

Os “postulados” que defendemos de aumento de matéria orgânica / fertilidade e de cobertura dos solos dos Montados tem como base o know-how da agricultura de conservação. Ou seja, a importância do “solo” e da microbiologia associada.

Mais matéria orgânica = Maior captação / retenção da água no solo, “tema importante” nos anos de seca – em especial nos solos mais fracos (ex^o : areias).

Mais matéria orgânica = melhor funcionamento da microbiologia envolvente das raízes do arvoredo e maior aproveitamento dos macro e micronutrientes.

Plantas anuais melhoradoras instaladas e cobertura com parte dos seus restos secos no Verão, em vez de solos inférteis descobertos expostos às temperaturas ou preenchidos por matos combustíveis e concorrentes, hidricamente, do arvoredo – em Montados de Charneca e outros, ondulados, de declive suave.

Manta de mato roçada, periodicamente, em Serra, com declives mais acentuados e solos pouco profundos.

Sabendo-se, ainda, que os benefícios gerais duma floresta mais densa, mas sem exageros de densidade teóricos - que dificultam a sua gestão, provocam autoconcorrência hídrica e a expõem a incêndios de virulência escusada - resultam numa melhor protecção do solo (contra extremos de temperaturas e de pluviosidade), não é difícil admitir que o adensamento dos Montados protegerá o solo e, fazendo-o, tal medida entra em simbiose com o próprio arvoredo, criando-se como que um “micro-clima” e interacção.

Não detectamos artigos científicos específicos com elenco de medidas especiais para protecção dos Montados contra os anos de seca ; o que existe, como se verá abaixo, em matéria de Sobreiros e Azinheiras, são artigos técnicos que descrevem as características e formas dos sobreiros em lidarem com a estação seca (normal), procurando água em limiões mais baixos do solo e o facto das azinheiras serem mais resilientes, à partida, às secas, embora limitadas, zonalmente, a solos mais fortes do interior do Alentejo.

Porém, com Verões extra-longos e anos de seca sucessiva, no Alentejo, tais mecanismos de gestão de água do arvoredo terão de ser auxiliados ou reforçados.

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A “Iniciativa Pró-Montado Alentejo” considera que é tempo de “come back to basics” ou seja ao “Solo”.

Um solo melhor que ajude, física, química e biologicamente tais mecanismos, ao proporcionar o melhor “ambiente” possível aos sistemas radiculares.

Não há produção vegetal sustentável sem um solo saudável.

Um solo saudável tem, ainda, um maior nível de captação de carbono atmosférico.

Assim sendo, apresentamos, entre outros, extractos de artigos notáveis da **FAO** e de faculdades americanas, com a vantagem de se expressarem em termos que permitem a sua compreensão em meios não técnicos e possibilitarem uma rápida decisão política.

Tomámos a liberdade, nos textos referidos, de destacar, apenas, os trechos com maior interesse para a floresta do Montado.

Considera esta “Iniciativa pró-Montado Alentejo” que os artigos expostos devem gerar suporte e consenso técnico suficiente para com as medidas básicas de adaptação do Montado que se propõem nesta “Iniciativa”.

Sempre será bom verificar/relembrar que no elenco dos seus Promotores e Aderentes se encontram professores, técnicos florestais e utilizadores especializados com várias dezenas de anos de experiência na matéria.

...

Apontado o caminho ao aumento da resiliência dos Montados adultos, face às alterações climáticas, promovendo a sua adaptação às mesmas, subsiste o problema de como o fazer em matéria de adensamento.

Não se podendo deixar de referir que o ano de 2018 evidenciou morte súbitas, em múltiplos locais, de sobreiros jovens, como nunca se tinha verificado, em jovens sobreiros até aos 20-25 anos. Mesmo em casos de regeneração natural.

Por outro lado e regressando ao tema anterior, não basta melhorar solo para proteger o Montado adulto existente. É preciso ensombrar para criar o tal “micro-clima”.

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Isso faz-se, adicionando e fazendo crescer, em cada hectare, com sucesso, árvores jovens.

E com rapidez, antes que as condições do clima se degradem mais.

Relativamente a este problema da resistência de sobreiros novos a Verões e/ou anos muito secos, assunto relevante quando, por exemplo, se pretende adensar manchas florestais em Charneca já com poucos sobreiros, apresenta-se, no final deste anexo, como “pista de reflexão para a resolução futura do problema” extractos do trabalho “Instalação e Manutenção de Povoamentos de novas Plantações de Povoamentos Regados” elaborado por uma equipa de investigação da Universidade de Évora.

A Fertirega, com gota-a-gota, criteriosamente aplicada e controlada, poderá resolver dois problemas importantes que ocorrem, frequentemente, nas operações de adensamento e agilizar a recuperação efectiva da densidade dos Montados :

- 1 – A claudicação frequente dos sobreiros jovens (agravada nos anos piores), com custo agravado, pela perda do investimento em protectores de porte significativo ;
- 2 – A potencialidade de se reporem as manchas “originais” de Montado, em Charneca, até às 100 árvores, recuperando-se em 10-20 anos, cerca de 40-50 anos de erosão climática e produtiva dessas manchas .

A sua viabilidade dependerá da existência de charcas (ou furos de baixo caudal, já que são, relativamente, poucas plantas por hectare), do custo da energia e seu acesso e ... da sua manutenção, criteriosa, ao longo de 10 anos.

Foi, entretanto, encomendado modelo-padrão de custeio de investimento e exploração para 2 tipos de disponibilidade de infraestruturas e manchas florestais, a adensar de 36 hectares. Em breve se verá se os custos são integráveis em limites aceitáveis para a medida 815 (Aumento da Resiliência Ambiental das Florestas) do PDR.

As primeiras expectativas são algo positivas, dada a evolução exponencial do uso dos sistemas de gota-a-gota pelo mundo e a redução de custos de tais sistemas associada.

Nesta fase, a “Iniciativa Pró-Montado Alentejo” apenas solicita que esta opção possa ser considerada nos sistemas de apoio ao investimento disponíveis, em

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matéria de adensamento já que o foi, recentemente, no caso das florestações de raiz.

Índice de consulta rápida dos artigos técnico-científicos :

- The importance of soil organic matter (FAO) – Pag. 4 (deste anexo) ;
 - SOILS AND TREES - IOWA State University – Pag. 14 ;
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The importance of soil organic matter - Key to drought-resistant soil and sustained food production - By **Alexandra Bot** FAO Consultant and **José Benites** FAO Land and Plant Nutrition Management Service

Healthy soil is the foundation of the food system

Plants obtain nutrients from two natural sources: organic matter and minerals.

Organic matter includes any plant or animal material that returns to the soil and goes through the decomposition process. In addition to providing nutrients and habitat to organisms living in the soil, **organic matter also binds soil particles into aggregates and improves the water holding capacity of soil.** Most soils contain 2-10 percent organic matter. However, even in small amounts, organic matter is very important.

Soil is a living, dynamic ecosystem. Healthy soil is teeming with microscopic and larger organisms that perform many vital functions including converting dead and decaying matter as well as minerals to plant nutrients. Different soil organisms feed on different organic substrates. Their biological activity depends on the organic matter supply.

Nutrient exchanges between organic matter, water and soil are essential to soil fertility and need to be maintained for sustainable production purposes.

Soil organic matter content is a function of organic matter inputs (residues and roots) and litter decomposition. It is related to moisture, temperature and aeration, physical and chemical properties of the soils as well as bioturbation (mixing by soil macrofauna), leaching by water and humus stabilization

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(organomineral complexes and aggregates). Land use and management practices also affect soil organic matter.

Most soil organic matter originates from plant tissue. Plant residues contain 60-90 percent moisture. The remaining dry matter consists of carbon (C), oxygen, hydrogen (H) and small amounts of sulphur (S), nitrogen (N), phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg). Although present in small amounts, these nutrients are very important from the viewpoint of soil fertility management.

Soil organic matter consists of a variety of components. These include, in varying proportions and many intermediate stages, an active organic fraction including microorganisms (10-40 percent), and resistant or stable organic matter (40-60 percent), also referred to as humus.

Forms and classification of soil organic matter have been described by Tate (1987) and Theng (1987). For practical purposes, organic matter may be divided into aboveground and belowground fractions. Aboveground organic matter comprises plant residues and animal residues; belowground organic matter consists of living soil fauna and microflora, partially decomposed plant and animal residues, and humic substances. The C:N ratio is also used to indicate the type of material and ease of decomposition; hard woody materials with a high C:N ratio being more resilient than soft leafy materials with a low C:N ratio.

Although soil organic matter can be partitioned conveniently into different fractions, these do not represent static end products. Instead, the amounts present reflect a dynamic equilibrium. The total amount and partitioning of organic matter in the soil is influenced by soil properties and by the quantity of annual inputs of plant and animal residues to the ecosystem. For example, in a given soil ecosystem, the rate of decomposition and accumulation of soil organic matter is determined by such soil properties as texture, pH, temperature, moisture, aeration, clay mineralogy and soil biological activities. A complication is that soil organic matter in turn influences or modifies many of these same soil properties.

Organic matter existing on the soil surface as raw plant residues helps protect the soil from the effect of rainfall, wind and sun. Removal, incorporation or burning of residues exposes the soil to negative climatic impacts, and removal or burning deprives the soil organisms of their primary energy source.

Organic matter releases nutrients in a plant-available form upon decomposition. In order to maintain this nutrient cycling system, the rate of organic matter addition from crop residues, manure and any other sources must equal the rate of decomposition, and take into account the rate of uptake by plants and losses by leaching and erosion.

Where the rate of addition is less than the rate of decomposition, soil organic matter declines. Conversely, where the rate of addition is higher than the rate of decomposition, soil organic matter increases. The term steady state describes a condition where the rate of addition is equal to the rate of decomposition.

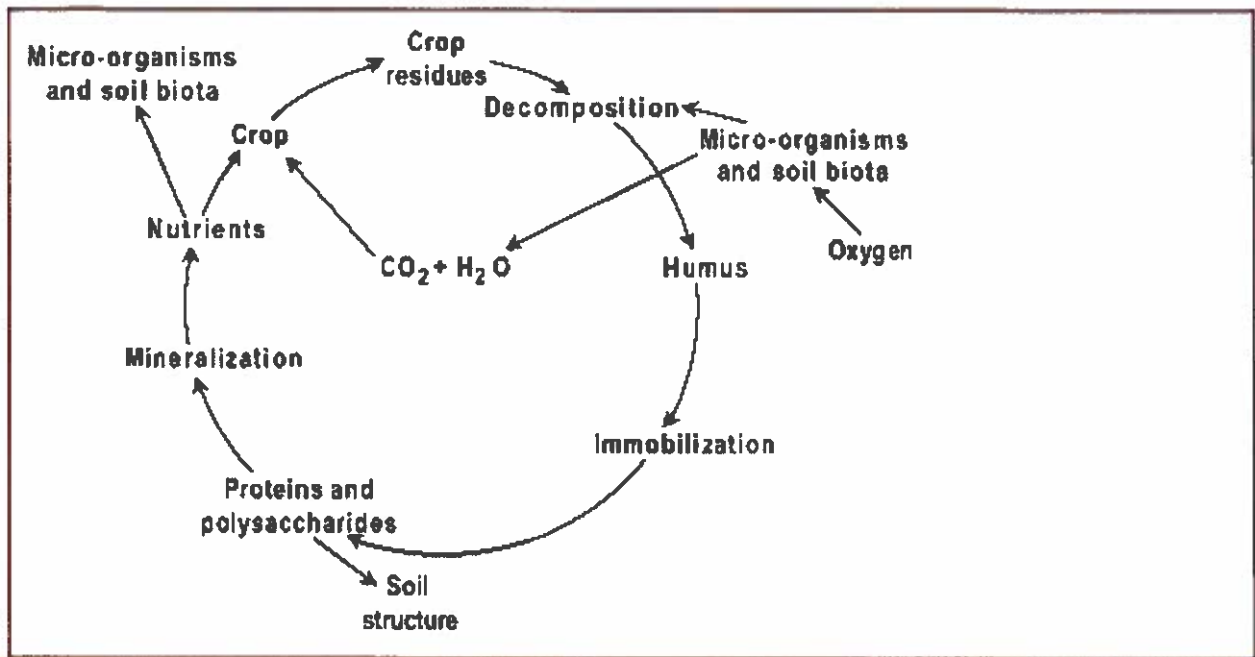
Soil organic matter

When plant residues are returned to the soil, various organic compounds undergo decomposition. Decomposition is a biological process that includes the physical breakdown and biochemical transformation of complex organic molecules of dead material into simpler organic and inorganic molecules (Juma, 1998).

The continual addition of decaying plant residues to the soil surface contributes to the biological activity and the carbon cycling process in the soil. Breakdown of soil organic matter and root growth and decay also contribute to these processes. Carbon cycling is the continuous transformation of organic and inorganic carbon compounds by plants and micro- and macro-organisms between the soil, plants and the atmosphere (Figure 2)

FIGURE
Carbon cycle

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Decomposition of organic matter is largely a biological process that occurs naturally. Its speed is determined by three major factors: soil organisms, the physical environment and the quality of the organic matter (Brussaard, 1994). In the decomposition process, different products are released: carbon dioxide (CO₂), energy, water, plant nutrients and resynthesized organic carbon compounds. Successive decomposition of dead material and modified organic matter results in the formation of a more complex organic matter called humus (Juma, 1998). This process is called humification. Humus affects soil properties. As it slowly decomposes, it colours the soil darker; increases soil aggregation and aggregate stability; increases the CEC (the ability to attract and retain nutrients); and contributes N, P and other nutrients.

