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Managing the Microclimate

Practical Note Spate Irrigation

Spate Irrigation Network Foundation

“When the century began, neither human numbers nor technology had the power radically to alter planetary systems. As the century closes, not only do vastly increased human numbers and their activities have that power, but major, unintended changes are occurring in the atmosphere, in soils, in waters, among plants and animals, and in the relationships among all of these. The rate of change is outstripping the ability of scientific disciplines and our current capabilities to assess and advise.”

The Brundtland Report, 1987

1. Building resilience through microclimate management

When changes are made in a landscape, changes are made to the microclimate. When farmers plant trees in or around their field, and when communities dig bunds to improve water retention, they change the local climate around them. Microclimate is a result of the interaction between the local topography, landscape characteristics and the regional climate.

In the global climate change debate, adaptation and mitigation are dominant concepts. The challenge is to create production systems that can withstand rising temperature and exacerbating weather events, while finding ways to sequester carbon from the air. Meanwhile, microclimates go largely unobserved and unattended. In view of the climate change that exists today, this is a huge missed opportunity. Micro-climate management offers much potential as a third way next to adaptation and mitigation that builds ecosystem resilience and brings positive impact for agricultural systems and biodiversity. Focusing on the microclimate is a pro-active approach to improve the landscape. Compared to global and regional climate scenarios, microclimates in landscapes are almost entirely unstudied (Chen et al. 1999).

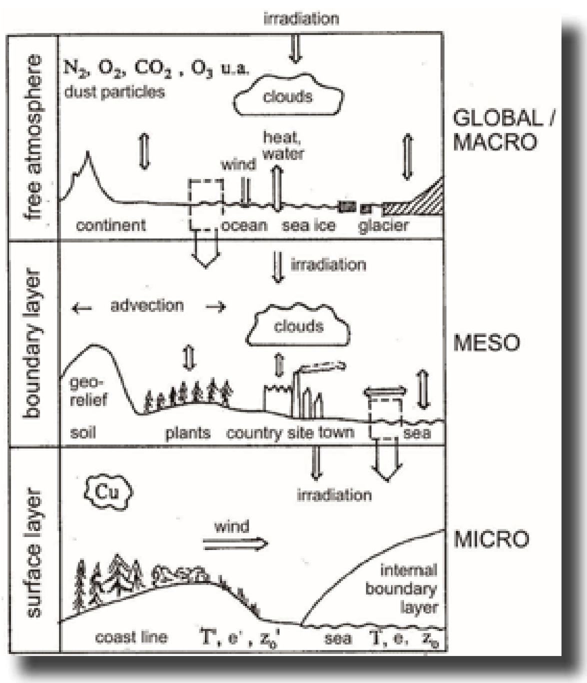


Figure 1: various climate scales and associated phenomena (Source: Foken 2008)

There is little chance that humans in the near future will be able to modify the climate, most notably temperatures, on any large scale (Gliessman 2015). However, when zooming in on landscapes and the agro-ecological systems within them, there is much that can be done, to the extent that a large share of the effects of global climate change can be buffered by building the microclimatic resilience of the landscape. Resilience has gained much importance as an overarching concept in the analysis of human-environment interactions and the way in which humans are affected by environmental change processes (Janssen & Ostrom 2006). Holling (1973) was the first to introduce resilience in relation to the stability of ecosystems. The Resilience Alliance defined it as “the capacity of a system to tolerate disturbance without collapsing into a qualitatively different state that is controlled by a different set of processes. A resilient system can withstand shocks and rebuild itself when necessary” (Walker & Salt 2006).

This Practical Note seeks to understand the interaction between different microclimate factors and also aims to offer examples of microclimate management interventions. Microclimate is composed out of a myriad of climatic conditions that come together in localised areas on the earth’s surface (Chen et al. 1999). It is critical to recognise the unique nature of microclimate of different zones, such as forests and fields, and the influence of such zones on landscape processes. In the end, microclimate is a determining factor in ecological processes as varied as plant regeneration and growth, soil respiration, nutrient cycling, and wildlife habitat, and is related to the spread of diseases, insects and natural disturbances such as fire. The term microclimate is often applied to space scales up to 100 m, which is followed by the mesoclimate that has a range up to 100 km (Foken 2008).

In the first section, the various microclimate components and their relationships are discussed. In the second part, microclimate management interventions are listed that together have potential to affect productive functions and transform landscapes.

2. Microclimate components

Microclimates are the localised, dynamic interplays between different processes in the surface layer, such as energy and matter exchange, radiation processes and effects of the underlying surface (Foken 2008). These again are determined by the specific landscape, soil conditions, vegetation, land use and water retention. The microclimate determines the moisture available in the soil and air to the different ecosystems, the presence of dew and frost, the actual temperatures for plant growth and germination, the vigour of soil biotic life, capacity to fixate nitrogen by soil biota and the occurrence of pests and diseases.

This section provides an overview of the various factors that determine the microclimate. Understanding the main characteristics of these factors, and how these can influence each other provides the building blocks for understanding how different management practices can transform the landscape, and how interventions can better be implemented for current and future needs.

2.1 Soil moisture

Soil moisture available for crops is determined by the soil's water storage capacity and the addition of water to a soil, which again is determined by its texture, structure, depth, organic matter content and biological activity. The texture of a soil determines its water storage capacity and influences the transfer of heat that can result in the loss and movement of moisture. Texture is determined by the relative amount of clay, silt and sand particles in the soil (Gliessman 2015). Figure 4 shows the different types of soil that are formed

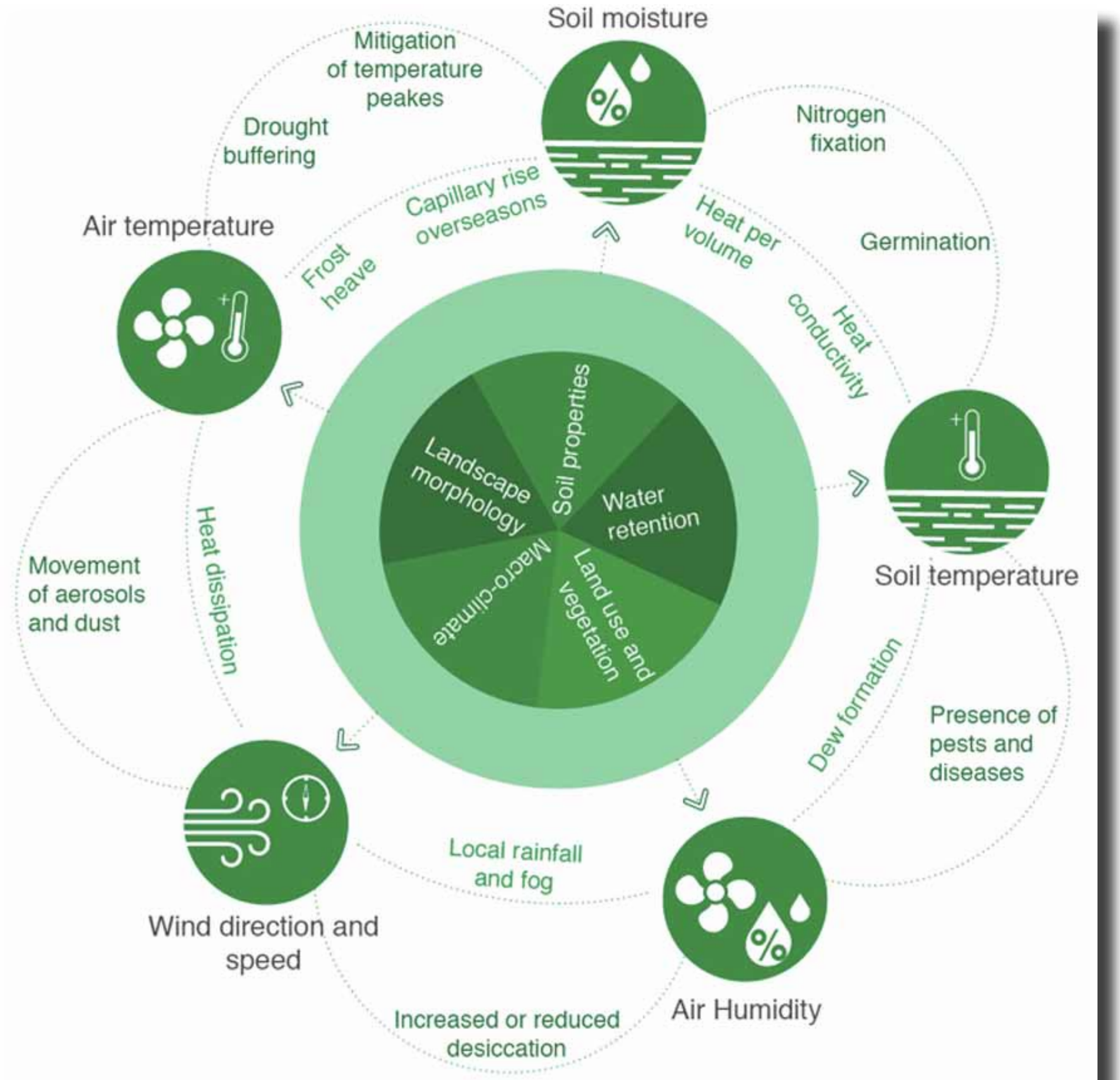


Figure 2: Microclimate components and interlinkages (Source MetaMeta, 2016)

