used for offsetting from
- Find a promising contour line (**long, simple in shape, not close to the borders**) and sketch a first guideline …
- … which has a loose, simplified (triangular) character, **considering only the major land shapes**
- … whose **valley center vertices** are **higher** in elevation **than ridge center vertices**
- … which **anticipates offset trajectories** and extends beyond the area of interest for convenient offsetting

→ Verification, adjustments or restart

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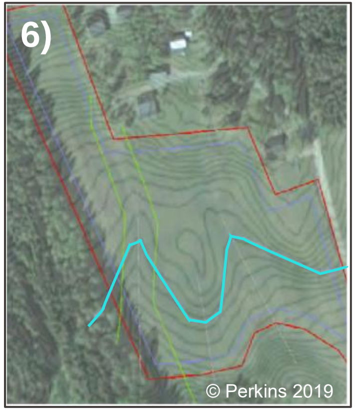

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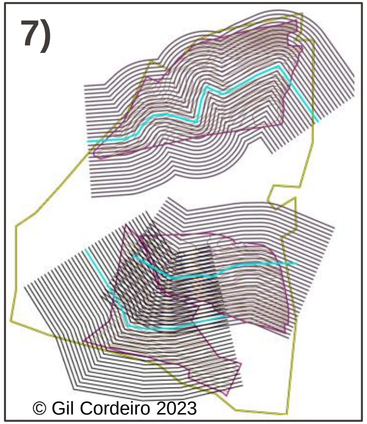
Modern approach: An iterative process! – [3/4]

7) Pattern development
by parallel offsetting of the guideline

- **Offset behavior** entirely **determined by** the **angles; Angles are preserved!**
- Vertex **trajectories follow** the angle's **bisecting line**
- When offsetting towards a curve's geometric center, its radius is reduced

→Anticipation of offset behavior and trajectories during guideline design for optimal uphill and downhill pattern development



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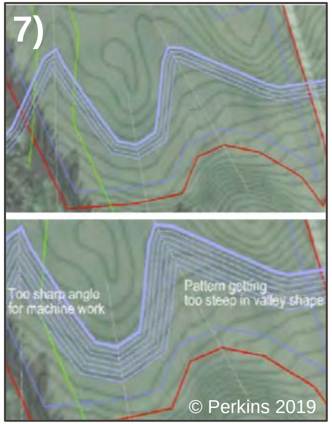

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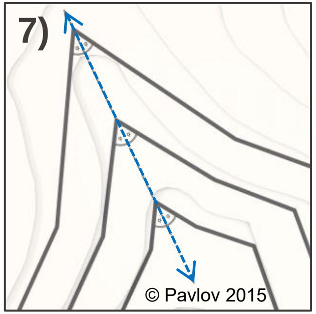
8) Angle smoothing

- Angles can be smoothened to **respect** tractor **turning angles** (usually max. 50°-55°)
- The resulting empty space between parallel lines can e.g. be utilized for locally enlarged AF bands
- For many angles, no smoothing required: Turns are naturally smoothened during implementation



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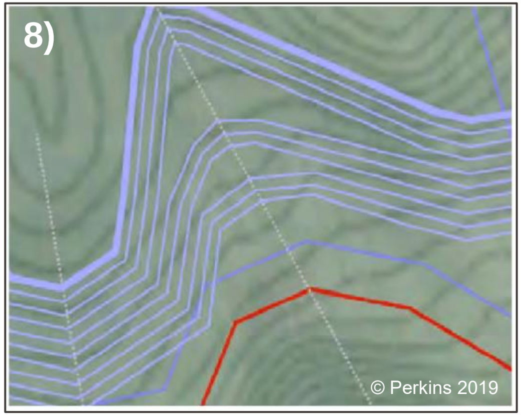