Soil organisms, including micro-organisms, use soil organic matter as food. As they break down the organic matter, any excess nutrients (N, P and S) are released into the soil in forms that plants can use. This release process is called mineralization. The waste products produced by micro-organisms are also soil organic matter. This waste material is less decomposable than the original plant and animal material, but it can be used by a large number of organisms. By breaking down carbon structures and rebuilding new ones or storing the C into their own biomass, soil biota plays the most important role in nutrient cycling processes and, thus, in the ability of a soil to provide the crop with sufficient nutrients to harvest a healthy product. The organic matter content, especially the more stable humus, increases the capacity to store water and store (sequester) C from the atmosphere.

Some functions of a healthy soil ecosystem

- Decompose organic matter towards humus.
- Retain N and other nutrients.
- Glue soil particles together for best structure.
- Protect roots from diseases and parasites.
- Make retained nutrients available to the plant.
- Produce hormones that help plants grow.
- Retain water.



Soil life plays a major role in many natural processes that determine nutrient and water availability for agricultural productivity. The primary activities of all living organisms are growing and reproducing. By-products from growing roots and plant residues feed soil organisms. In turn, soil organisms support plant health as they decompose organic matter, cycle nutrients, enhance soil structure and control the populations of soil organisms, both beneficial and harmful (pests and pathogens) in terms of crop productivity.

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The living part of soil organic matter includes a wide variety of micro-organisms such as bacteria, viruses, fungi, protozoa and algae. It also includes plant roots, insects, earthworms, and larger animals such as moles, mice and rabbits that spend part of their life in the soil. The living portion represents about 5 percent of the total soil organic matter. Micro-organisms, earthworms and insects help break down crop residues and manures by ingesting them and mixing them with the minerals in the soil, and in the process recycling energy and plant nutrients. Sticky substances on the skin of earthworms and those produced by fungi and bacteria help bind particles together. Earthworm casts are also more strongly aggregated (bound together) than the surrounding soil as a result of the mixing of organic matter and soil mineral material, as well as the intestinal mucus of the worm. Thus, the living part of the soil is responsible for keeping air and water available, providing plant nutrients, breaking down pollutants and maintaining the soil structure.

The composition of soil organisms depends on the food source (which in turn is season dependent). Therefore, the organisms are neither uniformly distributed through the soil nor uniformly present all year. However, in some cases their biogenic structures remain. Each species and group exists where it can find appropriate food supply, space, nutrients and moisture (Plate 2). Organisms occur wherever organic matter occurs (Ingham, 2000). Therefore, soil organisms are concentrated: around roots, in litter, on humus, on the surface of soil aggregates and in spaces between aggregates. For this reason, they are most prevalent in forested areas and cropping systems that leave a lot of biomass on the surface.

Essential functions performed by different members of soil organisms (biota)

Functions	Organisms involved
Maintenance of soil structure	Bioturbating invertebrates and plant roots, mycorrhizae and some other micro-organisms
Regulation of soil hydrological processes	Most bioturbating invertebrates and plant roots
Gas exchange and carbon sequestration (accumulation in soil)	Mostly micro-organisms and plant roots, some C protected in large compact biogenic invertebrate aggregates
Soil detoxification	Mostly micro-organisms
Nutrient cycling	Mostly micro-organisms and plant roots, some soil- and litter-feeding invertebrates
Decomposition of organic matter	Various saprophytic and litter-feeding invertebrates (detritivores), fungi, bacteria, actinomycetes and other micro-organisms
Suppression of pests, parasites and diseases	Plants, mycorrhizae and other fungi, nematodes, bacteria and various other micro-organisms, collembola, earthworms, various predators
Sources of food and medicines	Plant roots, various insects (crickets, beetle larvae, ants, termites), earthworms, vertebrates, micro-organisms and their by-products
Symbiotic and asymbiotic relationships with plants and their roots	Rhizobia, mycorrhizae, actinomycetes, diazotrophic bacteria and various other rhizosphere micro-organisms, ants
Plant growth control	Direct effects: plant roots, rhizobia, mycorrhizae, actinomycetes,

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(positive and negative)

pathogens, phytoparasitic nematodes, rhizophagous insects, plant-growth promoting rhizosphere micro-organisms, biocontrol agents
Indirect effects: most soil biota

Practices that increase soil organic matter

Increased concern about the environmental and economic impacts of conventional crop production has stimulated interest in alternative systems. Central to such systems is the need to promote and maintain soil biological processes and minimize fossil fuel inputs in the form of fertilizers, pesticides and mechanical cultivation. All activities aimed at the increase of organic matter in the soil (Box 3) help in creating a new equilibrium in the agro-ecosystem.

For a system of natural resource management to be balanced, and thus sustainable, it must be able to withstand sharp climatic fluctuations, and to evolve steadily in response to social changes and changes in the costs and availability of inputs of land, labour and knowledge. The more diverse and complex an agricultural system is, the more stable and sustainable it will be in the face of unpredictable vagaries of climate and market. Thus, annual crops, woody perennials and nonwoody perennials may be combined in various ways with livestock or trees, or both, in what are now commonly called agrosilvipastoral systems.

Different approaches are required for different soil and climate conditions. However, the activities will be based on the same principle: increasing biomass production in order to build active organic matter. Active organic matter provides habitat and food for beneficial soil organisms that help build soil structure and porosity, provide nutrients to plants, and improve the water holding capacity of the soil.

Several cases have demonstrated that it is possible to restore organic matter levels in the soil (Figure 8). Activities that promote the accumulation and supply of organic matter, such as the use of cover crops and refraining from burning, and those that reduce decomposition rates, such as reduced and zero tillage, lead to an increase in the organic matter content in the soil (Sampson and Scholes, 2000).

Increased biomass production

In dry conditions, water may be provided through irrigation or water harvesting. The increased water availability enhances biomass production, soil biological activity and plant residues and roots that provide organic matter.

Balanced fertilization

Where the supply of nutrients in the soil is ample, crops are more likely to grow well and produce large amounts of biomass. Fertilizers are needed in those cases where nutrients in the soil are lacking and cannot produce healthy crops (FAO, 2000) and sufficient biomass. Most soils in sub-Saharan Africa (SSA) are deficient in P (*fósforo, como em Portugal*). P is required not only for plant growth but also for N fixation. Unbalanced fertilization, for example mainly with N, may result in more weed competition, higher pest incidence and loss of quality of the product. Unbalanced fertilization eventually leads to unhealthy plants. Therefore, fertilizers should be applied in sufficient quantities and in balanced proportions. The efficiency of fertilizer use will be high where the organic matter content of the soil is also high. In very poor or depleted soils, crops use fertilizer applications inefficiently. When soil organic matter levels are restored, fertilizer can help maintain the revolving fund of nutrients in the soil by increasing crop yields and, consequently, the amount of residues returned to the soil.

Cover crops

Growing cover crops is one of the best practices for improving organic matter levels and, hence, soil quality.

The benefits of growing cover crops include:

- They prevent erosion by anchoring soil and lessening the impact of raindrops.

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- They add plant material to the soil for **organic matter replenishment**.
- Some, e.g. rye, bind excess nutrients in the soil and prevent leaching.
- Some, especially **leguminous species**, e.g. hairy vetch, **fix N in the soil for future use**.
- Most provide habitat for beneficial insects and other organisms.
- **They moderate soil temperatures and, hence, protect soil organisms.**



A range of crops can be used as vegetative cover, e.g. grains, legumes and oil crops. All have the potential to provide great benefit to the soil. However, some crops emphasize certain benefits; a useful consideration when planning a rotation scheme. It is important to start the first years with (cover) crops that cover the surface with a large amount of residues that decompose slowly (because of the high C:N ratio). Grasses and cereals are most appropriate for this stage, also because of their intensive rooting system, which improves the soil structure rapidly.

In the following years, when soil health has begun to improve, legumes can be incorporated in the rotation. **Leguminous crops enrich the soil with N and their residues decompose rapidly because of their low C:N ratio**. Later, when the system is stabilized, it is possible to include cover crops with an economic function, e.g. livestock fodder.

The selection of cover crops should depend on the presence of high levels of lignin and phenolic acids. These give the residues a higher resistance to decomposition and thus result in soil protection for a longer period and the production of more stable

Improved vegetative stands

In many places, low plant densities limit crop yields. Wide plant spacing is often practised as “a way to return power to the soil” or “to give the soil some rest”, but in reality it is an indicator that the soil is impoverished. **Plant spacing is usually determined by farmers in relation to soil fertility and available water or expected rainfall** (unless standard recommendations are enforced by extension). This means that plants are often spaced widely on depleted soils in arid and semi-arid regions with a view to ensuring an adequate provision of plant nutrients and water for all plants.

However, it is important to maintain the recommended plant spacing in order to optimize biomass production and rooting density and, hence, organic matter for food, moisture retention and habitat for soil organisms. Once the crop is established, reduced sunlight between closer crop rows may also reduce regrowth of weeds.

Reforestation and afforestation

Afforestation means the establishment of a forest on land that has not grown trees recently.

It can serve two principal soil and water conservation purposes: protection of erosion-prone areas, and revegetation and rehabilitation of degraded land (Plate 13). Afforestation is specifically used to provide protective cover in vulnerable, steep and mountainous areas. Afforestation helps to replenish timber resources and provide fuelwood and fodder (FAO, 1979).

The establishment of a forest cover under good management is an effective means of increasing organic matter production. However, the land must have the productive capacity to support an appropriate forest type, which differs according to climate, soil, slope and the specific purpose of the forest (timber production, livestock grazing, etc.). Therefore, the choice of species and the selection of an appropriate site are of particular importance for successful afforestation.

Creating drought-resistant soil

Inefficient use of rainwater

Drylands may have low crop yields not only because rainfall is irregular or insufficient, but also because significant proportions of rainfall, up to 40 percent, may disappear as runoff. This poor utilization of rainfall is partly the result of natural phenomena (relief, slope, rainfall intensity), but also of inadequate land management practices (i.e. burning of crop residues, excessive tillage, eliminating hedges, etc.) that

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reduce organic matter levels, destroy soil structure, eliminate beneficial soil fauna and do not favour water infiltration. However, water “lost” as runoff for one farmer is not lost for other water users downstream as it is used for recharging groundwater and river flows.

Where rainfall lands on the soil surface, a fraction infiltrates into the soil to replenish the soil water or flows through to recharge the groundwater. Another fraction may run off as overland flow and the remaining fraction evaporates back into the atmosphere directly from unprotected soil surfaces and from plant leaves.

The above-mentioned processes do not occur at the same moment, but some are instantaneous (runoff), taking place during a rainfall event, while others are continuous (evaporation and transpiration).

To minimize the impact of drought, soil needs to capture the rainwater that falls on it, store as much of that water as possible for future plant use, and allow for plant roots to penetrate and proliferate. Problems with or constraints on one or several of these conditions cause soil moisture to be one of the main limiting factors for crop growth.

The capacity of soil to retain and release water depends on a broad range of factors such as soil texture, soil depth, soil architecture (physical structure including pores), organic matter content and biological activity. However, appropriate soil management can improve this capacity.

Practices that increase soil moisture content can be categorized in three groups:

- (i) those that increase water infiltration;
- (ii) those that manage soil evaporation; and
- (iii) those that increase soil moisture storage capacities. All three are related to soil organic matter.

In order to create a drought-resistant soil, it is necessary to understand the most important factors influencing soil moisture.

Increased soil moisture

Organic matter influences the physical conditions of a soil in several ways. Plant residues that cover the soil surface protect the soil from sealing and crusting by raindrop impact, thereby enhancing rainwater infiltration and reducing runoff. Surface infiltration depends on a number of factors including aggregation and stability, pore continuity and stability, the existence of cracks, and the soil surface condition. Increased organic matter contributes indirectly to soil porosity (via increased soil faunal activity). Fresh organic matter stimulates the activity of macrofauna such as earthworms, which create burrows lined with the glue-like secretion from their bodies and are intermittently filled with worm cast material.

The proportion of rainwater that infiltrates into the soil depends on the amount of soil cover provided (Figure 12). The figure shows that on bare soils (cover = 0 tonnes/ha) runoff and thus soil erosion is greater than when the soil is protected with mulch. Crop residues left on the soil surface lead to improved soil aggregation and porosity, and an increase in the number of macropores, and thus to greater infiltration rates.

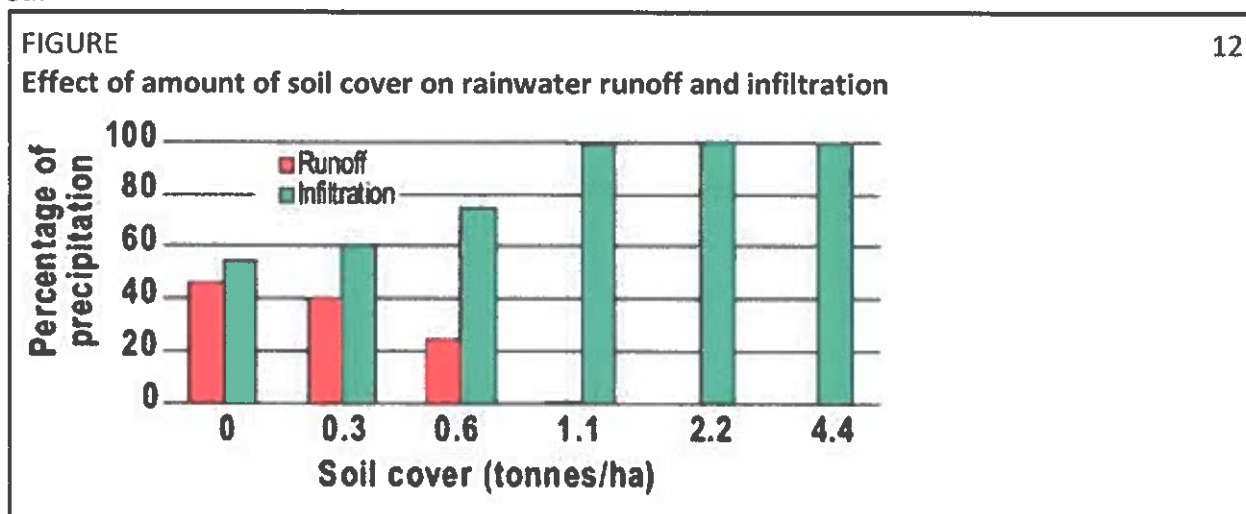
Increased levels of organic matter and associated soil fauna lead to greater pore space with the immediate result that water infiltrates more readily and can be held in the soil (Roth, 1985). The improved pore space is a consequence of the bioturbating activities of earthworms and other macro-organisms and channels left in the soil by decayed plant roots.