Box 1: Soil moisture availability and sowbugs

Sowbugs are crustaceans, 20 - 25 mm long and 5 mm wide, that are common to the arid flood spreading areas of Iran, such as the Gareh Bygone plains. They are ecosystem engineers as they can change the soil structure by altering the soil compaction through the creation of pore spaces that allow for better water infiltration. By burrowing in the soil, sowbugs ensure that soils in floodplains are not sealed by fine sediment. They help to aerate the soil and provide avenues for soil infiltration of water. Soil that are burrowed by the sowbug have higher organic matter, better structure, and are more resistant to erosion than other soils in the area. In the Gareh Bygone plains, their role is essential in forming macro-networks, and facilitating soil moisture and groundwater recharge rates (MetaMeta 2011). This allows water users in the floodplains to have groundwater available during a prolonged period of the year.

Figure 3: Sowbug entering its hole (Source: Kowsar 2009)

from these relative amounts. These particles each have different properties that influence the uptake of water and the transfer of energy and heat.

Clay particles are the smallest particles, have the highest surface area, and have most potential to absorb water. Sand has the largest particles and the lowest water absorption capacity (Bonan 2016). Thus, sandy soils will usually have lower moisture availability and a higher evaporation rate than clay soils. However, clay soils can harden in drought-prone areas, which will decrease

Table 1: Soil particle characteristics (Source: Bonan 2016)

Particle	Size (mm)	Pore size	Water holding capacity
Sand	0.05 - 2	Large	Low
Silt	0.002 - 0.05	Medium	Medium
Clay	< 0.002	Small	High

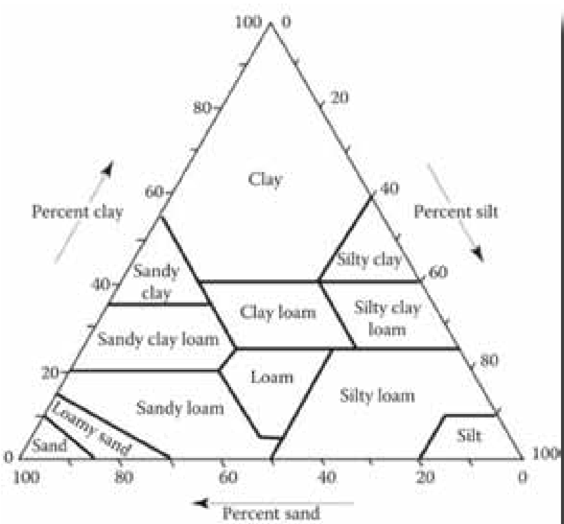


Figure 4: Soil texture classification scheme (Source: Gliessman 2015

infiltration and increase runoff, thereby decreasing water availability.

Soil texture, soil organic matter and biological activity at the surface and in the ground, together form the soil structure. The structure is related to the formation of micro- and macro-aggregates, being the ways in which the different particles are held together. A good structure can help resist wind and water erosion, as well as increase water percolation and storage capacity (Gliessman 2015). In addition, the soil's moisture retention capacity is influenced by its organic content. An increase in the organic carbon content improves the water retention capacity when soils are sandy, while it decreases the water retention capacity in fine-textured soils such as clay. For soils with an initial high carbon content, an increase of organic carbon increases their water retention capacity in any case (Rawls, 2003). Thus, an increase in organic matter can be beneficial, especially for coarse soils.

The type of soil and soil moisture have an important effect on erosion. Sandy soils hardly clump together, and are thus more susceptible to erosion. Silt and clay soils on the other hand form stronger aggregates. They are made up of smaller particles however. Soil moisture plays an important role in bonding soil particles, and helps to reduce wind erosion.

Table 2: Capillary rise range Source: (Brouwer et al. 1985)

Soil texture	Capillary rise (in cm)	Speed
Coarse (sand)	20 - 50	Quick
Medium	50 - 80	Medium
Fine (clay)	80 - several meters	Slow

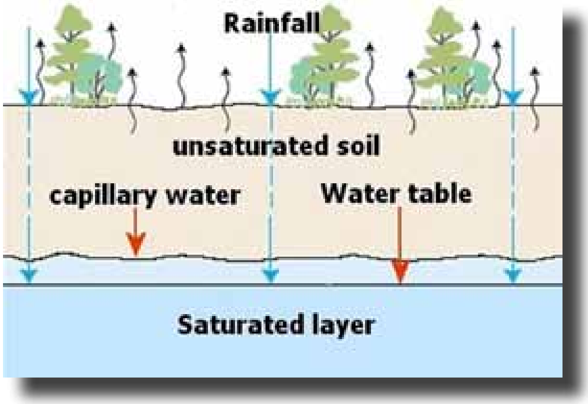


Figure 5: Capillary water in the soil (Source: Chilling tales 2016)

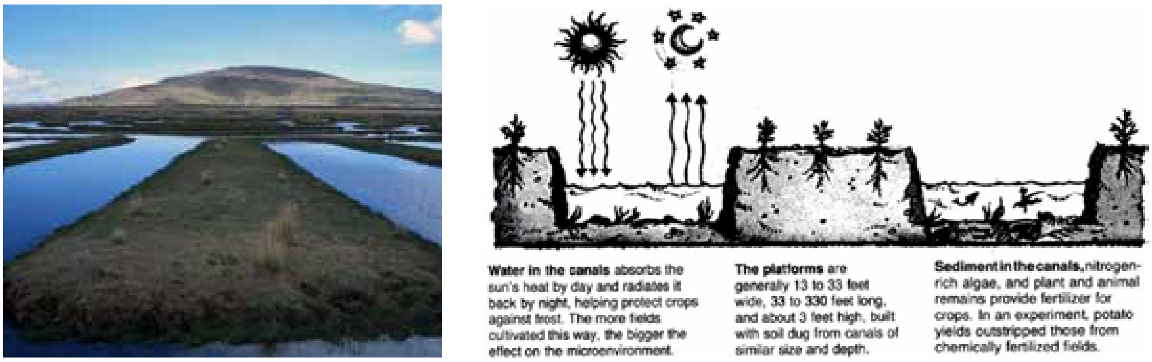
Capillary action

The movement of water in the soil is determined by infiltration, percolation, evaporation, transpiration and hydraulic lifting. Infiltration is the addition of water to a soil from precipitation or irrigation. Once infiltrated water saturates the upper soil layers, gravity pulls the water downwards, called percolation. Evaporation from the soil surface draws water upwards through capillary action, as the water deficit that is created at the soil surface attracts deeper water molecules. Similarly, plant

Box 2: Microclimate practices in the Andes

From the Andes to Amazonia, raised fields known as Suka Kollus (Bolivia) and Waru-Waru (Peru) can be found, being an agricultural technique in flood-prone mountain plains that were used by pre-Columbian societies (Lombardo et al. 2011). The canals around the fields, when filled with water, act as a water buffer against prevailing night frost, and provide moisture for crops.