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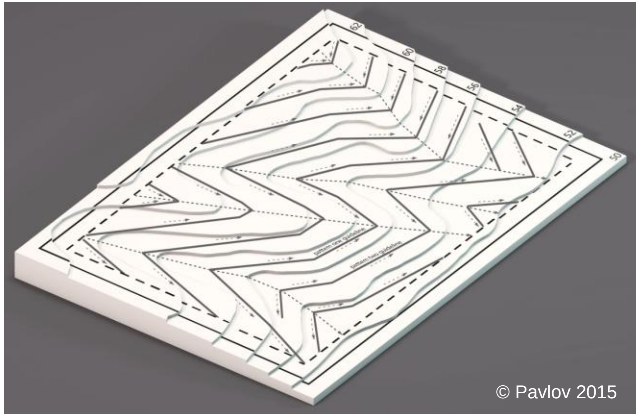
Modern approach: An iterative process! – [4/4]

9) <u>Pattern verification: Checklist</u>

→ Design adjustments if necessary

- Compliance with Keyline principles: **Water flow directions**[1] and **Equidistance**
- **Slope** along machining trajectories and at critical points (angles, end of row)
- **Smooth transitions** if multiple patterns
- **Steering angles**
- **Headlands**
- **Simplicity**



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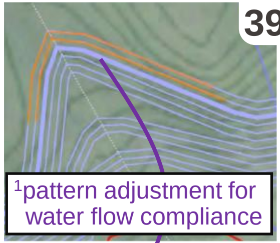
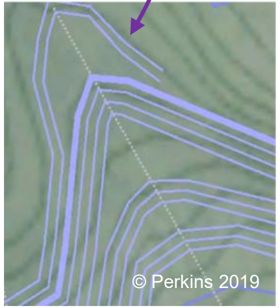


[1]pattern adjustment for water flow compliance



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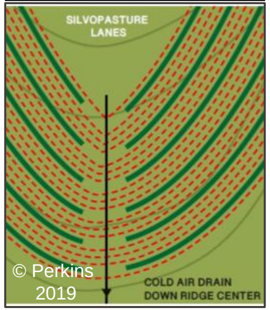
Simplicity

- **Sound and functional**
- **Practicable** for implementation
- **Convenient** for farming

“Convenience to be favored over theoretical perfection!”

[2]cold air drainage



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Further hints

- Working with **triangular lines** for easy manipulation, offset anticipation and effective communication
- For the sake of overall simplicity **pattern anomalies** such as local flow inversions are disregarded when rare and insignificant in scale
- **Steep slopes** (> 20°) might implicate significant design compromises for compatibility with machinery
- Provide downhill **cold air drainage**[2] by designing a gap along ridge centerlines, if frost management is relevant

Swales and Offstream Dams

Swales (ditches and drains)

- **On-contour** Swales: Level, no slope
  - Active infiltration of rainfall to build water tables
  - Well suited for permeable soils with occasional but heavy rainfall
- **Off-contour** Swales (0.25%-1% slope from valleys to ridges)
  - Collect water, convey to reservoirs, connect reservoirs
  - Optional: Integration of steps and pools along the channel for active infiltration
- Culverts for tractor crossings and optional swale bottom outlets
- Combination with AF for increased water uptake


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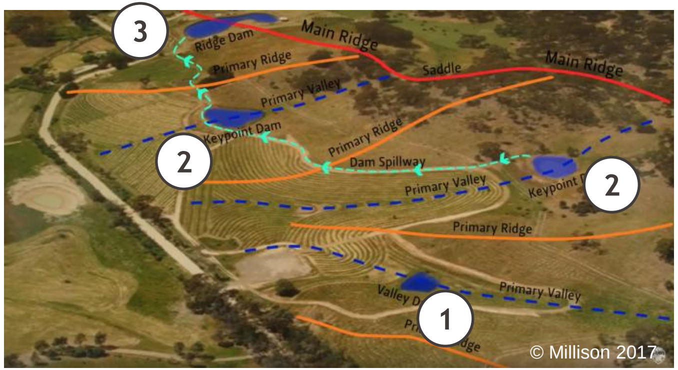

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Offstream dams to impound excess rainwater

Elevation

1) **Valley dam**
Largest water storage capacity but low in the landscape

2) **Keypoint dam**
Often good landscape geometry and high clay content

3) **Ridge dam**
Sufficient building material, good accessibility, safe overtopping behavior