On a site in southern Brazil, rainwater infiltration increased from 20 mm/h under conventional tillage to 45 mm/h under no tillage (Calegari, Darolt and Ferro, 1998). Over a long period, improved organic matter promoted good soil structure and macroporosity. Water infiltrates easily, similar to forest soils (Figure 13).

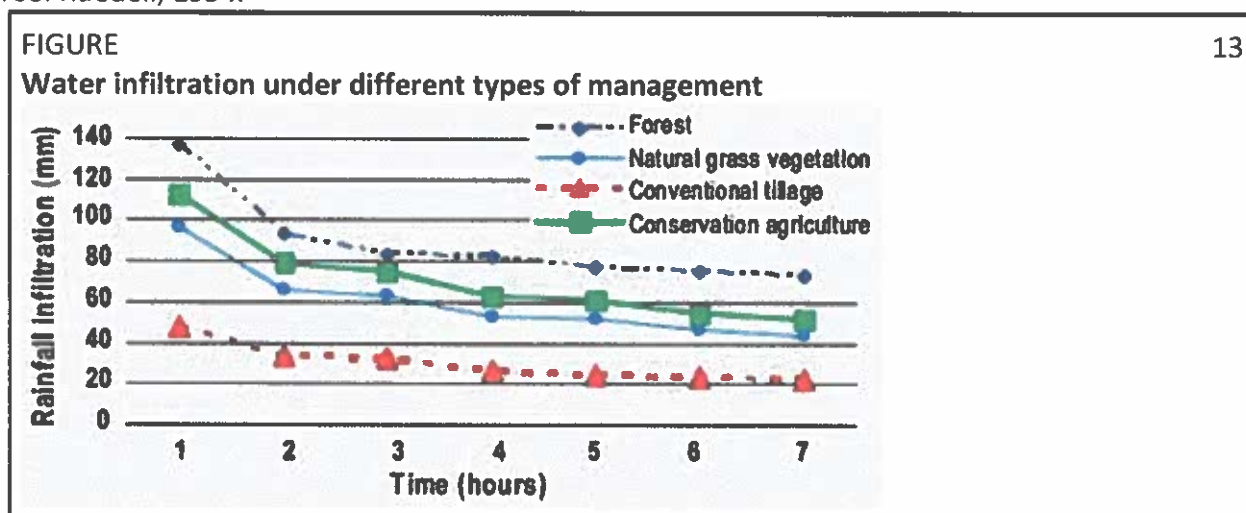
The consequence of increased water infiltration combined with a higher organic matter content is increased soil storage of water (Figure 14). Organic matter contributes to the stability of soil aggregates and pores through the bonding or adhesion properties of organic materials, such as bacterial waste

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products, organic gels, fungal hyphae and worm secretions and casts. Moreover, organic matter intimately mixed with mineral soil materials has a considerable influence in increasing moisture holding capacity. Especially in the topsoil, where the organic matter content is greater, more water can be stored.



Source: Ruedell, 1994.



Source: Machado, 1976.

The addition of organic matter to the soil usually increases the water holding capacity of the soil. This is because the addition of organic matter increases the number of micropores and macropores in the soil either by “gluing” soil particles together or by creating favourable living conditions for soil organisms. **Certain types of soil organic matter can hold up to 20 times their weight in water (Reicosky, 2005).** Hudson (1994) showed that for each 1-percent increase in soil organic matter, the available water holding capacity in the soil increased by 3.7 percent. Soil water is held by adhesive and cohesive forces within the soil and an increase in pore space will lead to an increase in water holding capacity of the soil. As a consequence, less irrigation water is needed to irrigate the same crop (Table 5).

Reduced soil erosion and improved water quality

The less the soil is covered with vegetation, mulches, crop residues, etc., the more the soil is exposed to the impact of raindrops. When a raindrop hits bare soil, the energy of the velocity detaches individual soil particles from soil clods. These particles can clog surface pores and form many thin, rather impermeable layers of sediment at the surface, referred to as surface crusts. They can range from a few millimetres to 1 cm or more; and they are usually made up of sandy or silty particles. These surface crusts hinder the passage of rainwater into the profile, with the consequence that runoff increases. This breaking down of soil aggregates by raindrops into smaller particles depends on the stability of the aggregates, which largely depends on the organic matter content.

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Increased soil cover can result in reduced soil erosion rates close to the regeneration rate of the soil or even lower, as reported by Debarba and Amado (1997) for an oats and vetch/maize cropping system (Figure 16).

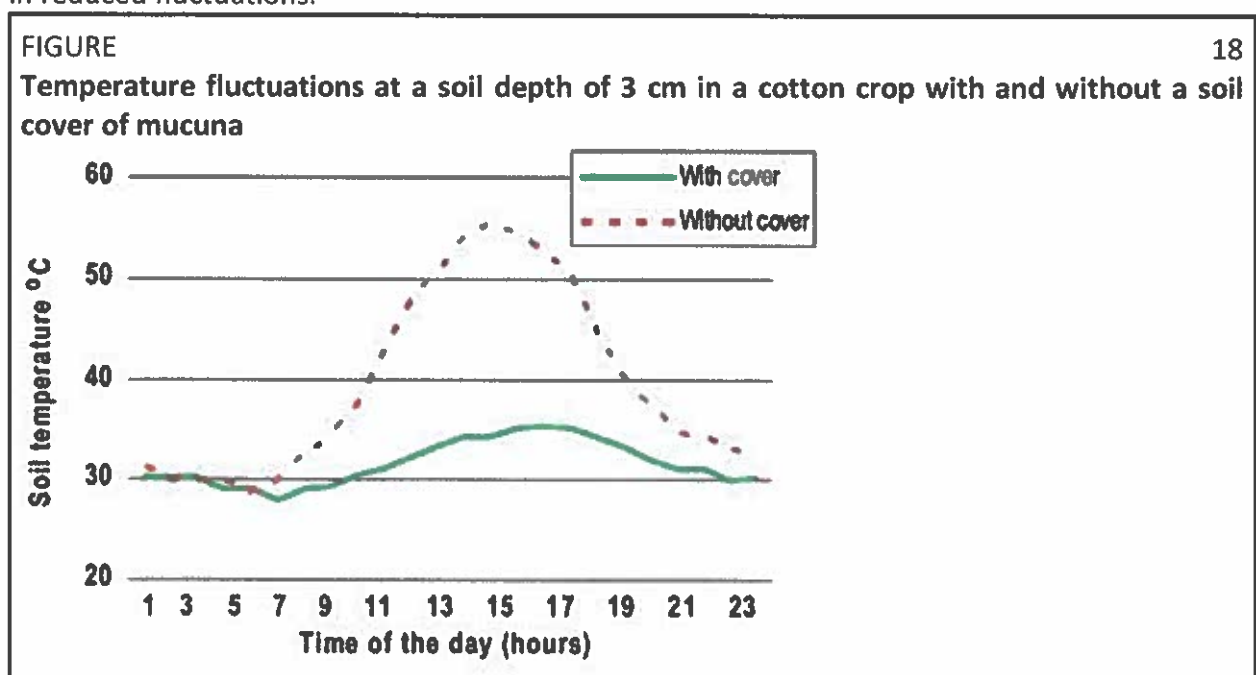
Soil erosion fills surface water reservoirs with sediment, reducing their water storage capacity. Sedimentation also reduces the buffering and filtering capacity of wetlands and the flood-control capacity of floodplains. Sediment in surface water increases wear and tear in hydroelectric installations and pumps, resulting in greater maintenance costs and more frequent replacement of turbines. Sediments can also reach the sea (Plate 23), harming fish, shellfish and coral. Eroded soil contains fertilizers, pesticides and herbicides; all sources of potentially harmful off-site impacts.

When the soil is protected with mulch, more water infiltrates into the soil rather than running off the surface. This causes streams to be fed more by subsurface flow rather than by surface runoff. The consequence is that the surface water is cleaner and resembles groundwater more closely compared with areas where erosion and runoff predominate. Greater infiltration should reduce flooding by increased water storage in soil and slow release to streams. Increased infiltration also improves groundwater recharge, thus increasing well supplies.

Soil cover protects the soil against the impact of raindrops, prevents the loss of water from the soil through evaporation, and also protects the soil from the heating effect of the sun. Soil temperature influences the absorption of water and nutrients by plants, seed germination and root development, as well as soil microbial activity and crusting and hardening of the soil.

Roots absorb more water at higher soil temperatures up to a maximum of 35 °C. Higher temperatures restrict water absorption. Soil temperatures that are too high are a major constraint on crop production in many parts of the tropics. Maximum temperatures exceeding 40 °C at 5 cm depth and 50 °C at 1 cm depth are commonly observed in tilled soil during the growing season, sometimes with extremes of up to 70 °C. Such high temperatures have an adverse effect not only on seedling establishment and crop growth but also on the growth and development of the micro-organism population. The ideal rootzone temperature for germination and seedling growth ranges from 25 to 35 °C.

Mulching with crop residues or cover crops regulates soil temperature. The soil cover reflects a large part of solar energy back into the atmosphere, and thus reduces the temperature of the soil surface. This results in a lower maximum soil temperature in mulched compared with unmulched soil (Figure 18) and in reduced fluctuations.



Source: Derpsch, 1993.

Increased fertilizer efficiency

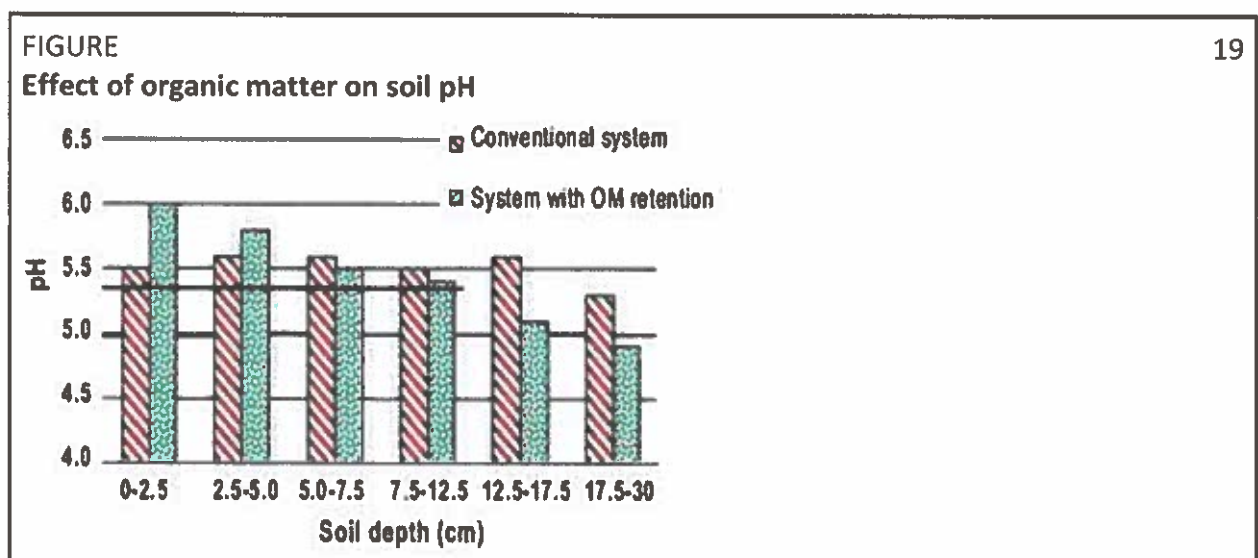
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The two major soil fertility constraints of the West African savannah and in the subhumid and semi-arid regions of SSA are low inherent nutrient reserve and rapid acidification under continuous cultivation as a consequence of low buffering or cation exchange capacity (Jones and Wild, 1975). Generally, these constraints are tackled by applying chemical fertilizers and lime. However, the application of inorganic fertilizers on depleted soils often fails to provide the expected benefits. This is basically because of low organic matter and low biological activity in the soil.

The chemical and nutritional benefits of organic matter are related to the cycling of plant nutrients and the ability of the soil to supply nutrients for plant growth. Organic matter retains plant nutrients and prevents them leaching to deeper soil layers. Microorganisms are responsible for the mineralization and immobilization of N, P and S through the decomposition of organic matter (Duxbury, Smith and Doran, 1989). Thus, they contribute to the gradual and continuous liberation of plant nutrients. Available nutrients that are not taken up by the plants are retained by soil organisms. In organic-matter depleted soils, these nutrients would be lost from the system through leaching and runoff.