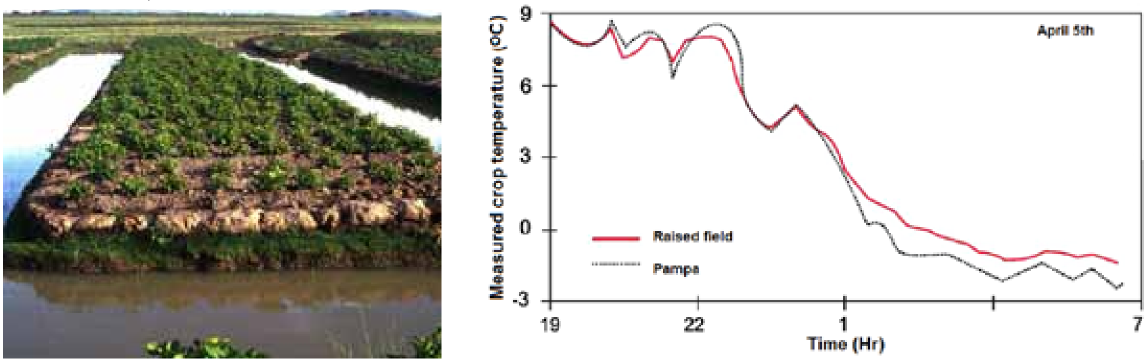
Figure 6: Functioning of the raised fields (Source: Agricultures Network 2013)



This is achieved by letting the sunlight heat up the water stored in the canals between the raised fields. The stored heat is released at night, generating moisture which will be available as condensed water to the crops (Lhomme & Vacher 2003). According to Roldán and colleagues (2004) the moisture raises the relative humidity by 3.3 percent, compared to the surrounding plains.

Depending of the soil texture, plant coverage, soil humidity and depth, raised fields and surrounding areas present temperature differences. This is described by Lhomme & Vacher (2003) in figure 7. The soil temperature in the suka kollus shows lower temperature variability in relation to the pampas system. In the study, the diurnal temperature range for the pampas was found to be between 10.7 - 20 °C, while in the suka kollus, the temperature laid between 11.5 - 18 °C (Angelo et al. 2008). The moderate temperatures of suka kollus' soils improve their resilience against extreme climates.

Figure 7: Evening and night temperature within the suka kollus and outside (pampa) (Source: Lhomme & Vacher 2003)



transpiration creates a water deficit around the root zones, as water is absorbed through the root hairs.

The speed at which capillary action can move water in the soil depends on the water deficit at the surface layer or around the plant roots, and on the soil type as well. Most sandy soils facilitate a rapid movement, as pore spaces are bigger and hold water less tightly. However, as the capillary movement takes place against gravity, finely textured soils like clay can provide better conditions to facilitate the upward movement of water and hence reach higher (Brouwer et al. 1985). This water movement is part of the diurnal and seasonal cycle. For the diurnal cycle, the water deficit in the soil which is created during the day is compensated for by water movement during the night, given the availability of groundwater.

Upward movement of water through the soil can occur up to several months after the last precipitation. In areas dominated by one or two wet seasons, this ensures water availability after the rainy season has ended, thus enabling a second cropping period. The availability of water is further influenced by the depth at which soil moisture can be found. Some of the available soil moisture will be at a depth that is not reachable for some plants, while it is available to others.

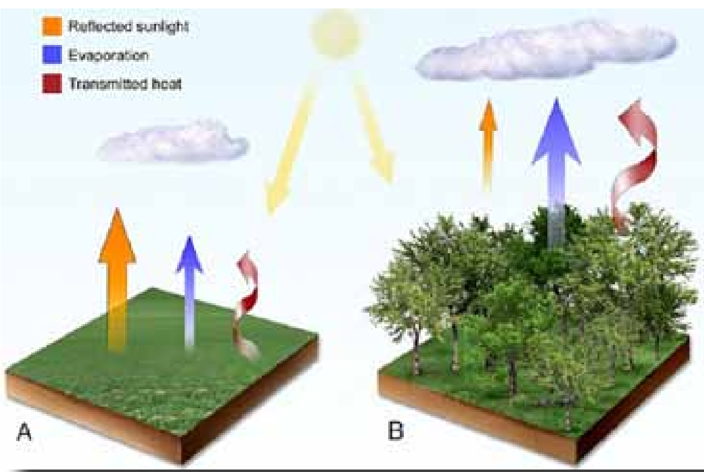
Soil moisture and microclimate

Soil moisture is one of the most important microclimate determinants. The thermal conductivity and heat capacity of the soil is greatly increased when soil moisture is present (Bona 2016). Evapotranspiration is the process of transferring water from the surface to the atmosphere, which takes a high amount of energy compared to heating the air. Thus, areas with available soil moisture have a more balanced microclimate with lower air and soil temperatures. This not only facilitates plant growth, but also affects weather patterns and local rainfall patterns. On the contrary, when there is only limited soil moisture more energy is available for sensible heating and near-surface air temperatures increase. In the past decade, there has been much research on the relationship between a lack of soil moisture and the occurrence of extreme temperatures and heat waves, both at the local and regional scale (Seneviratne et al. 2010). The balancing influence of soil moisture also counts for low temperatures as well, as wet soils stay warm longer than dry soils during frost events.

When a good level of soil moisture is available soil biotic life can prevail. Micro-organisms break down organic matter and release nutrients, which contributes to soil fertility. Optimal conditions are met when moisture takes up around 60 percent of the available water pore space. An excess of water prevents the supply of oxygen, which can lead microbial activity to slow, stop, or turn anaerobic, which will have negative effects on plant growth (Bot & Benites 2005b). Hence, in areas with regular flooding, proper drainage is required to ensure good soil fertility. Furthermore, excess water can cause nutrients to be lost due to leeching. On the other hand, low moisture levels decrease enzyme activity, which will hamper nutrient releasing processes. Nitrogen cycling is especially affected, already being a limiting nutrient in many soils (Sardans & Peñuelas 2005).

2.2 Soil temperature

Soil temperature is determined by incoming radiation, and thermal conductivity and heat capacity of the soil. The extent to which incoming radiation is absorbed or reflected is influenced by soil colour. Darker soil tends to absorb a higher fraction of solar radiation, while lighter soils tend to reflect radiation and to be cooler. Thermal



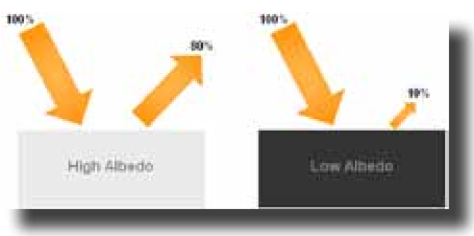


Figure 8: Albedo effect from croplands (A) and forests (B) (Source: Jackson et al. 2008)

Table 3: Thermal conductivity and heat capacity (soil water content as percentage of saturation) (Source: Bonan 2016)

	Thermal conductivity ($W\ m^{-1}\ K^{-1}$)	Heat capacity ($MJ\ m^{-3}\ K^{-1}$)
Soil component		
Quartz	8.80	2.13
Clay minerals	2.92	2.38
Organic matter	0.25	2.50
Water	0.57	4.18
Air	0.02	0.0012
Sandy soil (porosity = 0.4)		
0%	0.30	1.28
50%	1.80	2.12
100%	2.20	2.96
Clay soil (porosity = 0.4)		
0%	0.25	1.42
50%	1.18	2.25
100%	1.58	3.10
Peat soil (porosity = 0.8)		
0%	0.06	0.5
50%	0.29	2.18
100%	0.50	3.87

conductivity is the rate in which a soil transfers heat, and a higher conductivity means that radiation can flow in and out of the soil at a higher rate. In other words, it indicates the speed at which a soil heats up and cools down. Soils with high thermal conductivity lose energy faster, and thus cool down quicker. This is important to understand the movement of water and the formation of dew. Heat capacity deals with the ability of a soil to store heat. This can be noticed during colder nights, when heat slowly releases from the soil and heats the surface air. In highlands, soil moisture is used to help reduce frost occurrence. However, when temperatures are continuously low, frost heaving can occur. The expanding ice in the soil then causes the ground to swell (Bonan 2016).

Factors that determine thermal conductivity and heat capacity of the soil are the soil texture or mineral composition, porosity, soil moisture and organic matter. The presence of soil moisture greatly increases the thermal conductivity, as water is twenty times more conductive than air (Bonan 2016). Soil organic matter has a very low thermal conductivity when compared to the mineral soils, and thus acts as an insulating agent that keeps heat out of the soil during the day, and prevents heat from escaping during the night. This prevents moisture from evaporating during the day, while preventing soil temperatures from going below freezing at night. Sandy soils generally have a higher thermal conductivity, while clay soils have a lower one. The thermal conductivity and heat capacity of various soil types are shown in table 3 (Nicholson 2012).