4) **Contour dam**
For locations where other dam types are not feasible

5) **Saddle dam**
Can be fed from four directions

6) **Turkey’s nest dam / Hilltop dam**
Filled with a pump from downhill reservoirs

Reservoir planning

1) General analysis and assessment
   Needs, Site characteristics, Climate,
   Risk (e.g. landslides, slumping)

2) Topographic survey
   Possible reservoir placements and serial connections

3) Catchment analysis

4) On-site geotechnical assessment
   Soil profile and clay content

5) Dam dimensioning
   - Shallow shores → Water vegetation
     → Wave action buffer + nutrient cleaning
   - Inside slopes ideally 1:3 – 1:2 (for the first 2-3m)
   - Outside slopes ideally 1:2 – 1:1

6) Drains and spillways
   - Analysis: Catchment size? Flow paths? Land-use? …?
   - Special features: Contour-line swale spillway? Trickle tube? …?

7) Natural sealing
   Local loam, Sodium bentonite, Quicklime (Calcium oxide)

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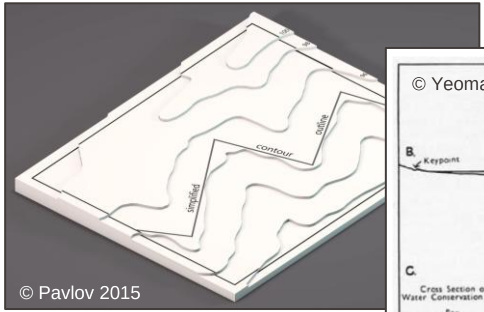
EPFL