Phosphate fixation and unavailability is a major soil fertility constraint in acid soils containing large amounts of free iron and aluminium oxides. In comparing the P-sorption capacity of surface and subsurface soil samples, Uehara and Gilman (1981) provided indirect evidence that soil organic matter can reduce the P-sorption capacity of such soils. This implies that for high P-fixing soils, i.e. oxide-rich soils derived from volcanic and ferro-magnesian rocks, management systems that are capable of accumulating and maintaining greater amounts of calcium-saturated soil organic matter in the surface horizon would increase P availability from both organic and fertilizer sources.

Weak acids, such as the organic acids in humus, do not relinquish their hydrogen (H) easily. H is part of the humus carboxyl (-COOH) under acidic conditions. When a soil is limed and the acidity decreases, there is a greater tendency for the H⁺ to be removed from humic acids and to react with hydroxyl (OH⁻) to form water. The carboxyl groups on the humus develop negative charge as the positively charged H is removed. When the pH of a soil is increased, the release of H from carboxyl groups helps to buffer the increase in pH and at the same time creates the CEC (negative charge). With an increase in organic matter, the soil recovers its natural buffer capacity; this means an increase in pH in acid soils (Figure 19).



Note: Original pH level was 5.3.
Source: Mielniczuk, 1996.

The role of conservation agriculture in organic matter deposition and carbon sequestration

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Principles of conservation agriculture

Conservation agriculture makes use of soil biological activity and cropping systems to reduce the excessive disturbance of the soil and to maintain the crop residues on the soil surface in order to minimize damage to the environment and provide organic matter and nutrients. It is based on four principles:

- minimal mechanical soil disturbance, mainly through direct seeding;
- permanent soil cover, organic matter supply through the preservation of crop residues and cover crops;
- crop rotation for biocontrol and efficient use of the soil profile;
- minimal soil compaction.

Increased carbon sequestration

World soils are important reservoirs of active C and play a major role in the global carbon cycle. As such, soil can be either a source or sink for atmospheric CO₂ depending on land use and the management of soil and vegetation (Lal, 2005) (Figure 23). The conversion of native ecosystems (e.g. forests, grasslands and wetlands) to agricultural uses, and the continuous harvesting of plant materials, has led to significant losses of plant biomass and C (Davidson and Ackerman, 1993), thereby increasing the CO₂ level in the atmosphere.

... soil can play a part in mitigating CO₂ levels (Paustian, 2002). This removal process is achieved naturally, and quite effectively, through photosynthesis. Living plants take CO₂ from the air in the presence of sunlight and water, convert it into seeds, leaves, stems and roots. Part of the CO₂ is retained or “sequestered”, or stored as C in the soil when decomposed.

SOILS AND TREES - IOWA STATE UNIVERSITY - University Extension

Soils are the single most important factor responsible for tree growth. Soils provide trees and shrubs with water, nutrients, and root anchorage. Under normal and undisturbed conditions, Iowa has the best soils in the world for tree growth. But, we have great variability in soils and soil types; not all soils are equally suited for all species of trees and shrubs. Soils are often modified in the urban environment to the disadvantage of tree growth through such activities as topsoil removal, addition of soil or fill, compaction of soil, burial of construction materials, construction of pavements, drainage impediments, and other activities.

The volume of soil available can limit plantings or reduce growth and vigor of trees and shrubs. Ideal conditions require 15 to 24 inches of top soil, that is well drained contains nutrients required for tree growth, and has the capacity to hold air, water, and organic matter. As topsoil depth decreases, the potential for survival and growth of woody vegetation decreases.

Soils have chemical, physical and biological properties. Chemical properties that vary from site to site include available nutrients, soil pH, and organic matter content. Lack of nutrients or the unavailability of nutrients will limit plant growth. Soil pH, a measure of acidity or alkalinity affects the availability of some nutrients. The ideal pH range for tree growth is 5.5 to 6.5.

Some trees begin to exhibit nutrient deficiency symptoms (especially iron) at higher soil pH's. Organic matter in the soil contributes to tree growth by improving soil structure, nutrient availability, and water holding capacity.

The physical aspects of the soil are as important as the chemical properties. Soil texture (proportion of sand, silt, and clay) is an important factor in water holding capacity. Soils with large pore spaces (sand)

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retain less moisture than fine soils; soils containing mostly clay will be wet or poorly drained. Under optimum conditions, the pore space in soil should be 50% air and 50% water.

Compaction of soils decreases pore space and increases plant stress by reducing availability of oxygen to the roots.

Soils also are alive with a wide range of bacteria, fungi, and other organisms which contribute favorably to the soil environment.

INFLUENCE OF SOIL ORGANIC MATTER - ON FOREST PRODUCTIVITY*

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Soil organic matter (SOM) is generally assumed to be important to forest productivity, but its direct influence has been difficult to clearly demonstrate. SOM has a myriad of interactions with other soil properties, and levels of SOM depend on plant factors such as productivity and litter chemistry, and on environmental factors such as temperature and water. SOM is thus both cause and effect with respect to productivity.

..., circumstantial evidence indicates that SOM positively affects long-term forest productivity, with its specific role and contribution depending on the limiting site factors. In coarse-textured soils, SOM is important for retaining water and for supplying and retaining nutrients. As soils become finer, those roles become less important but its role in promoting favourable soil physical properties increases.

..., because of the strong ties of SOM to a wide range of soil properties and functions across soil textures, most prudent forest management regimes should maintain or enhance SOM levels.

...

Because of the generally positive relationship of SOM to productivity, SOM is often used in assessing soil quality, "The capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health," (Doran & Parkin 1994, p. 7).

Many soil properties that have been suggested as measures of quality are directly or indirectly linked to SOM, such as total organic carbon (C) and nitrogen (N), labile organic carbon, microbial biomass carbon and nitrogen, potentially mineralisable nitrogen, soil respiration, and the ratio of microbial biomass carbon/total organic carbon (Doran & Parkin 1994; Larson & Pierce 1994).

As a reflection of its perceived importance, SOM is one of the indicators used in the Montreal Protocol, an international set of indicators of sustainable forest management (Ramakrishna & Davidson 1998).

Thus, there is a continuing focus on SOM with respect to soil quality, whether related to sustained productivity, biodiversity, or other ecosystem attributes.

BASIC RELATIONSHIPS

The soil properties that affect forest productivity are those providing a suitable environment for and adequate quantities of water and nutrients to roots, the interface between the soil and the plant. Succinctly, "Site quality is largely determined by soil properties, or other features of site, which influence the *quality* and *quantity* of growing space for tree roots" (Coile 1952).

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Soil properties, including SOM, are commonly inter-related, and these relationships are so strong that it has been suggested that a major source of variation in soil properties is simply the amount of organic matter (Federer *et al.* 1993).

The inter-relationships between soil properties and SOM can be expressed qualitatively, and *pedotransfer functions* (Bouma 1989) express those relationships quantitatively.

These are statistical or empirical functions used to relate soil characteristics with one another and to estimate soil properties that are too difficult or expensive to measure directly.

Physical Properties

Soil aggregation, the coherence of particles into discrete peds or structural units, is strongly influenced by SOM (Rawls *et al.* 1991).

The resulting relative volume of solids and voids and the pore-size distribution affects the capacity of the soil to transport and store water and gases.

Tree roots, living organs, require both water and adequate oxygen for aerobic respiration. Soil bulk density, an indirect measure of the volume of solids and voids, is therefore related to the quality of a soil for root growth.

Roots also require a medium into and through which they can grow without major impediment. Soil strength, which can limit root penetration even in soils with adequate aeration (Unger & Kaspar 1994), increases with increasing bulk density and with decreasing water content (Unger & Kaspar 1994) (Fig. 1). Bulk density is therefore a key soil property affecting both the quality (aeration) and the quantity (penetrability) of root growing space.

This is recognised by development of such indices as the "growth-limiting bulk density", above which root growth essentially stops (Daddow & Warrington 1983).

The bulk density of most surface soils is closely related to SOM; a relatively small increase in SOM in soils with low SOM leads to a large decrease in bulk density, while in soils with higher SOM density changes more slowly.

...

Chemical Properties

In addition to influencing soil physical properties, SOM also influences chemical properties. Nutrients that occur primarily as cations (calcium (Ca), magnesium (Mg), and potassium (K)) are retained by negatively-charged exchange sites, including soil clays and SOM. Although the cation exchange capacity (CEC) of clays is usually emphasised, SOM is important in many forest soils because they are relatively low in clay.

The CEC of SOM increases with pH (Helling *et al.* 1964; Kalisz & Stone 1980), and for  soils vary in and are often low in pH.

As a result, the reported CEC of SOM in forest floor varies from about 20 to 55 cmolc/kg of organic matter, and in mineral soil from 40 to 165 cmoykg (Mader 1953; Hoyle 1973; Kalicz & Stone 1980; Ross *et al.* 1991; Santore *et al.* 1995; Grigal unpubl. data).

In spite of that range, SOM is clearly important in retaining cations. Rates of weathering, the dissolution of minerals, and subsequent release of constituent ions, are enhanced by SOM.

Organic acids associated with SOM (e.g., Boyle & Voigt 1973) act as ligands by forming complexes with mineral surfaces (Bloom & Nater 1991) and reduce the activities of some mineral components (Boyle *et al.* 1974), in both cases increasing rates of weathering. Conversely, mineralisation of SOM, described below, may also release elements in solution and increase their chemical activities, slowing weathering (Zabowski *et al.* 1994). The difficulty of clearly isolating the role of SOM in ecosystem processes is illustrated by its multiple and counteracting roles in weathering.

Biological Properties

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Soil organisms play a vital role in decomposing organic matter, releasing inorganic forms of nutrients available for plant uptake (i.e., mineralisation), and enhancing soil structural characteristics important for maintaining adequate soil water and air relations.

The vast majority of soil organisms are heterotrophs, depending on SOM for carbon and energy.

Activities of soil biological communities are strongly affected by physical and chemical properties related to SOM, and they also feedback to influence those properties.

Usually, the functioning of the entire microbial population is more relevant for addressing questions of sustainable site productivity than is its composition.

Carbon in microbial biomass comprises 1–3% of total soil organic carbon across a range of vegetation and soil types (Jenkinson & Ladd 1981; Vance *et al* 1987; Martikainen & Palojarvi 1990; Wolters & Joergensen 1991; Sparling 1992), and a close relationship appears to exist between microbial biomass and the rapidly cycling fraction of SOM (Janzen *et al* 1992).

Quantities of carbon and nitrogen within microbial biomass have been directly related to above-ground net primary production across a range of forests and other ecosystems in North America (Myrold *et al* 1989; Zak *et al* 1994). While they do not directly decompose SOM, soil fauna are closely linked with the soil microbial community in organic matter decomposition, nitrogen and phosphorus mineralisation, and soil structural development (Lavelle 1997). Fauna influence mineralisation by grazing on fungi and bacteria, serving as their food, and dispersing fungal inoculum (Lussenhop 1992).

Mineralisation Essential plant nutrients in SOM, derived from living material, are released by mineralisation and can be used by plants, adsorbed within the soil, or become susceptible to hydrologic losses.

Literally hundreds of studies of mineralisation have been widely reviewed and synthesised (e.g., Binkley & Hart 1989; Gressel & McColl 1997; Johnson 1992b, 1995), and we will simply re-emphasise some of the key points with respect to SOM. Nitrogen release via mineralisation is usually emphasised (Johnson 1992b) because (a) virtually the entire pool of nitrogen in forests is organically bound, (b) nitrogen availability is low relative to plant uptake, and (c) additions of nitrogen via fertiliser application increase tree growth in most forests.

Annual nitrogen mineralisation statistically explains virtually all of the variation in productivity in some systems (e.g., Lennon *et al* 1985; Nadelhoffer *et al* 1985; Pastor *et al* 1984; Zak *et al* 1989; Reich *et al* 1997).

Because of the complex interactions among SOM, microbes, and other environmental factors, and because rates of mineralisation and the total quantities of mineralised nitrogen are both affected by the same environmental factors that influence plant growth, such relationships should not be considered simple cause-and-effect.

For example, in Scandinavian systems with the same lodgepole pine (*Pinus contorta* Dougl.) cover type, site productivity was most strongly related to temperature variables, especially the length of the growing season (Fries *et al* 1998).

The positive relationship of temperature to nitrogen mineralisation may explain this observation, but nitrogen availability (Yin 1992) and nitrogen concentration in foliage (Yin 1993) and fine roots (Yin & Perry 1991) appear to decrease with increasing temperature.

This indicates that at higher temperatures available nitrogen is more fully used by trees, leading to reductions in soil concentrations and a dilution in plant tissue.

Forest productivity is often limited by phosphorus availability (Gressel & McColl 1997).



As a legacy of the agronomic background of soil science, including a short-term (annual) view of nutrient availability and an emphasis on inorganic fertilisers, available soil phosphorus is usually considered to be primarily affected by inorganic compounds.

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The importance of organic phosphorus has been demonstrated in many forest systems, because of both a longer-term perspective and continuous nutrient cycling (Kelly *et al* 1983; Turner & Lambert 1988; Bekunda *et al* 1990; Polglase *et al* 1992).

Sulphur is another essential plant nutrient that is closely linked to SOM (David *et al* 1995), and its availability is a concern for some sites in the Pacific Northwest (Edmonds & Hsiang 1987) and in the Southern Hemisphere, often where fertiliser application has increased availability of other nutrients.

In most of North America and Europe, atmospheric deposition supplies adequate sulphur for plants (Johnson 1984), but because the magnitude of these inorganic inputs is relatively independent of either the nitrogen or phosphorus status of the system, the stoichiometric ratios of sulphur to either phosphorus or nitrogen among vegetation components and species are more variable than are ratios between phosphorus and nitrogen (Homann & Harrison 1992).