While heat capacity is very similar between sandy, clay and peat soils, the presence of soil moisture creates large differences. Deserts generally have sandy soils and low soil moisture. In effect, this means that high thermal conductivity exists, while having a low heat capacity. Heat flows in and out of the soil at a high rate, contributing to high soil temperatures during the day and low temperatures at night.

Soil temperature and microclimate

Heat transfer into the soil during the day transports heat away from the direct surface and leads to lower temperatures. When the surface is cooler at night, the soil's heat transfer direction is reversed, and heat is released to the surface, thereby balancing out extremes. The same process also occurs over longer time scales, with heat being stored during warmer months and released in colder months (Bonan 2016). Soil temperature influences crop growth by providing the warmth necessary for seeds, plant roots and micro-organisms in the soil. High soil temperatures can negatively affect plant growth, while extreme temperatures can stall biological processes of micro-organisms (FAO 2016). On the other hand, low soil temperatures inhibit water uptake by plants, inhibit nitrification and thereby reducing soil fertility, and increase desiccation when simultaneously air temperatures are higher (Gliessman 2015). Both high and low soil temperatures play a distinct role by increasing or decreasing evapotranspiration from plants. Soil moisture plays a key role, as higher soil moisture will lead to evaporation, taking a higher amount of energy and thus lowering local temperatures during the day, while increasing surface temperatures during the night.

2.3 Air temperature

Incoming and outgoing radiation is the most important determinant of local air temperature. There are several on-site characteristics and modifications possible. Local vegetation can increase transpiration, which lowers the local temperature and increases humidity. Vegetation can also provide shading, (partially) decreasing radiation from reaching lower situated plants or surface levels. Using the cooling effect of moisture

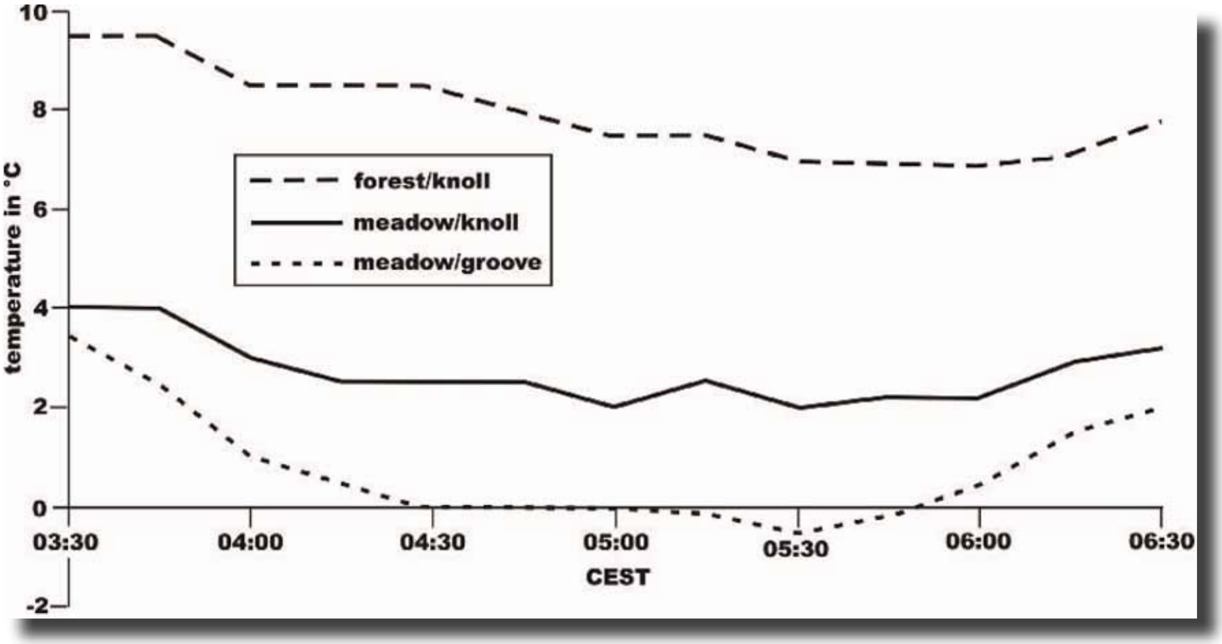


Figure 9: Temperature plot during the night between a small hill (knoll) and a groove (150 m away) in the Ecological-Botanical Garden of the University of Bayreuth on May 14th 1998 (Source: Foken 2008)

in the soil to decrease the overall air temperature can mean increased crop yields through mitigating extreme temperatures. The incoming and outgoing radiation balance shows the input of energy into the system that is used for crucial processes such as warming the air and soil, photosynthesis, and evapotranspiration.

Local albedo is the reflectivity of a surface and determines how much radiation is absorbed. It plays a large role in determining local air temperatures, and can vary greatly according to the local conditions. Local topography plays a large role in determining the incoming radiation. Aspect, being the direction a slope is facing, influences the amount of radiation received as well as shading. Soil albedo is mainly determined by the moisture content. The interaction between rainfall and air temperature is important, as precipitation changes the local albedo and provides moisture for evaporation. In general, a dry soil has higher albedo than a wet soil. Croplands have a higher albedo than forests, meaning that croplands reflect more sunlight back into the atmosphere, resulting in lower surface heat (Jackson et al. 2008). Vegetation and organic material has a very low albedo and hence absorb a lot of sunlight (Nicholson 2012). However, more evapotranspiration also takes place in forests, which transmits heat back into the air in the form of water vapour. This shows that several conflicting factors lead to warming and cooling effects from different kinds of land use, making it not a simple task to determine effects on the microclimate.

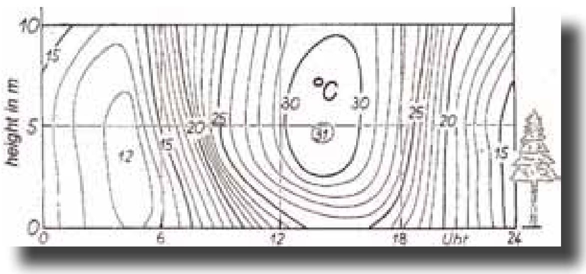


Figure 10: Daily cycle of air temperature in and above a forest (Source: According to Baumgartner (1956) in Foken (2008))

Air temperature and microclimate

While the overall air temperature is a result of various radiation processes taking place, conditions in the temperature profile within a few meters from the surface change rapidly. Temperature, as well as moisture and wind, is affected by surface processes and properties with which it interacts. Vegetation changes the radiation balance through shading, while being a barrier to wind (Gliessman 2015). Figure 10 shows the typical daily temperature cycle in a forest. The maximum air temperature occurs in the upper crown, usually about one to two hours after local noon (Foken 2008). Below the crown, the daytime temperatures are lower. At night, minimum temperatures occur in the upper crown due to the cooling of the earth's surface and the air near the ground, called radiation cooling. This particularly happens with a clear sky, calm wind and low humidity. Particularly in the evening, a forest is warmer than its surroundings.

The air temperature range, and diurnal and seasonal fluctuations, play a large role in determining the local flora and fauna. All organisms have an optimum temperature for growing, and their minimum and maximum temperature thresholds

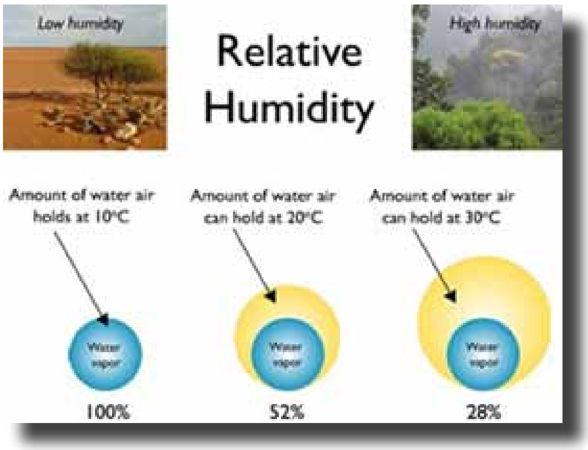


Figure 11: Relative humidity for different temperatures (Source: Fondriest Environmental Inc. 2016)

vary for different growing stages. For example, maize development is hindered above 35 °C, while rice has maximum temperature threshold between 36 - 40 °C. When these are exceeded, growth is delayed or even prevented, which can result in yield losses or even plant loss, even in cases where sufficient water is present. For shade crops, such as coffee, the effect is even more strongly pronounced. The optimal range of Arabica is 18 - 21 °C, with reduced photosynthesis between 24 - 34 °C, and no photosynthesis above that (Lin 2007). Extreme heat causes plant processes to shut-down. As the release of moisture from transpiration is inhibited, and possible further heat stress is caused (Luo 2011; Gliessman 2015). Higher air temperatures also have an influence on the spread and effects of pests and diseases, as plants become more susceptible to disease (Beresford & Fullerton 1989).