Keyline design considerations

- General considerations
  → c.f. "Agroforestry design considerations"
- Agro-ecosystems thinking
  → Integrated site design with
  many interconnected elements
- Reservoir planning
  - **Water uses and needs**
  - Potential **supply and transport**
    → Roofs, Sealed ground, Roads and driveways
  - **System dynamics** (Initial VS. Projected conditions)
    → Future development of runoff coefficients
    → Strategic long-term planning of reservoir locations and dimensions (constantly evolving supply and demand)
- Irrigation systems
  - **Pressurized irrigation systems** for best efficiency
  - **Driplines**: require approx. 7m pressure head
  - Low-pressure **sprinklers**: require max 17m pressure head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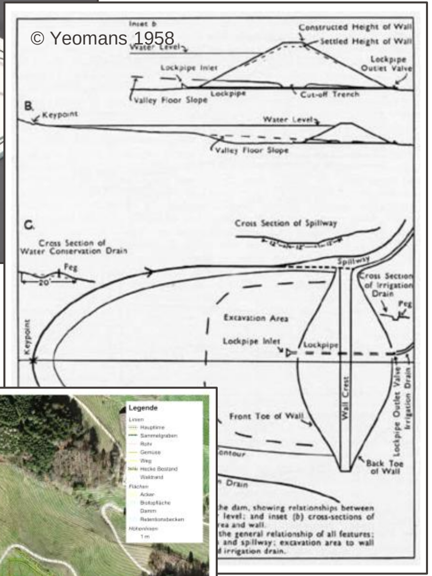
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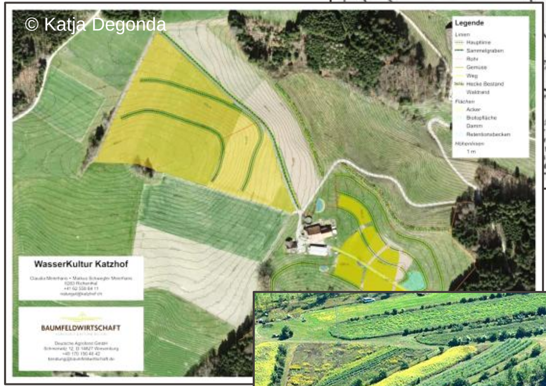
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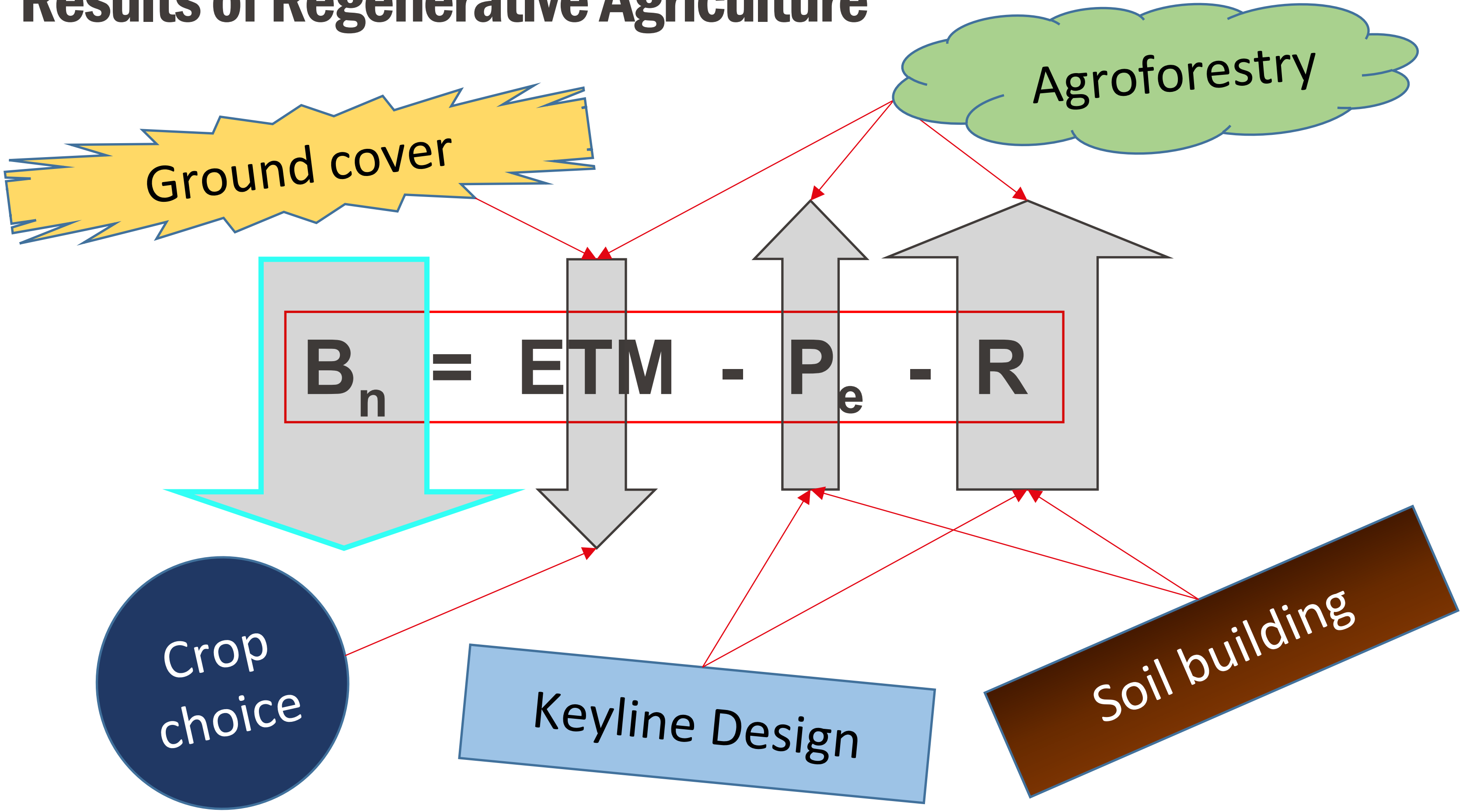
Results of Regenerative Agriculture