Mineralisation is fundamentally a microbial process, and is influenced by factors affecting microbial activity including pool sizes, characteristics of the organic matter, and environmental conditions. The link between climate and rate of litter decomposition is well documented (Meentemeyer 1978; and others), as is that between climate and mass of SOM (Grigal & Ohmann 1992; Homann *et al* 1995; Johnson 1995; Gardenas 1998; and many others).

Coping with Drought

João S. Pereira, Cathy Kurz-Besson, and M. Manuela Chaves

Cork oak survives in its native habitats thanks to its ability to withstand the long, dry, and hot summers of the Mediterranean region, when soil and atmosphere water deficits combine with high light intensity and high temperatures to make life difficult for perennial plants (Pereira *et al.* 2004).

Recent changes in the region’s climate, such as consistent warming and a significant reduction of springtime precipitation, have increased environmental adversity and unpredictability (Pausas 2004). Moreover, the frequency of droughts has increased dramatically in the last twenty-five years in the western Mediterranean (Miranda *et al.* 2002), and episodes of high tree mortality occur more and more frequently, especially in severe drought years (Pereira *et al.* 2006).

Water deficits may also be critical in generalized cork oak decline associated with root pathogens because trees infected with pathogens, such as root rot (*Phytophthora cinnamomi*), are more vulnerable to water deficit induced damage than uninfected trees (Desprez-Loustau *et al.* 2006) (see Color Plate 11).

The main question we address in this chapter is how cork oak copes with drought. This is relevant not only for assessing the vulnerability of cork oak to soil degradation and climate change but also for general management and conservation programs, including the restoration and reintegration of fragmented cork oak landscapes. Indeed, increased aridity is the most likely cause for the low regeneration rates observed in cork oak (see Chapters 10 and 20).

Therefore, many restoration projects based on artificial regeneration may fail because of postplanting water deficits. Similarly, postfire resprouting of trees may fail because of drought stress.

The Limits of Survival

In areas with Mediterranean-type climate, most trees avoid dehydration of their living tissues during water deficits by reducing water loss or preserving access to soil water (Walter 1973; Pereira *et al.* 2006). Whereas *stomatal* closure and leaf shedding may limit water losses, deep root systems provide

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access to water, free from the competition of coexisting plants with shallower roots. However, when water deficits prevail and both these strategies fail, the tree may die. How and when does that occur?

Without soil water replenishment, plant dehydration becomes unavoidable.

As drought progresses, the resulting plant water deficits may cause the cavitation of some water columns in the xylem water transport system. If water deficits and cavitation persist, those conduits may become embolized, thus losing the capacity to transport water. Persistence of drought may lead to a state in which the hydraulic integrity of the tree is lost.

When runaway embolism occurs in the whole trunk, severing the connection between tree roots and shoots, water is no longer delivered to the leaves and other living tissues, and eventually the entire tree dries out. In such cases, trees lose their ability to resprout, even when water becomes available once again. The limit to this catastrophic loss of xylem conductivity is set by the xylem vulnerability to water deficits, that is, the values of leaf water potential at which most xylem elements fail to function.

Whereas many seedlings are eliminated by such processes in the first summer season of drought, in large trees this does not occur at once. Indeed, it may take a long time, usually long enough to allow other agents, namely pathogens or insects, to join the attack.

In other words, when a tree dies it has usually undergone a gradual period of weakening (Jenkins and Pallardy 1995). To understand and counteract this process, we need to know how to measure plant water status. The most common measure used is leaf water potential, which is denoted by the symbol (Ψ). Leaf water potential is an approximate indication of the difficulty plants experience in extracting moisture from the soil. By convention, a value near zero indicates plants that are well hydrated, whereas negative Ψ values signify that water is held by soil matrix forces in a way that is not easily taken up by plants. When measured at dawn or predawn (pd), this assay indicates whether there is an abundance of water in the soil (values near 0) or water is scarce near the roots (negative values). The lowest Ψ_{pd} values usually occur at the end of the summer and depend on the annual precipitation amount (Figure 6.1). In general, leaf water potential near -4 MPa corresponds to the minima measured in healthy cork oak trees in the field (David et al. 2007; Figure 6.1).

The Control of Water Loss

How do trees manage their water status so as to avoid disaster? It is currently assumed that stomatal functioning evolved to control water losses so that plant water status is maintained above the threshold of xylem runaway embolism, thus preventing the plant from losing its water transport capability (Jones and Sutherland 1991; Jackson et al. 2000). How does cork oak compare to other plants in terms of xylem vulnerability? Compared with another evergreen species, western holm oak (*Quercus ilex* subsp. *rotundifolia*), whole-tree hydraulic conductance and minimum midday leaf water potential were higher in cork oak, suggesting greater drought resistance of holm oak (David et al. 2007). In fact, western holm oak occupies drier sites than cork oak when they occur sympatrically. However, when compared with less drought-resistant, deciduous oaks, cork oak has been shown to have lower hydraulic vulnerability limits (Tyree and Cochard 1996; Nardini and Tyree 1999).

Using water sparingly is just one way for plants to resist drought or avoid it altogether. It is costly to the plant because when stomata close, transpiration is indeed reduced, but photosynthetic carbon assimilation drops as well.

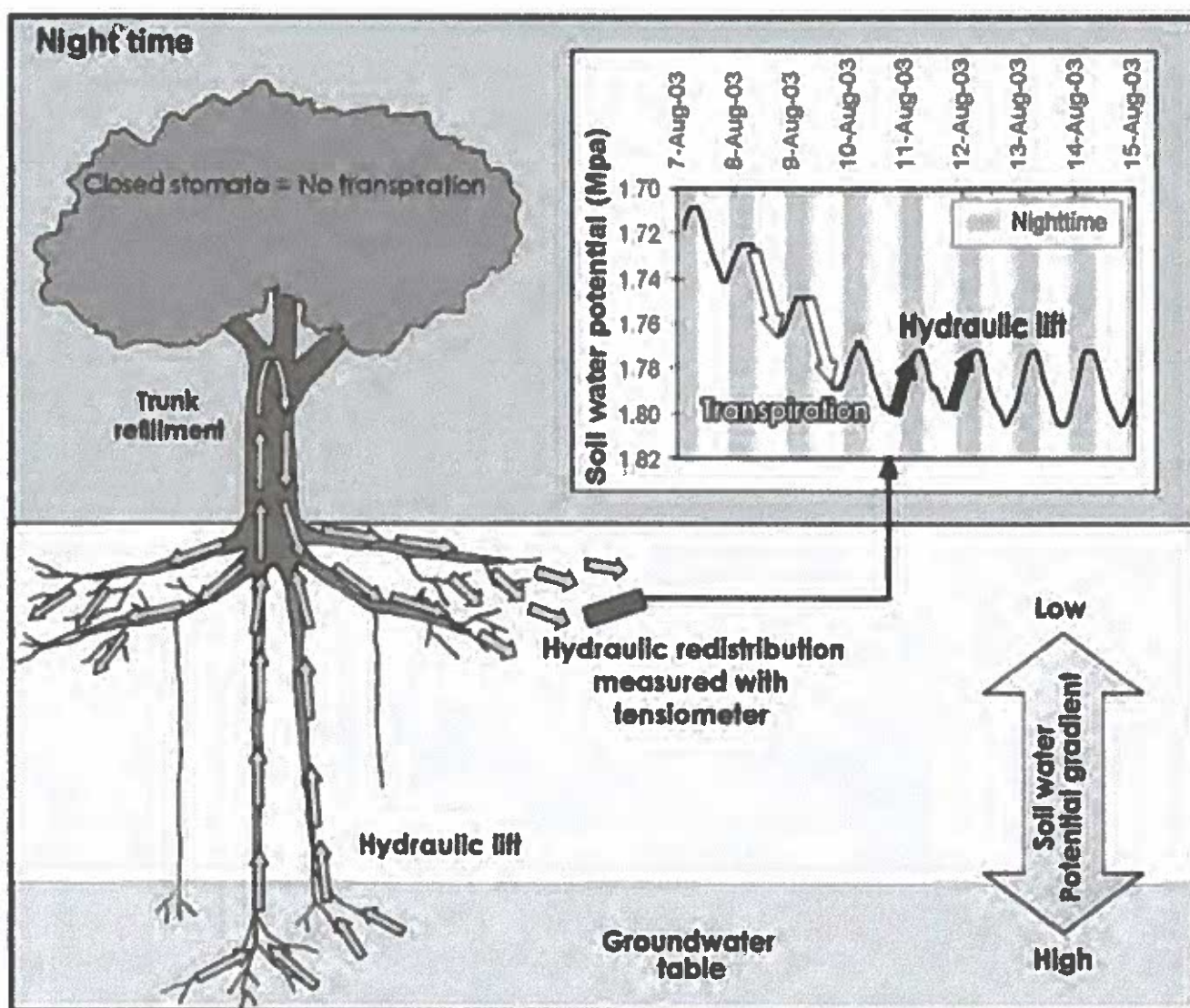
Cork oak trees keep their stomata more open at lower leaf water potentials than do more mesophytic species, such as turkey oak and Portuguese oak (Ksontini et al. 1998; Nardini et al. 1999), confirming this species' intermediate drought tolerance between the more mesophytic deciduous oaks and the evergreen holm oak. But if a drought-resistant plant keeps its stomata open when water runs short, it must compensate somehow for water loss. This is the topic we explore in the next section. *Water*

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Acquisition, Root Systems, and Hydraulic Lift To avoid dehydration and compensate for water loss, many Mediterranean woody plants have deep roots and extract water from a large volume of soil (Pereira et al. 2006). In a study carried out in Portugal, more than 70 percent of the water transpired by holm and cork oaks during the dry season was derived from groundwater (David et al. 2007). As a result, these deep-rooted species do not reach leaf water potentials as low as those observed in semi-deciduous, shallow-rooted rockrose species in the same region that dehydrate to the point of -5.5 MPa leaf water potential (Werner et al. 1999).

Mediterranean evergreen oak trees have a large number of roots growing horizontally and extending much farther than the crown projection limits and a few root branches growing geotropically toward the subsoil (Verdaguer et al. 2000; David et al. 2004). One study in Portugal showed that cork oak trees had root activity in two layers of the soil, one 40 to 100 centimeters deep and another reaching deep subsoil layers or the groundwater table (Kurz-Besson et al. 2006; Otieno et al. 2006). The upper (horizontal) roots allow the plant to acquire nutrients and water in the wet season, whereas deeper roots obtain water after desiccation of the upper soil horizons during the dry season. Survival through the summer results from the combination of low transpiration (stomata closed) and water uptake from deeper soil. In summer this root positioning allows some redistribution of groundwater to the shallower root system at night, through the process known as *hydraulic lift* (Figure 6.2).

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Figure 6.2. Hydraulic lift occurs at night, when cork oak stomata are closed. The soil water potential gradient between shallow and deep soil layers induces water transport through roots from deeper to shallower soil layers via hydraulic lift. After trunks are refilled, some water may be available for redistribution into shallow soil layers through fine roots (hydraulic redistribution). Hydraulic lift was illustrated using tensiometer measurements. The daily fluctuation in soil water potential resulting from transpiration (decrease) and hydraulic lift (increase) is illustrated in the insert (data in insert from Kurz-Besson et al. 2006).

Hydraulic lift is a passive mechanism driven by a water potential gradient that transports water through the root system of a tree or shrub, from deep, moist soil layers up to shallower and drier soil layers (Richards and Caldwell 1987). This mechanism can contribute to an increase plant transpiration the next day by providing water temporarily stored in upper soil layers. This water is also available to shallower-rooted neighboring plants (Dawson 1993; Caldwell et al. 1998; Kurz-Besson et al. 2006). Hydraulic-lifted water appears to help maintain some fine root activity in the upper soil horizons during the dry summer, thus permitting some nutrient uptake at a time of limited nutrient availability.

To survive drought, roots must be able to absorb water from soil that is drying out. This can be accomplished through the decrease of cell water potential achieved by osmotic adjustment. Because water moves from less negative to more negative potentials, a decrease in cell water potential, due to solute accumulation, should enable trees to extract water from a drying soil (i.e., more negative potential). Otieno et al. (2006) found a substantial osmotic adjustment in cork oak trees between May and July and observed a decrease in cell wall elasticity, allowing leaf water potential to decrease without forcing the tissue to lose too much water. More rigid cell walls also allow a rapid resumption of water uptake after rain and plant recovery. This is of great importance for survival in climatic regions with a long dry season and highly variable rainfall (Pereira et al. 2006).

Water Deficits and Growth

Water deficits affect plant growth by inhibiting cell growth, including the leaf area displayed for photosynthesis, and by causing a decrease in net carbon gain through decreases in the rates of photosynthetic carbon assimilation caused by stomatal closure. If leaf tissues become even more dehydrated, the chloroplast chemical machinery may be adversely and permanently affected (Chaves et al. 2002).

The evergreen habit is advantageous in Mediterranean-type climates because it allows plants to take advantage of every environmentally favourable opportunity for carbon uptake and growth (Larcher 2000). However, as summer drought progresses, foliage must withstand high temperatures and high exposure to sunlight. Simultaneously, as stomata close, transpiration decreases, thus reducing the capability for leaf evaporative cooling. Under these circumstances—high temperatures and high light—the energy of incident solar radiation becomes excessive and may inhibit photosynthesis or damage leaf tissues. Thus, not all the energy captured by leaf pigments can be used for assimilation because the supply of carbon dioxide is limited by stomatal closure.

To avoid damage to the photosynthetic apparatus, various protective adaptations are needed. Anatomical or morphological adaptations, including small and thick leaves, which are well adapted to hot, dry summers, allow efficient heat dissipation and an efficient control of water loss by stomatal closure (see Chapter 1). Dense trichome layers (Larcher 2000) and steep leaf angles (Werner et al. 1999) also help reduce incident light intensity. Thick leaves with high leaf area: mass ratios optimize carbon gain per unit of water lost by transpiration during the prolonged hot and dry periods (Givnish 1979).