2.4 Air humidity

Air humidity is the result of evapotranspiration, which is induced by available radiation and moisture. It is the basis for cloud, fog and dew formation. The air temperature determines the amount of water vapour the air can hold, with warm air being able to hold more water vapour than cold air. Warmer weather promotes evaporation, which in turn increases air humidity. Relative humidity is a measure of the ratio of water vapour in the air compared to the amount of water vapour the air can hold. A relative humidity of 25 percent thus indicates that the air is holding 25 percent of the total water vapour it could hold. A relative humidity of 100 percent means the air is saturated, and mist, fog and clouds will start to form. At smaller scales, changes in temperature can push the relative humidity to 100 percent, reaching dew point temperature (Gliessman 2015).

Dew occurs when the temperature at the surface is lower to or equals the dew point temperature. Air moisture in the form of water vapour then condenses on a colder surface to form dew (Agam & Berliner 2006). Dew needs a relatively cold surface upon which it can be deposited. Fog occurs when the atmospheric water vapour concentration reaches the saturation point, regardless of conditions at the surface. Thus, fog is a purely atmospheric process. The deposition of moisture is caused by settling and interception, rather than the formation of droplets at a cool surface. Many of the effects of fog deposition are like those of dew deposition.

Air humidity, combined with temperature changes during the diurnal cycle, can lead to dew formation. Dew can be an important source of moisture for plant growth in arid and semi-arid environments. There are a number of local examples (Nicholson 2012). In the Andes, 5 - 10 mm a year is accumulated, while in the Negev desert, where most dew research has taken place, dew forms on 200 nights a year, with a total of 30 mm a year. Dew is used directly through leaf surface absorption, reduces transpiration and can kick-start photosynthesis in the early hours due to leaf water saturation (Tomaszkiewicz et al. 2014). Air moisture can thus serve as an important addition to the water that plants require, especially in arid and semi-arid regions (Agam & Berliner 2006). Dew also affects the albedo, both of soils and plant canopies. While it moistens, and darkens the soil, lowering its albedo, it leaves a reflective surface on leaves, increasing their albedo.

Air humidity and microclimate

High air humidity slows down transpiration from plants, since humid air does not absorb water vapour as easily as dry air does. Here, the presence of local wind is essential to mix the local atmosphere as it transports humid air away from vegetation (Nicholson 2012; Bonan 2016). High air humidity, in combination to changes in the air temperature can lead to rainfall in a landscape, in case circumstances make air humidity reach saturation point.

Local winds also play a role in dew formation. While light wind was found to help dew formation in unsheltered sites, moderate to strong winds were found to inhibit dew formation (Richards 2004). The presence of vegetation that acts as a windbreak or provides shade plays a role in the formation and duration of dew. By lessening wind speeds, windbreaks can assist in the formation of dew, but also reduce it as local warmer air layers are not removed. The shade from vegetation helps to reduce local surface temperatures, which

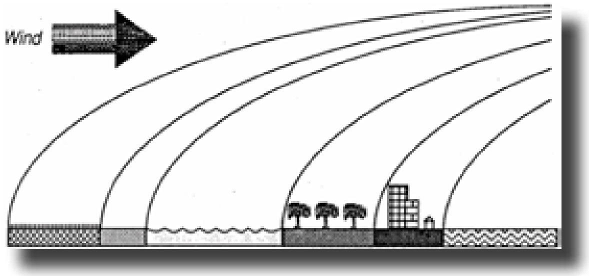


Figure 12: Generation of internal boundary layers above an inhomogeneous surface (Source: Foken 2008)

increases the chances of dew formation (Agam & Berliner, 2006). The presence of wind to transport air humidity can play a significant role in both increasing and decreasing local humidity. A dramatic example is the monsoon, where warm air laden with moisture moves inland.

2.5 Wind direction and speed

At a large scale, pressure differences cause air movement. At smaller scales, topography, temperature differences and barriers can induce different wind directions and speeds. At a local scale, landscape morphology such as the presence of water bodies and mountains plays an important role. Microclimatic phenomena include small-scale circulation systems, such as mountain and valley winds, land-sea wind circulations, and katabatic winds (Foken, 2008). For example, during warmer months, land mass heats up faster than the water surface, causing winds to blow towards the land. At night, the direction reverses as winds blow towards the warmer water surface. With regards to mountains and hills, warm air starts to rise upslope during the day (valley wind), while at night the cool air moves downslope (mountain wind) (Gliessman, 2015). At the farm level, wind can be stimulated through corridors or blocked through the presence of vegetation or shelterbelts. While large-scale pressure fields cause wind speed and direction, the topography of a landscape and obstacles influence the winds, leading to small-scale climate differences. Wind velocity in and above a forest is greatly reduced due to friction.

Wind and microclimate

Wind can have a cooling effect by removing the boundary layer of warm air around a plant. This can also increase water consumption by the plant, as removing the layer and replacing it with drier air will causes increased transpiration. Wind can cause temperatures to be warmer or cooler depending on the ambient temperature (Bonan 2016; Gliessman, 2015). In addition, air movement in the canopy of vegetation is essential to maintain good CO_2 levels for growth, remove excess humidity and lower the overall humidity level, thereby reducing the potential for diseases. Furthermore, many cereal crops are wind pollinated.

Landscapes tend to have heterogeneous surfaces with much difference in surface characteristics (Foken 2008). In combination with wind, this can result in a complicated flow system, that is dependent on the surface's roughness, and humidity and temperature profile. These profiles can shift

Box 3: Soil and water conservation measures in Ethiopia

In 2010, the Ethiopian government launched a land restoration programme with the aim to double agricultural productivity by improving the management of natural resources and agricultural lands (IWMI, 2015). Extensive water harvesting and re-greening efforts were undertaken. Both physical and biological soil and water conservation measures were introduced in more than 3.000 watersheds, with soil bunds and stone bunds being constructed on almost all upper, mid and bottom slopes.

In the Raya Azebo valley in northern Ethiopia's Tigray region, farmers reported that the treatment led to an increase in humidity and a decrease in local temperatures. Areas close to stone bunds show high soil fertility, partially due to a decreased loss of soil organic matter, and partially due to increased soil moisture availability. Similarly, the placement of bunds led to noticeably higher soil moisture, higher water retention, and cooler soil temperatures. The increased soil moisture retention has caused soil moisture to be available for longer after the rainy season. In addition, frost intensity and potential crop damage has decreased as the increased soil moisture protects the soil.

In Tigray, local forms of reforestation and area exclosures have led to an increased intensity of springs and soil moisture in areas surrounding the cropland. This is likely due to improved infiltration of rainfall and a better water storage capacity of the soil. Together with water harvesting measures, it is an example of how microclimate processes can come together to transform a landscape.

downwind, forming a layer of discontinuity that is called the internal boundary layer. In this way, neighbouring areas can affect and be affected by certain land use types and related surface temperature and moisture levels.

Wind can act as a transporter of nutrients like soil particles from other places, and seeds, but also diseases and pests. As with pollination, bacteria and fungi depend on wind to spread to a new host, while insects also make use of wind to expand their range (Gliessman 2015). There are also direct mechanical effects from wind such as possible damage to leaves and crops. Sediments suspended in the wind hit leaves and stems from plants, causing structural damage. Another effect is wind erosion, and the loss of top soil that reduces soil fertility. This can have a cascading effect on the microclimate through a loss of vegetation potential and soil moisture storage capacity (Ong et al. 2015).

3. Towards a toolkit for microclimate interventions

Microclimates may either buffer against climate change or amplify its effects, be it temperature peaks, droughts, or more irregular or delayed rainfall. It is thus important to know how the dynamics between microclimate components and across scales can be influenced and managed (Chen et al. 1999). The microclimate and its interactions is a wide-ranging topic. Issues related to ecosystems, biodiversity, soils, food, water, energy and livelihoods need to be addressed holistically. This gives rise to the need for strategies that guide investments in landscapes to ensure that achieving one goal does not undermine the ability to achieve the others. It is a call for intensive change; not making isolated interventions, but having a critical sum of measures that creates systemic change at the landscape level (Van Steenbergen et al. 2011). There are numerous examples of areas where high density watershed improvements have caused change. Parts of India, China, Thailand, Ethiopia and Rwanda have seen an increase in shallow groundwater tables, moisture availability and vegetation intensity. Agricultural productivity jumped not only because of more moisture but due to gentler microclimates and higher nitrogen availability as well.