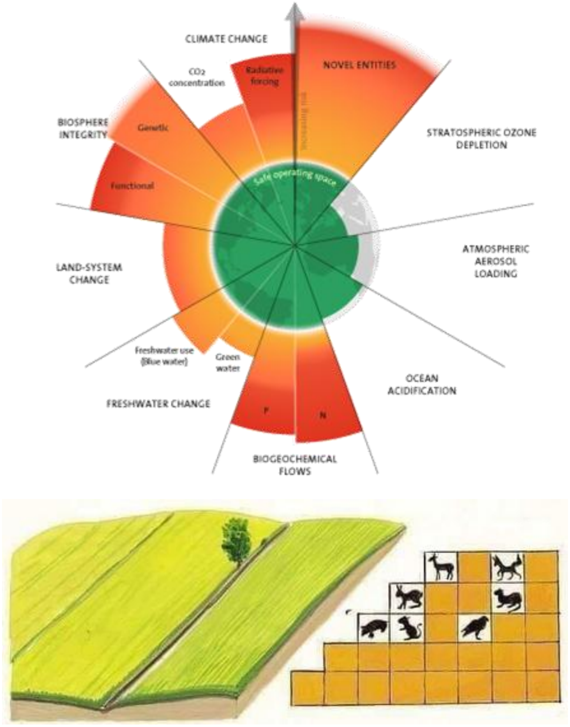
Results of Regenerative Agriculture

Farms which

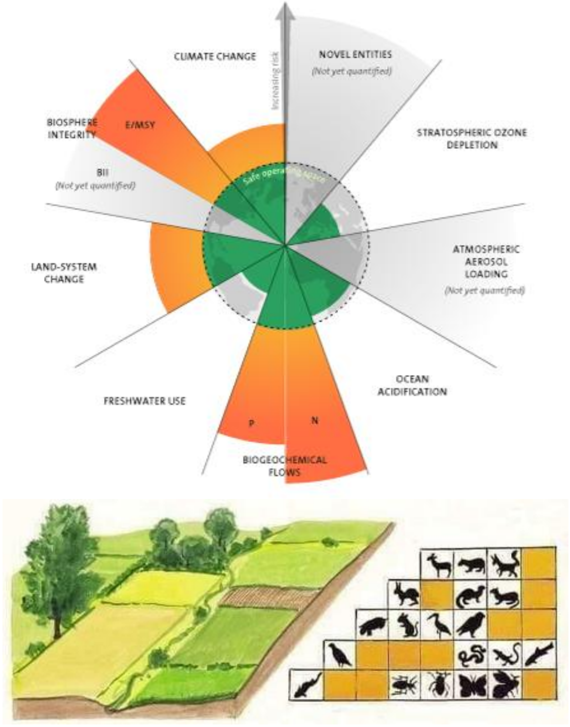
- Recharge **aquifers** instead of depleting groundwater
- Take care of our **surface waters**
- Increase and fill **green water** stocks
- Contribute to regional **flood mitigation**
- Boost **biodiversity**
- Are climate-proof / **Climate plasticity**
- Sequester **carbon**
- Are highly **productive**
- And **economically stable**

Results of Regenerative Agriculture

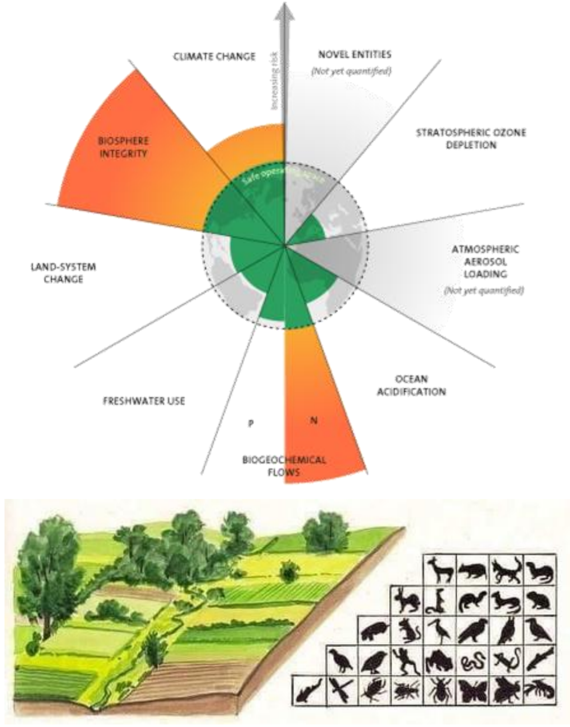
2023



2030 ?



2035 ?



So, let’s start and plant some trees! Thank you!

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