As a consequence of the combination of stresses occurring in summer, photosynthesis declines in the second half of the season, as compared to early July (Faria et al. 1996, 1998). This late-summer decrease in net CO₂ uptake, affecting most Mediterranean woody species, is associated with a decrease in

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photochemical efficiency, most marked during the warmest part of the day, when carbon assimilation is limited by low stomatal conductance. This results from increased internal dissipation of excess energy in chloroplasts. In fact, more than 60 percent of the light energy absorbed by tree leaves at midday is dissipated on a hot September day. This serves as an important protective mechanism under drought conditions and is associated with the existence of large pools of xanthophyll pigments (carotenoids) that are able to dissipate the excess energy in the chloroplasts (Garcia-Plazaola et al. 1997).

The fraction of excitation energy that is not thermally dissipated in the chloroplast may induce oxidative stress. High concentrations of antioxidants occur in cork oak leaves in the summer (Faria et al. 1996). The loss of chlorophyll in response to summer stress, observed in cork oak leaves, is also a form of protection of photosynthetic machinery because a lower proportion of the incident light is absorbed by the chloroplasts, thus avoiding oxidative stress.

In southwestern Europe, 2004 and 2005 were exceptionally dry; in southern Portugal, it was the driest episode in the last 140 years. From October 2004 to June 2005, total precipitation was roughly 40 percent of the longterm average (Garcia-Herrera et al. 2007). The cork oak trees studied by Otieno et al. (2006) suffered severe water stress during this season, with low carbon assimilation rates and a 32 percent decrease in annual trunk diameter increment as compared to 2004. During dry years, trees tend to produce narrow annual rings. In some cases, the annual ring is not formed at all or a second “false” ring occurs when cambial activity resumes after a dry period (Cherubini et al. 2003). In the next section we will see how this relates to cork production.

Water Deficits and Cork Stripping

Cork stripping may induce generalized stress in trees. The nature of this stress remains obscure, although stomata appeared to be more sensitive to water deficits in stripped trees (closing at higher leaf water potential than those in control trees) (Werner and Correia 1996). Concurrently, bark stripping stimulates the phellogen, the plant meristem that produces cork. Shortly after stripping, cork production takes precedence over wood growth, and as a result, the annual ring of wood is not formed or remains vestigial for one or even two years. In extremely dry years, a major problem may result from the inhibition of phellogen activity. The attempt to strip the cork will be frustrated by sealing of the interface *phellogen*; cork and the bark will separate not through the phellogen layer (see Chapters 1 and 5) but through the vascular *cambium*. Unlike the phellogen, the vascular cambium does not regenerate, and stripping the bark under such conditions may lead to trunk damage (large scars) and eventually tree death. The timing of the onset of plant water deficits determines the deadline of safe cork stripping in late spring and early summer. The period during which cork can be stripped ends earlier in dry than in wetter locations.

Conclusions

Cork oaks are good examples of *isohydric* trees, that is, plants that survive dry seasons by avoiding severe dehydration. For that purpose, they rely heavily on water supply from large, deep root systems to compensate for transpiration water loss, which persists even with stomata partly closed. Deep rooting gives trees access to soil water unavailable to shallow-rooted plants. This has two major practical consequences. First, as discussed in Chapter 10, seedling survival will be negligible if roots do not reach a safe soil depth before the onset of the first dry summer. Therefore, restoration techniques must be geared to support early growth of a healthy, well-formed root system (but see also Chapter 11). Second, adult cork oak trees may become vulnerable to drought if repeated dry years (or a shift in climate toward greater aridity) prevent the replenishment of groundwater supplies. As a consequence, the successful restoration of cork oak ecosystems depends on an understanding of plant and soil water

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relationships and matching of restored and managed landscape features so as to optimize cork oak trees' access to water during the dry season.

Likewise, chronic infections by root pathogens and poor root system development caused by soil characteristics or poor silvicultural techniques may reduce the effective size of the active root system, reducing the trees' ability to cope with drought. Therefore, all these factors must be monitored carefully.

In the next chapter we will consider yet another contributing factor to cork oak trees' ability to cope with drought: the symbiotic relationship of tree roots with mycorrhizal fungi.

Synergy of extreme drought and shrub invasion reduce ecosystem functioning and resilience in water-limited climates

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Extreme drought events and plant invasions are major drivers of global change that can critically affect ecosystem functioning and alter ecosystem-atmosphere exchange. Invaders are expanding worldwide and extreme drought events are projected to increase in frequency and intensity. However, very little is known on how these drivers may interact to affect the functioning and resilience of ecosystems to extreme events. Using a manipulative shrub removal experiment and the co-occurrence of an extreme drought event (2011/2012) in a Mediterranean woodland, we show that native shrub invasion and extreme drought synergistically reduced ecosystem transpiration and the resilience of key-stone oak tree species. Ecosystem transpiration was dominated by the water use of the invasive shrub *Cistus ladanifer*, which further increased after the extreme drought event. Meanwhile, the transpiration of key-stone tree species decreased, indicating a competitive advantage in favour of the invader. Our results suggest that in Mediterranean-type climates the invasion of water spending species and projected recurrent extreme drought events may synergistically cause critical drought tolerance thresholds of key-stone tree species to be surpassed, corroborating observed higher tree mortality in the invaded ecosystems. Ultimately, this may shift seasonally water limited ecosystems into less desirable alternative states dominated by water spending invasive shrubs.

Severe dry years in a Mediterranean environment are primarily characterised by a lack of winter precipitation, which is the rainiest season. The strong negative precipitation anomaly in 2011/2012 was observed all over Southwest Europe²⁹, but affected primarily Iberia, where annual precipitation was regionally below 300 mm (Supplementary Fig. S1). The winter precipitation (December to February) was as low as 12.4% of long-term mean over the southwest Iberian Peninsula (Fig. 1a). Such extremely low winter precipitation is very uncommon in a Mediterranean-type climate, and was associated with exceptional large-scale atmospheric flow conditions over the North Atlantic and Europe³⁰: the eddy-driven jet stream and rain-producing cyclones were shifted northward, associated with the recurrence of strong and persistent atmospheric ridges west of Iberia (see also Supplementary Discussion). The extreme dry winter was followed by a moderate and severe drought in spring and summer (about 71% and 7.5% of long-term mean precipitation respectively; Supplementary Fig. S1 and Supplementary Discussion). 2011/2012 was in fact the second driest year since 1950 (Fig. 1b), depicting precipitation

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deficits close to the driest year (2004/2005). Note that the extreme drought year of 2011/2012 was preceded and followed by years with slightly above average precipitation (Figs 1 and 2c).

There are large differences between species-specific critical thresholds beyond which extensive cavitation results in failure of the hydraulic transport system⁹. **The invasive shrubs were able to endure much lower soil water potentials and drier soil conditions** (Fig. 3, Supplementary Fig. S2) than trees as a result of lower critical cavitation thresholds^{27,31} (Supplementary Discussion). As oak trees have higher critical thresholds, they generally follow a drought avoiding, conservative water use strategy²¹, down-regulating stomatal transpiration (Fig. 2a) to avoid critical decline in leaf water potentials and detrimental runaway cavitation^{9,31}. The effectiveness of this strategy is reflected in the rapid recovery of tree transpiration after the severe drought event in uninvaded stands ($p < 0.05$, $n = 4$; Fig. 4b). However, the significant reduction in water potential of trees in invaded stands diminished the tree hydraulic “safety margin”⁹ (Supplementary Fig. S2), which has recently been shown to be low for many tree species worldwide⁹. Consequently, trees in invaded stands were more vulnerable to hydraulic failure.

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The impact of the synergistic effects of shrub invasion and extreme drought is most visible when comparing tree transpiration in invaded and uninvaded stands over the three years (Fig. 4a). The extreme drought event strongly reduced transpiration, which was more pronounced in trees in invaded stands. Resistance³⁵, i.e. the capacity of trees to withstand severe drought, was not significantly different between stands ($p > 0.05$, $n = 4$; Fig. 4b), probably due to the overriding effect of the severe drought on trees. However, most remarkably, trees in invaded stands were not able to recover in the following wetter year maintaining lower transpiration rates, and showing lower resilience³⁵ to the extreme drought ($p < 0.05$, $n = 4$; Fig. 4a), probably indicating severe damage of the hydraulic system³⁶ and diminished access to deeper water pools^{14,37}. **The high density of shrubs in invaded stands with their dense shallow rooting system^{32,33} must have contributed to the drying out of the surface soil layers (Fig. 3) and could have resulted in a decreased deep soil moisture recharge, contributing to the lower recovery and resilience of the cork-oak trees in the invaded stands.**

Widespread crown condition decline, food web disruption, and amplified tree mortality with increased climate change-type drought

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Climate change is progressively increasing severe drought events in the Northern Hemisphere, causing regional tree die-off events and contributing to the global reduction of the carbon sink efficiency of forests. There is a critical lack of integrated community-wide assessments of drought-induced responses in forests at the macroecological scale, **including defoliation, mortality, and food web responses.** Here we report a generalized increase in crown defoliation in southern European forests occurring during 1987–2007. **Forest tree species have consistently and significantly altered their crown leaf structures, with increased percentages of defoliation in the drier parts of their distributions in response to increased water deficit.** We assessed the demographic responses of trees associated with increased defoliation in southern European forests, **specifically in the Iberian Peninsula region.** **We found that defoliation trends are paralleled by significant increases in tree mortality rates in drier areas that are related to tree density and temperature effects.** Furthermore, we show that **severe drought impacts are**

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associated with sudden changes in insect and fungal defoliation dynamics, creating long-term disruptive effects of drought on food webs. Our results reveal a complex geographical mosaic of species-specific responses to climate change–driven drought pressures on the Iberian Peninsula, with an overwhelmingly predominant trend toward increased drought damage.

Global climate change is expected to cause progressively increased frequency and severity of drought events and heat waves in the Northern Hemisphere (1, 2). Globally, increased drought impacts have already been recorded over the last several decades, with anthropogenic forcing widely accepted as the most plausible cause (2–7). These drought impacts have presumably altered carbon cycling dynamics over extensive areas, possibly contributing to the progressive global reduction in the efficiency of terrestrial sinks (5, 7, 8). Major drought impacts on vegetation are to be expected in arid and semiarid biomes, which usually respond to increased water deficit with greater reductions in productivity, although drought-induced tree mortality occurs across a broad range of forest types and mean climate conditions (9). In semiarid and Mediterranean systems, several studies have recently reported increased plant mortality rates and die-off events, reduced seedling recruitment, long-term shifts in vegetation composition, reduced radial growth, and increased crown defoliation responses (9–13). Severe droughts also modify forest biogeochemical cycles by increasing nutrient loss through premature leaf fall without complete nutrient translocation (14). In addition, several studies have suggested the existence of important drought-induced cascading effects at higher trophic levels, affecting vertebrate, invertebrate, and fungal consumer populations; promoting insect outbreaks; and altering fundamental mutualistic processes, such as seed dispersal and pollination (10, 11, 15). Overall, the long-term effects of climate change–type droughts may alter forest physiological responses over extensive areas (10, 11, 15), potentially leading to extensive tree mortality and associated consequences for earth system processes (9, 16).

In the Mediterranean basin and meridional Europe, long-term climatic series and multiproxy studies have demonstrated an unprecedented and significant increase in heat waves and drought impacts over the last several decades (6, 12, 17–20). In line with these findings, the significant increase in the frequency of positive phases of the North Atlantic Oscillation during winter over the last several decades has promoted a northward shift of the Atlantic storm track and possibly triggered droughts and heat waves in southern Europe (21, 22). Comparisons of observational data over the last several decades and regional climate change simulations have identified the Mediterranean basin as a hot spot of hydrological cycle changes, and several regional and global models have consistently predicted increased drought impacts and heat waves in this area in the subsequent decades (23, 24). Droughts produce heterogeneous spatial and temporal impacts, however, and local studies have reported a wide variety of site-dependent and species-specific trends, including both positive and negative physiological responses in forest tree species (14). These differing findings preclude making generalizations based on available data at the local scale, and highlight the need for extensive community-wide assessments of the impacts of drought (11). We currently lack large-scale, integrative, community-wide assessments of drought-induced forest responses, such as tree crown defoliation, mortality, and food web responses.

European national crown condition inventories derived from the International Cooperative Program on Assessment and Monitoring of Air Pollution Effects on Forests (hereinafter the ICP Forest Inventory) provide yearly species-specific measures of the percentage of defoliation of tree crowns over a wide geographic area (25). During drought periods, a reduction in total leaf-transpiration area is a basic response of temperate and Mediterranean forests (26). Forests affected by drought reduce overall tree transpiration through adjustments in total leaf area, allowing improved tree water balance and restoring leaf-specific hydraulic conductivity (26). In the present study, we gathered crown defoliation data from the ICP Forest Inventories (25) to assess the macroecological impacts of drought on water-limited southern European forests over the 20-y period of 1987–2006.

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All of the forest tree species that we examined in the Iberian Peninsula have experienced a significant increase in crown defoliation over the last two decades, attributable mainly to the impacts of drought. The observed defoliation trends are consistent with increased tree mortality rates in drier areas and with sudden dynamic changes at higher trophic levels. Our results show that Iberian forests are experiencing long-term chronic effects due to severe climate change–related droughts, and that these effects are progressively more pronounced in more xeric localities.