Microclimate management is aimed towards creating more resilient agriculture that is less vulnerable to temperature extremes and variability (Gliessman 2015). There are several interventions that can affect the microclimate and hence the ability of an area to cope with, and even make beneficial use of, the larger climate change. The introduction of land and water management practices can have a cascading effect on the landscape, where small changes come together for larger local and regional transformation. Increased water availability can lead to cooler temperatures, facilitate vegetation growth, and in turn positively influence water availability again. The various microclimate components are inextricably linked to each another. Changing one component will have effects on local agriculture and the landscape.

In the following, three 'intervention clusters' are proposed. Understanding how different measures affect the microclimate, and how this in turn works in a local context is important to determine the best land and water management intervention for a specific landscape.

Table 4: The effects of different types of water storage on microclimate components

Water buffering	Techniques in use	Effect on soil moisture	Effect on soil temperature	Effect on air humidity	Effect on air temperature	Effect on wind direction and speed
Open storage	Surface ponds and micro-dams	Limited - fringe effects dependent on seepage	Not significant	**Significant - more rainfall, higher air moisture and more dew**	**Cooling effect of surface evaporation**	Limited - causing local difference in temperature and hence air pressure
Soil moisture	Eyebrows, stone bunds, flood water spreaders, terraces, gully plugging and fog collection	**Direct and significant impact on soil moisture**	**Soil temperature more balanced**	**Significant closer to the ground - more dew and white frost, increased air moisture**	Some cooling effect	Not significant
Shallow groundwater	Infiltration trenches, infiltration ponds and wells	**Delayed effect - contribute to soil moisture later in the season**	Some delayed moderation effect on soil temperature	Not so significant	Not significant	None

Figure 13: Water buffering measures in Tigray, Ethiopia (Source: MetaMeta 2016)

> *"Ten years ago, the moisture quickly evaporated, but now the moisture is conserved in the soil for a longer time and the dew can wet your feet in the morning."*
>
> *Farmer in the Raya valley, Tigray 2016*

Cluster 1: water buffering

The availability of moisture is a key microclimate determinant, as it evens out temperature peaks and lows, both in the air and the soil at different depths. Hence, it is important to better retain water at the landscape level by applying water harvesting,

Box 4: Fog collection and regreening in Llomas de Meija, Peru

The drylands of the Atacama Desert represent an example of a *fogscape* (Salbitano, 2010), being an ecosystem that relies on the interplays between fog, vegetation and soils. Fog represents a vital resource for biodiversity and bring considerable microclimatic benefits to arid drylands, in terms of the presence of soil moisture and vegetation. Local tree species have the capacity to take advantage from the advection fog fluxes from the sea, by intercepting and condensating fog on their leaves. Fog moisture then becomes available moisture for the surrounding arid landscape.

In recent decades, fogscapes have been subject to general degradation caused by an increase in deforestation. In the late 1990s, a research project was launched with the aim to rehabilitate the area of Llomas de Meija in Peru with artificial fog collectors. These collectors consist of a metal frame, and are covered with a synthetic mesh, replicating the effect of leaf surfaces.

Figure 14 Fog collectors (Source: climatetechwiki.org 2016)

Figure 15 Fog collectors in Llomas de Meija (Source: Bresci 1997)

The project results showed that standard reforestation interventions had unsatisfactory results without the supplemental irrigation provided by the fog collectors. At the same time, in places where the collectors were present, trees were able to sustain themselves and supported smaller vegetation and local ecosystems, after two years of artificial fog collection (Semenzato, 1998).

Fogscapes can be found along a number of coastlines in Chile, Peru, United States, Morocco, South Africa, Dominican Republic and Spain (Canary Islands). In various semi-arid inland locations, such as in Ethiopia, Guatemala, Yemen and Tanzania, they can also be found. Their impact on local climate dynamics is significant.

floodwater diversion, and erosion and drainage control measures. Increased moisture availability will influence dew formation and a reduced risk of night frost. Moreover, soil moisture availability will give a boost to the ability of soil bacteria to fixate nitrogen and add to the overall fertility of the landscape. A related phenomenon is capillary rise that takes place over time. Particularly in semi-arid areas, water that is stored as shallow groundwater rises back to the root zone later in the season when night temperatures drop, allowing for a second crop or boosting the standing crop.

"The rainfall pattern has considerably decreased, but due to the conservation measures on our farm, soil moisture has increased in my land as well as production"

Farmer in the Raya valley, Tigray 2016

Water harvesting is basically the collection of water runoff for its productive use (Critchley 1991). The purpose and type of water harvesting can differ, and this has different effects on the microclimate. The three types that can be distinguished are water harvesting for soil moisture, for open storage and for groundwater recharge. While they all aim to increase the overall water availability for the landscape, the different types of water harvesting can have different effects on the microclimate.

Water harvesting that focuses on soil moisture storage increases the available water in the soil profile. In arid areas, this mitigates warm temperatures during the day and cool temperatures during the night, both in the soil and in the air, directly above the surface. It protects against temperature extremes, such as night frost. There is increased moisture for evapotranspiration to increase the local humidity, which in turn lowers the air temperature. The same is accomplished with water harvesting techniques that use open storage. When not used directly for irrigation, surface water lowers the local air temperature and increases air humidity. When used for irrigation, it will have similar effects as soil moisture storage.

Water harvesting for groundwater recharge to make water available over a longer period, compared to soil moisture storage. Higher groundwater levels in the upper watershed could support the development of springs at the bottom of the hill. Recharged groundwater can also return to the soil during times of drought through capillary action, aiding plants and improving the microclimate in a similar way as soil moisture storage. Good understanding of groundwater dynamics is critical to design and implement soil and water conservation measures that harvest water and reduce runoff.

The effects of water harvesting on the microclimate cannot be seen in isolation, as a changed microclimate can aid further soil moisture recharge, through improved infiltration, percolation, added shade from agroforestry made possible by increased moisture, and increased biological activity that improves both available nutrients and the soil profile. Water harvesting hence is often not done in isolation, but rather combines different approaches, such as agroforestry and re-greening.

"Definitely, there is a difference these years. It is as different as someone who has eaten compared to someone who has not eaten. The production has increased and the soil now can hold moisture for around a week in the hot sun."

"We are making an association with the farmers from the watershed, to manage the re-greening measures and share the benefits of the watershed together."

Farmer in the Raya valley, Tigray 2016

Cluster 2: re-greening

Through appropriate design and management, farmers can create or maintain microclimatic conditions that favour the sustainability of a cropping system. Manipulation of radiation and wind is an important factor of microclimate management (Stigter 2011), and can be done

Table 5: Agroforestry objectives and examples (Source: Mbow et al. 2014)

Objective	Example
Increase soil fertility	Soil structure / nutrient fixing trees (e.g. *Faidherba albida*) Windbreak trees (e.g. *Azadirachta indica*) Erosion control (e.g. *Acacia senegal, Anacardium occidentale*)
Increase availability of water, and reduced incoming radiation	Conservation agriculture (moisture retention) Shade trees to reduce evaporation and facilitate growth of shade-tolerant plants (e.g. *Andansonia digitata*, Azadirachta indica, *Magnifera indica* and *Parkia biglobosa*)

Table 6: Agroforestry categories

Category	Definition	
Alley cropping	Rows of trees with a wide spacing, and companion crop growing in alleyways between the rows	
Multistrata systems	Perennials that require shade, such as coffee plants are covered by trees	
Protective systems	Trees and shrubs are used as windbreaks and shelterbelts	
Silvo-pasture systems	A combination of forestry and grazing	
Woodlots	The use of forest for timber, firewood, fodder and land reclamation	

Box 5: Agroforestry and resource competition

A discussion related to the introduction of trees and forests in agriculture is the possibility of resource competition. The use of soil nutrients and water competes with those used for cropping, especially in arid and semi-arid regions. The positive effects of a windbreak, increased shade and runoff capture could be negated by the increased water use, reducing rather than improving yields. However, more trees could also tap into different water reservoirs, as they use deeper groundwater than seasonal crops. Hydraulic lifting further makes soil moisture available to crops that would otherwise not be available (Lott et al. 2009; Ong et al. 2015). There is no consensus on whether agroforestry has a beneficial or negative effect on local natural resources, and strategies differ in different regions. A famous example of beneficial agroforestry is the Faidherbia albida tree that sheds its leaves in the rainy season, reducing competition for water and sunlight when crops need it most.

by increasing the number of trees in a landscape. Microclimate variables like solar radiation, air temperature at the surface and soil temperature are highly sensitive to changes in the type of vegetation. Like soil moisture, vegetation affects how much heat is absorbed in an area and how much is radiated. It affects the circulation of air temperature at different layers, the speed and direction of winds and the movement of dust particles among others. The presence of small forests in an open landscape can create local winds. Re-greening affects soil structure, nutrient cycling and soil moisture relations (Gliessman 2015). Branches and leaves provide habitats for an array of animal life and shed leaves that provide soil cover and modify the soil environment, being an important source of organic matter as they decay. By altering the structure of the canopy, a new environment is created with a different set of climatic responses (Chen et al. 1999).

"The sun duration and mountain shades have an effect on the evaporation of soil moisture. Soil moisture is lost faster in the fields who get early sunlight."

Farmer in the Raya valley, Tigray 2016

Table 7: Windbreak yield increase (Source: Kort 1988)

Crop	Yield increase (%) Compared to no barriers)
Alfalfa	99
Millet	44
Clover	25
Barley	25
Rice	24
Winter wheat	23
Rye	19
Corn	12
Spring wheat	8

Agro-ecosystems that are resilient in the face of climate change are also those that do the least harm to the ecological foundations of agriculture (Gliessman 2015). Farms are at the cross section of many microclimate processes that need to be integrated. Agroforestry is one of the more researched areas of microclimate management. It deals with farm and livestock management through the addition or retention of trees and other woody perennials to benefit from ecological and economic interactions (Nair 1985). Agroforestry is commonly classified in three types: agro-silvo-cultural, silvo-pastoral and agro-silvo-pastoral, according to the combination of crops, trees and pasture. These can be subdivided in several types and systems. Table 6 shows a number of agroforestry examples.

"There is a temperature difference. Due to the trees that grow in the revegetated area, it is much cooler. It also makes us happy be around the greener area."

Farmer in the Raya valley, Tigray 2016

Within a cropping system, the conditions of temperature, moisture, light, wind and atmospheric quality vary with specific location (Gliessman

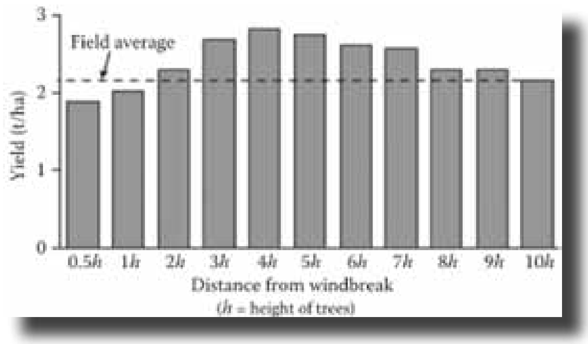


Figure 16: Soybean yield at distance from windbreak (Source: Gliesssman 2015)

2015). Conditions above the canopy, in the interior, at the soil surface and below the soil into the root zone can vary greatly, and such a vertical transect within the cropping system is called the microclimatic profile. Conditions in the various zones should not cause problems for the crops. This could happen when warm wind run through the system while the soil is very cold, causing plant desiccation as the roots are unable to absorb water fast enough to offset the loss.

Agroforestry has different implications for the microclimate, depending on the type and characteristics of the agroforestry system. Advantages of agroforestry are increased soil moisture retention, reduced water loss from soil evaporation and crop transpiration, and increased soil fertility. The addition of litter fall, root biomass and nutrient capture increases the overall health of the soil that crops can make use of (Lasco et al. 2014). Agroforestry can also be a buffer against climate variability and extremes. Through providing shaded areas and shelter, the overall climate variability is reduced, such as in coffee plantations (Lin 2007).

Box 6: Forests and local rainfall

An ongoing area of research is the effect of forests on rainfall. This can be divided in a smaller scale focused 'demand' school and a regional scale focused 'supply' school way of thinking. The demand school proposes that forests compete for water availability. In their view, trees increase interception and evapotranspiration and reduce downstream runoff. The supply school on the other hand, states that the impact of forests must be seen at a larger scale, where local evapotranspiration contributes to the biotic pump and increases water cycle intensity. This school argues that precipitation recycling both raises the likelihood of local rainfall events, as well as the transportation of moist air inland (Ellison et al. 2012).

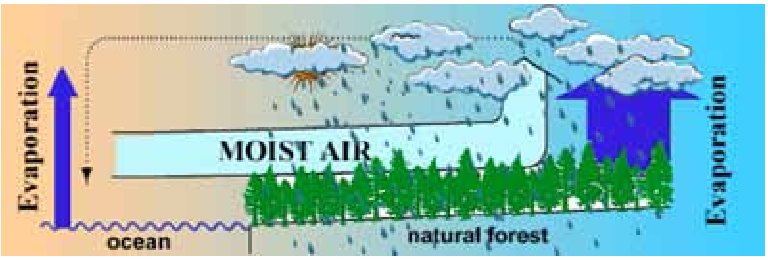
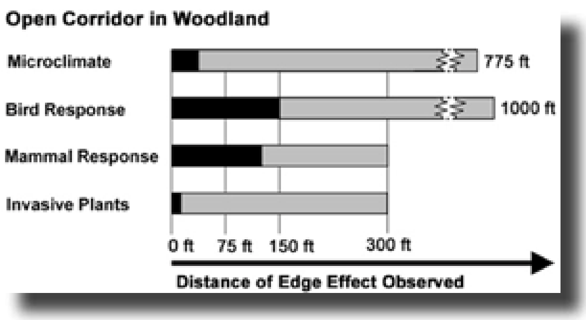


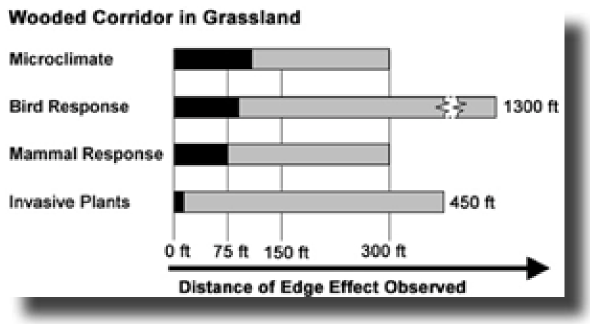
Figure 17: Biotic pump (Source: Sheil 2014)

As the question of scale suggests, the impact of forests on water availability not only relates to the water that forests use, but also to where the water ends up. Recent studies state that forests have an important role in inducing rainfall. Increased relative humidity and lower temperatures contribute to a higher likelihood of precipitation events. The release of aerosols by trees also helps cloud formation. Other than precipitation, fog and dew capture is enhanced by forests as they provide surfaces and cooling, which further aids local water availability (Bruijnzeel 2001; 2004; Ellison et al. 2012).

Box 7: Understanding local rainfall

- Local rainfall, even a little, can trigger more rainfall. This is known as the threshold effect. Once it starts to rain, it continues to rain;
- There is balance and tension between local and regional rainfall. If rain is generated locally, it can come down elsewhere;
- Evaporation has two sometimes opposite effects, being a lower temperature and more air humidity. The lower air temperature can create the so-called monsoon edge effect. With cooling, the temperature gradient gets less, and less moisture sucked into the air;
- The albedo effect of vegetation causes thermic rise, of which rainfall can be a result when the air is moist:
    - Grassland has a high albedo so little energy is left for thermic rise;
    - Forest has a lower albedo so more energy remains in the canopy for thermic rise. Moisture in the air will rise higher and this creates more rainfall.