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Our present findings add to the increasing number of reports of drought-induced tree mortality responses, regional forest die-offs, and vegetation shifts around the globe (9). All of this empirical evidence highlights the need for improved long-term networks devoted to monitoring the impacts of climate change on forest health, functional trait variation, genetic variation, and forest demography (9). Critically, the diverse physiological mechanisms implicated in the reported defoliation and mortality responses also remain to be elucidated. These may include long-distance phloem transport effects, carbon reserve dynamics, metabolic unbalances, and/or hydraulic failure processes (46).

Finally, our results demonstrate that extreme droughts can substantially disrupt insect and fungi communities across extensive areas and induce long-term changes in community structure. These findings are consistent with previous studies that have reported 10-fold reductions in arthropod richness and abundance after long-lasting severe droughts and have identified foliage quantity and quality as important drivers of community structure (30, 31). Severe persistent droughts produce parallel disruptions in different groups, affecting ecto-mycorrhizal fungi (15), defoliating fungi, herbivore and predator canopy insects, and parasitoids (30, 31). Bottom-up effects on vertebrate trophic chains have been poorly quantified but might occur, given the structural importance of insect resource channels in vertebrate networks in the Mediterranean basin (47, 48). Whether large-scale food web disruptions produced by drought can influence the extinction risk of vulnerable insect species and secondary consumers is an open question that warrants further research. This topic may emerge as a relevant concern related to the conservation of currently endangered biotic communities in the Mediterranean basin (49).

Water-use strategies in two co-occurring Mediterranean evergreen oaks: surviving the summer drought

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Summary In the Mediterranean evergreen oakwoodlands of southern Portugal, the main tree species are *Quercus ilex* ssp. *rotundifolia* Lam. (holm oak) and *Quercus suber* L. (cork oak).

We studied a savannah-type woodland where these species coexist, with the aim of better understanding the mechanisms of tree adaptation to seasonal drought. In both species, seasonal variations in transpiration and predawn leaf water potential showed a maximum in spring followed by a decline through the rainless summer and a recovery with autumn rainfall. Although the observed decrease in predawn leaf water potential in summer indicates soil water depletion, trees maintained transpiration rates above 0.7 mm day⁻¹ during the summer drought. By that time, more than 70% of the transpired water was being taken from groundwater sources. The daily fluctuations in soil water content suggest that some root uptake of groundwater was mediated through the upper soil layers by hydraulic lift.

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During the dry season, *Q. ilex* maintained higher predawn leaf water potentials, canopy conductances and transpiration rates than *Q. suber*. The higher water status of *Q. ilex* was likely associated with their deeper root systems compared with *Q. suber*.

Whole-tree hydraulic conductance and minimum midday leaf water potential were lower in *Q. ilex*, indicating that *Q. ilex* was more tolerant to drought than *Q. suber*. Overall, *Q. ilex* seemed to have more effective drought avoidance and drought tolerance mechanisms than *Q. suber*.

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Drought resistance strategies of Q. ilex and Q. suber During the summer drought, Ψ_{pd} (Figure 3), g_c (Figure 6) and E (Figures 1 and 2) were higher in *Q. ilex* than in *Q. suber*.

Mediavilla and Escudero (2003) also found higher summer Ψ_{pd} in *Q. ilex* than in *Q. suber* in a study carried out near Salamanca, Spain. However, under pre-drought conditions, *Q. suber* had a higher g_c than *Q. ilex*, which is in accordance with the more mesophytic leaves of *Q. suber*, as well as higher specific leaf area (SLA) and higher photosynthetic capacity, as observed in previous work (Faria et al. 1998, Vaz 2005). The higher water status of *Q. ilex* trees during the summer drought can be explained only by the possession by this species of a deeper or more effective root system compared with that of *Q. suber*, because climate, soilwater (Figure 7) and groundwater level (Figure 1) were similar in the two experimental plots.

It is well known that different courses of seasonal plant water status usually reflect different rooting habits (e.g., Canadell et al. 1996). Compared with *Q. suber*, the higher transpiration rates of *Q. ilex* during the summer drought (Figures 1 and 2) were mainly a result of the higher Ψ_{pd} in this species (Figure 3), which resulted in higher sap flow driving forces (Figure 4). These higher sap flow driving forces in *Q. ilex* during the summer resulted in higher E despite a lower k (Figure 5).

No difference between species was found in ΔD_{xyl} , ΔD_{sw} or ΔD_{gw} in August 2002.

Minimum leaf water potential is usually considered a cavitation threshold (Cochard et al. 1996, Salleo et al. 2000, Sperry 2000, Lopez et al. 2005), corresponding to the need for stomatal closure to prevent Ψ from falling below the cavitation threshold (Jackson et al. 2000, Buckley and Mott 2002). The m/b ratio remained close to the theoretical value of 0.6 throughout the spring and summer in both species (Table 1).

This means that both *Q. ilex* and *Q. suber* were efficiently regulating Ψ while the drought progressed, thereby preventing xylem embolism (Oren et al. 1999). The Ψ cavitation threshold is species-specific (Tyree and Sperry 1989), and is lower in drought-adapted species (Sperry 2000, Lemoine et al. 2001).

There is always a safety margin between the minimum values of Ψ observed in the field and complete xylem embolism (Sperry 2000). In our study, minimum leafwater potentials observed in the field were -3.5 and -3.0 MPa for *Q. ilex* and *Q. suber*, respectively. The lower value of Ψ_{md} in *Q. ilex* suggest that this species is less vulnerable to embolism than *Q. suber*. This feature is confirmed by the vulnerability curves to embolism presented by Tyree and Cochard (1996) for both oak species.

Whole-tree hydraulic conductance did not vary much over time in either species, but it was significantly lower in *Q. ilex* than in *Q. suber* (2.28×10^{-5} versus 3.15×10^{-5} kg m $^{-2}$ s $^{-1}$ MPa $^{-1}$). Lower k values are acknowledged to be a drought tolerance feature (Nardini and Tyree 1999, Lemoine et al. 2001, Martinez-Vilalta et al. 2002).

In dry environments, the ability to tolerate drought is more important than the ability to transport water rapidly (Nardini and Tyree 1999, Lemoine et al. 2001) and there is usually a trade-off between hydraulic efficiency and resistance to xylem cavitation (Martinez-Vilalta et al. 2002). Therefore, species with lower k values will tend to be less vulnerable to xylem embolism. Additionally, a low k helps to limit sap flow from roots to leaves, thereby promoting more conservative water use (Lemoine et al. 2001). In *Q. ilex*, k

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was lower and seasonal water use more conservative than in *Q. suber*. The reduction in *E* from spring to the end of summer was only about 65% in *Q. ilex* compared with about 80% in *Q. suber*.

In summary, *Q. ilex ssp. rotundifolia* seems to have more effective drought avoidance and drought tolerance mechanisms than *Q. suber*. This is in accordance with the geographical distribution and leaf phenology of these species: *Q. ilex* occupies dryer inland areas and has a leaf lifespan of more than 18 months, whereas *Q. suber* has a shorter leaf longevity (about 12 months), dominates in the wetter western areas and can be considered as transitional between evergreen and deciduous oaks (Pereira et al. 1987). Therefore, it may be expected that *Q. suber* will suffer more than *Q. ilex* if drought severity in these Mediterranean ecosystems increases.

Drought impact on carbon and water cycling in a Mediterranean *Quercus suber* L. woodland during the extreme drought event in 2012

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Savannah-type ecosystems account for 26–30% of global gross primary productivity GPP, with water being one of the major driving factors. In Europe, savannah-type woodlands cover an area of about 1.5 million ha. Here, the recent past has shown a significant decrease in precipitation *P* in winter and spring as well as a decrease in total annual precipitation. Strong effects on local water balance and carbon sink strength have thus been reported due to changes in precipitation regime.

The objective of this study is to quantify the impact of the extreme drought event in 2012 on the water balance, gross primary productivity and carbon sink strength of a typical Portuguese cork-oak woodland (montado) compared to the wet year of 2011. Physiological responses of the dominant tree species *Quercus suber* (L.) are disentangled employing combined photosynthesis and stomatal conductance modelling.

Precipitation effectiveness *ET/P* increased from 86% in 2011 to 122% in the 2012 dry year due to deep soil or groundwater access of the *Q. suber* trees leaving no water for groundwater replenishment.

Understorey and overstorey GPP were strongly reduced, by 53 and 28%, respectively, in 2012 compared to 2011, due to the late onset of the autumn rains in 2011 and an additional severe winter/spring drought. However, the ecosystem was still a carbon sink in both years, but with a 38% reduced sink strength under extreme drought in 2012 compared to 2011. The combined photosynthesis–stomatal conductance model yielded the best results if it was allowed to adjust photosynthetic and stomatal parameters simultaneously. If stomatal response was modelled with the Leuning approach, which allows for a different sensitivity to vapour pressure deficit, the stomatal model parameters were highly coupled. A change in either of the parameters needed to be compensated by the other to guarantee a stable sensitivity of stomatal conductance to assimilation, independent of variations in vapour pressure deficit. The *Q. suber* trees showed a 37% reduced stomatal conductance during the drought period of 2012 compared to 2011, due to water supply limitations. In response to reduced leaf-internal CO₂ availability, the trees strongly reduced the apparent maximum carboxylation rate by 43% in 2012 compared to 2011. Unexpectedly, the optimum temperature *T*_{opt} of the maximum electron transport rate decreased during the drought period, enhancing the susceptibility of the trees to high temperature stress during the summer.

Our results suggest that, if the trend of decreasing annual precipitation and changed precipitation patterns on the Iberian Peninsula continues, sustained effects on local groundwater reservoirs, understorey species composition and tree mortality have to be expected in the long term. To model the

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effect of drought on the montado ecosystem successfully, variable apparent maximum carboxylation rate $V_{c,max}$, stomatal conductance parameter m and vapour pressure deficit sensitivity parameter D_0 need to be incorporated into photosynthesis–stomatal conductance modelling.

Sobreiro, uma barreira contra a desertificação - WWF

A desertificação é um problema crescente em muitos países e regiões do mundo e o seu combate uma missão à escala global.

A Conferência das Nações Unidas sobre Ambiente e Desenvolvimento no Rio de Janeiro, em 1992, veio justamente alertar para o avanço da desertificação e para os perigos que lhe são inerentes, criando um programa para inverter a sua escalada, consubstanciado na Convenção de Combate à Desertificação, aprovada 1994.

O Mediterrâneo está classificado no Anexo IV desta mesma Convenção como uma região particularmente vulnerável à desertificação.

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O relatório Millenium Ecosystem Assessment (MEA)(2005) das Nações Unidas, aponta também a abordagem ao problema da desertificação como uma prioridade, chamando a atenção para a vulnerabilidade aos problemas ambientais e de pobreza das populações que vivem nas regiões mais secas.

A desertificação afecta sobretudo as populações com menos recursos, provocando, frequentemente, o abandono das terras. Estima-se que cerca 1/6 das populações do Mali e do Burkina Faso tenham sido deslocadas devido à desertificação. Na Mauritânia, e durante um período de 25 anos, a população que vive na capital aumentou de 9 para 41%, enquanto que a população nómada diminuiu de 73% para 7% devido à desertificação. Também no vale do Senegal cerca de 2/5 da população emigrou havendo mais população da região de Bakel a viver em França do que nas aldeias que deixaram. A desertificação é também referida como um dos factores responsáveis pela emigração dos Mexicanos para os EUA.

É recomendável focar o combate à desertificação na prevenção, pois a reabilitação de áreas degradadas é extremamente dispendiosa e com resultados limitados.

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A nível nacional, a azinheira é, no entanto, a espécie com maior percentagem de distribuição em zonas susceptíveis à desertificação. Nestas áreas mais susceptíveis, o pinheiro manso, a alfarrobeira e o medronheiro ocupam parcelas significativas, logo abaixo do sobreiro em termos percentuais (ver gráfico). Estes dados sugerem que espécies como o pinheiro manso podem complementar a azinheira e o sobreiro nas zonas de solos mais áridos, originando produtos de elevado valor económico, como o pinhão e a semente de alfarroba e simultaneamente cumprindo funções de protecção de solo.

O sobreiro destaca-se como um dos maiores tesouros naturais de Portugal pela excelência dos serviços ambientais que presta. Destacam-se a conservação dos solos, a regulação do ciclo da água, a fixação de carbono e a conservação da biodiversidade.

O sobreiro como instrumento de prevenção da desertificação

O montado e os bosques de sobreiro, formando sistemas ecológica e economicamente sustentáveis, funcionam como um importante instrumento de prevenção contra a desertificação. De facto, desde que adequadamente geridos, estes sistemas, geram níveis elevados de biodiversidade, melhoram a matéria orgânica dos solos, contribuem para a regulação do ciclo hidrológico e travam o despovoamento.

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Como é que o sobreiro gera biodiversidade?

Uma das características mais importantes das florestas de sobreiro é a sua diversidade em arbustos, ervas e árvores, que proporcionam abrigo e alimento a diferentes espécies de aves e mamíferos. Rapinas ameaçadas como a Águia de Bonelli e mamíferos como o Lince Ibérico, o felino mais ameaçado do mundo, têm nas florestas de sobreiro o seu habitat de eleição.

Sendo uma árvore de folha perene (mantém-se verde todo o ano), a copa origina um microclima (maior humidade, temperatura mais baixa e sombra, em particular durante o quente e seco Verão Mediterrânico), que favorece um conjunto de espécies de plantas, frequentemente diferentes das que ocorrem fora da influência da copa da árvore.

Também devido à acumulação de folhas por baixo da copa, onde o solo beneficia em nutrientes, verifica-se o desenvolvimento de diferentes plantas, incrementando a biodiversidade. É possível, no montado, encontrar cerca de 135 espécies de plantas diferentes por 1000 m².