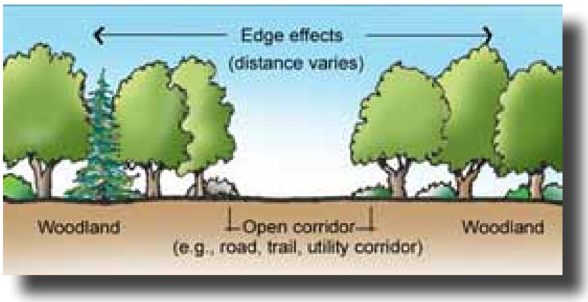


Figure 18: The principle of microclimatic edge effects, on corridors (Source: USDA National Agroforestry Centre 2016)

Shade effects

The presence of trees provides a shading effect to both soil and crops, depending on the composition of the land. This can be a full canopy above the crops, like with coffee production, or a partial canopy to not influence incoming radiation too much, while benefiting from shelter effects. Shade has a direct effect on soil temperature, and moisture loss from evaporation and transpiration. By reducing incoming radiation, soil moisture is lost at a lower rate. Furthermore, reduced air temperature can benefit crops that are sensitive to heat, such as coffee and cocoa (Lasco et al. 2014; Lin 2007). Possible negative consequences from shading are that reduced solar radiation might inhibit plant growth, rather than promote it (Ong et al. 2015). However, Lott et al. (2009) raise the point that in arid and semi-arid environments, the improved microclimate and enhanced soil fertility outweighs any negative effects.

Changes in the soil temperature can be induced

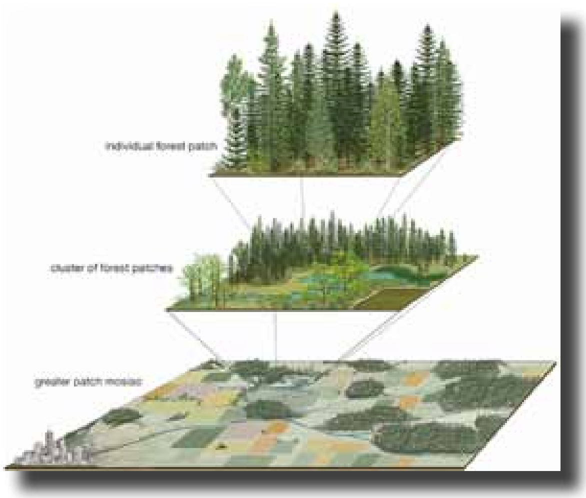


Figure 19: Patch dynamics at different scales (Source: Britannica 2014)

by covering the surface of the soil. Growing a cover crop is one well-recognised method to do so, and brings additional positive effects related to organic matter content of the soil, seed germination and moisture conservation (Gliessman 2015). Trees and other tall plants that create a canopy (overstory) that covers other plants greatly modify temperature conditions under the canopy. Shade from the canopy reduces solar gain at the surface of the soil, and helps the soil to retain moisture. Removal of overstory vegetation destroys the ability of canopies to buffer the understory and moderate levels of incoming and outgoing radiation (Chen et al. 1999).

Windbreaks

Trees that are used as windbreak protect a field from prevailing wind patterns, greatly lowering the wind speed before reaching crops. The temperature behind the shelterbelt is usually slightly higher, as the cooling effect from wind no longer applies. Humidity is higher as well, as it is no longer transported away. Reduced exposure to wind and increased humidity reduces evapotranspiration rates from both soil and crops and can increase water use efficiency. A further positive effect is reduced kinetic impacts from wind, such as crop leaf damage and loss of top soil due to erosion.

A major consideration, as with other agroforestry measures, is the increased water use from trees used in windbreaks. Areas where water is scarce may see reduced yields, especially when a new agro-forestry scheme is started and newly planted trees compete for water with crops. However, at later stages, tree roots may provide additional access to water during times of drought as they pull water up from deeper in the soil, otherwise

Figure 20: Re-greening efforts in the hills of Tigray, Ethiopia (Source: MetaMeta 2016)

unreachable to crops. In an extensive review of windbreak effects on crops, Kort (1988) summarised the positive benefits of windbreaks on crops (see table 7). Gliessman (2015) describes a study that shows yield increases from 5 to 50 percent. The maximum benefits are between 3 and 6 tree heights from the crop, with benefits reported up to 10 tree heights away from the windbreak. An example of the distance effects to the windbreak is given in figure 16. Reduced yields close to the windbreak are probably the result of excessive shading or resource competition.

Soils

Canopy interception of precipitation reduces surface compaction and improves infiltration by the soil. Similarly, roots and biological activity surrounding the trees, and reduced evaporation in shaded areas improves soil texture and infiltration, especially in arid and semi-arid regions. Cover crops that are planted in between active crop plants are called living mulch. Mulching creates a buffer between the soil and solar radiation, providing a means of reducing soil evaporation through reduced temperatures as well as reduced exposure to wind. Such living mulch can change the albedo of the soil surface and raise the temperature of the air immediately above the crop (Gliessman 2015). For dry mulch, straw from wheat, oats and barley are commonly used, while water hyacinth (*Eichhornia crassipes*) and duckweed (*Lemna spp.*) are also useful. The combined effect is a greater amount of soil moisture. Plant-derived mulch will eventually become part of the soil, adding to its organic matter content. Another possibility is to let a mulch accumulate naturally, by using a no-tillage system. Crop residues are left on the surface, forming a layer that modifies soil temperature and prevents moisture loss.

The effect of soil type and the presence of mulch on dew formation has several complexities. While it was assumed that mulching with faster cooling than the underlying soil would assist in dew formation this turns out not to be the case (Li 2002). The explanation for this was sought in the relationships between soil properties and water adsorption. Similarly, positive properties of soil mulch for dew formation at night were offset by higher evaporative losses during the day (Li 2002; Graf et al. 2008). The deposit of dew droplets on leaves can also serve as an impeding factor, facilitating the growth of bacteria and fungi (Agam & Berliner 2006).

Cluster 3: land use planning

Microclimate dynamics are directly related to all landscape components, including vegetation, corridors – streams, roads and powerlines – and transition zones between patches, such as edges between forests and openings (Chen et al. 1999). Microclimatic variance is especially dramatic in transitional zones (also called ecotones) between adjacent ecosystems. Due to increased land use fragmentation, such edge environments where climatic and biotic changes can be seen have become a major portion of landscapes. Changes in physical and biotic environments affect ecological processes as varied as plant regeneration, dispersal of seeds, nutrient cycling and wildlife interactions.

Microclimate change, such as temperature increases, caused by intensive land use change may have greater impacts at both local and regional scales than modifications predicted from the greenhouse effect (Chen et al. 1999). It is important to recognise that different features in the landscape – within patches, between patches, through ecotones, across the landscape – have distinct microclimates. Microclimatic patterns across the landscape are highly specific to an ecosystem, due to differences in topography and land use structure. Microclimatic insights can provide vital information when trying to explain other ecological processes and developing management option for a landscape. Microclimate influences the distribution of fauna as varied as butterflies, amphibians, reptiles and birds (Chen et al. 1999). Hence, manipulating the microclimate by altering the structural environment can thus be a useful tool in both wildlife and ecosystem conservation.

"Due to the intervention, the day temperature and night temperature is warmer and fluctuates less. For us, this is an indication that we will have good summer rainfall."

Farmer in the Raya valley, Tigray 2016

Area closure and reforestation

The promotion and protection of existing forested lands has benefits to the local microclimate in the surrounding areas as well. The effects of area closure are like agroforestry, with the added benefit of reduced competition for native flora and fauna. Soils benefits from reduced erosion as it is protected by trees and root systems, and its water holding capacity is increased by an improved soil structure from biological activity (Balana et al. 2012). Adjacent lands also benefit. Reduced surface runoff can reduce local erosion of top soils and valuable nutrients, especially in arid and semi-arid areas. Furthermore, increased water infiltration, percolation and transport can make soil moisture to become available for local use in times of drought, through capillary rise. As with exclosures, reforestation changes the microclimate through mitigating climate extremes, encouraging biological activity and intensifying the hydrological cycle.

"The acacia trees that were regenerated due to the intervention are effective to conserve moisture and act as a wind break and as a living fence. They work as soil erosion prevention."

Farmer in the Raya valley, Tigray 2016

Landscape restoration, microclimate management and sustainable development are topics that require a sound understanding of natural processes and supportive ecosystems. This relates to the study of meta-systematics, which focuses on how systems in perpetual motion relate with, and affect, one another (Gliessman 2015). This can only be done competently by combining insights from many fields of human knowledge and experience. The impact of microclimate management measures will be similar in diverse locations at the small-scale (Chen et al. 1999). However, how this works out at different scales needs to be carefully considered. There is a need to examine microclimatic characteristics at multiple scales and consider cumulative effects, rather than to simply assess the importance of microclimate independently at each scale.

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Practical Note #27

Colofon

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For more information: www.spate-irrigation.org.

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