Como é que o sobreiro contribui para o aumento de fertilidade do solo?

O sobreiro ocorre principalmente em dois tipos de solos bastante distintos: solos delgados de xisto (Litossolos nas serras) e solos profundos de areias (Pódzois no vale do Tejo e vale do Sado).

Os solos xistosos favorecem a ocorrência de sobreiral com árvores mais pequenas, mas de maior número e acompanhadas de maior densidade de arbustos.

Nestas zonas, devido ao declive, o risco de erosão é maior e o sobreiro tem uma função de protecção do solo, uma vez que evita a erosão. A má gestão do solo pode levar à degradação da floresta e ao início dos processos de desertificação.

É nos solos mais profundos (com uma espessura efectiva superior a 1,5 metros) de textura arenosa, derivados dos depósitos sedimentares grosseiros terciários do Tejo e do Sado, que se concentra a maior e melhor distribuição do sobreiro.

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Os sobreiros enriquecem a matéria orgânica do solo, pois as árvores retiram os nutrientes de níveis mais profundos e transformam-nos em matéria orgânica, nas folhas através da fotossíntese. Os nutrientes são depois devolvidos ao solo com a queda das folhas, originando solo produtivo.

A intervenção ao nível do solo é fundamental porque, para além da sua importância para a vitalidade do sobreiro, influencia directamente os fenómenos de erosão, que conduzem à degradação do próprio solo.

Uma má gestão do solo pode desencadear um ciclo de degradação, quando a perda de solo é uma dificuldade acrescida para a vegetação, e a consequente perda de coberto arbóreo facilita, por sua vez, a maior perda de solo.

Como o sobreiro contribui para a regulação do ciclo hidrológico?

Do total de água originada pela precipitação cerca de 20 a 30% tende a perder-se por escoamento superficial. Ou seja, a água corre à superfície, não chegando a infiltrar-se no solo.

Estes valores variam consoante as regiões, sendo a bacia hidrográfica do Guadiana uma das zonas mais susceptível à desertificação e de menor área florestal.

Esta é a zona onde se regista em Portugal o maior valor de escoamento superficial (29%) (ver tabela).

Ao aumentar os níveis de matéria orgânica dos solos, as florestas de sobreiro contribuem para uma melhor retenção de água, facilitam a sua infiltração no solo e diminuem as perdas por escoamento superficial, regulando o ciclo hidrológico.

O sobreiro como instrumento de reabilitação de áreas desertificadas

No caso da reabilitação de áreas já degradadas, ou em avançado estado de desertificação, o sobreiro desempenha igualmente um papel importante, em particular quando associado a outras espécies mediterrânicas, como a azinheira e o pinheiro manso.

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A azinheira é uma das espécies florestais mais resistentes à aridez, sendo 90% da sua área de distribuição em Portugal coincidente com a área susceptível à desertificação. Em condições semiáridas, principalmente em zonas de invernos mais frios, a azinheira substitui o sobreiro. No caso do pinheiro manso, espécie também resistente à secura, 70% da sua área de distribuição em Portugal é coincidente com a área susceptível à desertificação.

Em situações de restauro, o sobreiro deve ser utilizado preferencialmente nas exposições viradas a Norte e em solos mais profundos. As restantes espécies devem ser utilizadas nas exposições viradas a Sul e a Oeste, em solos mais delgados ou locais mais áridos.

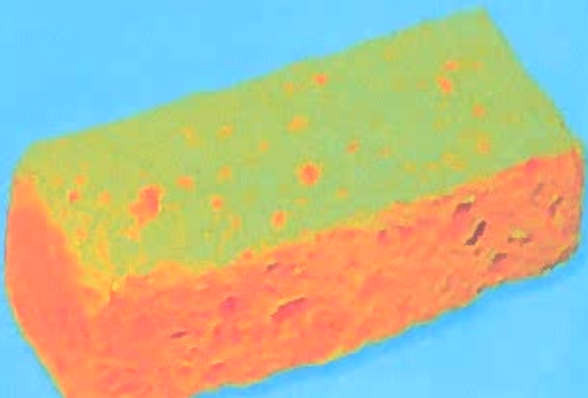
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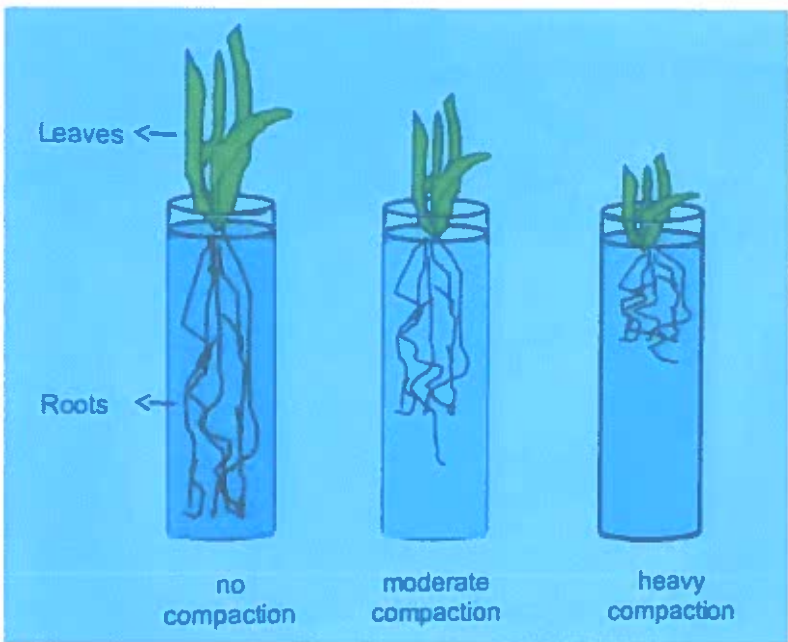
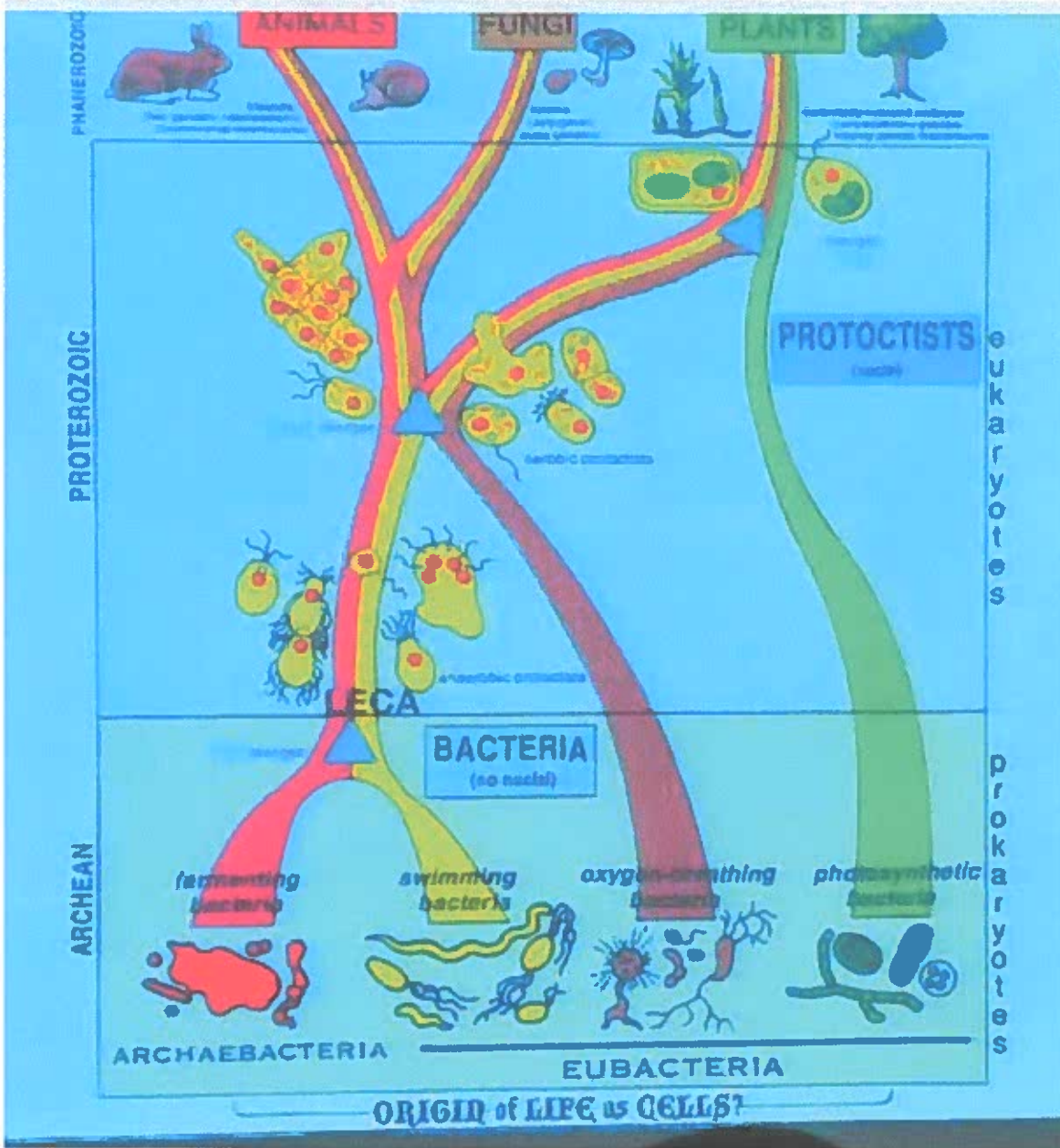
Clifford Allan Redin Savory (born 15 September 1935) is a Zimbabwean ecologist, livestock farmer, environmentalist, and president and co-founder of the Savory Institute. He originated Holistic management (agriculture),^[1] a systems thinking approach to managing resources.

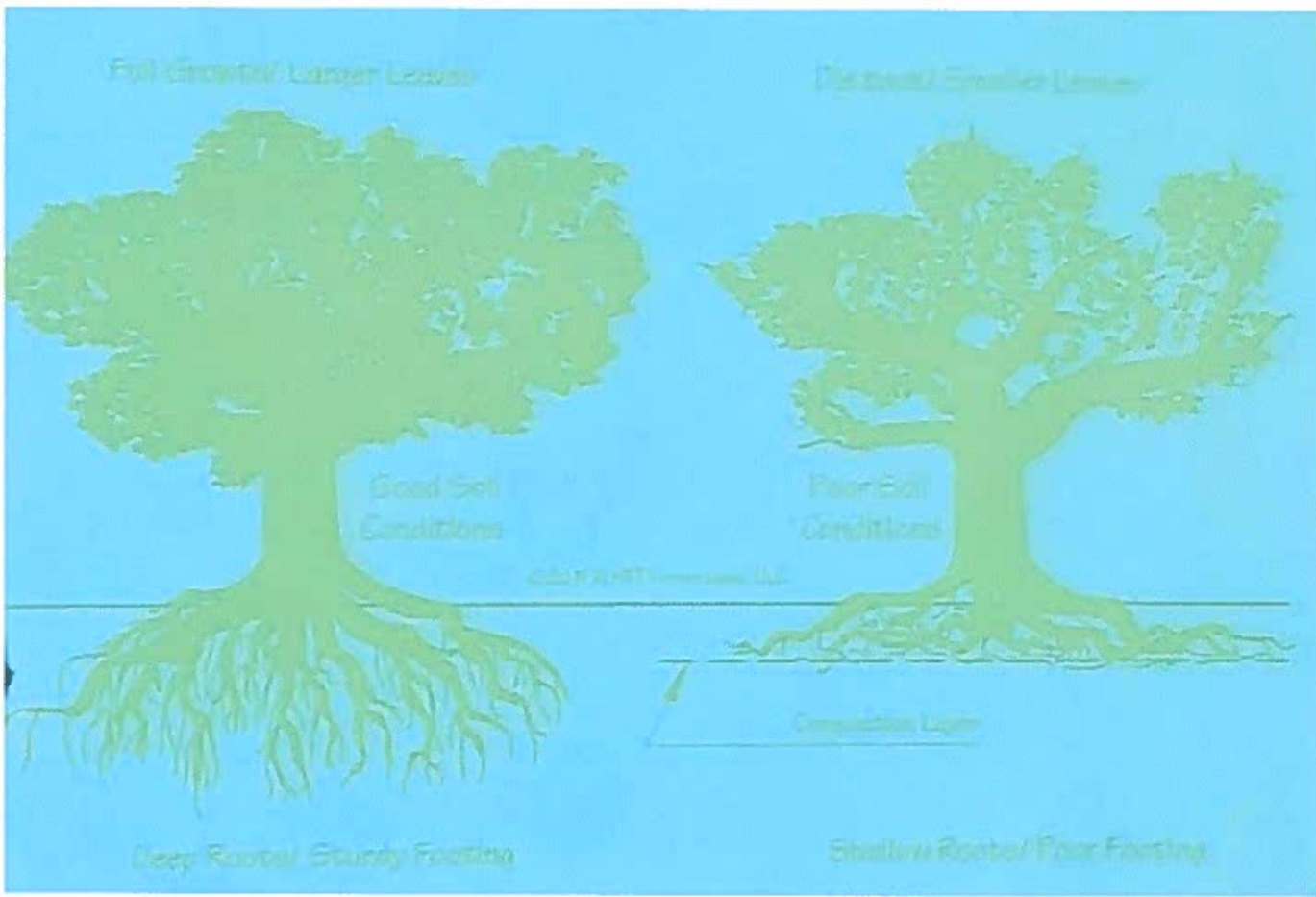
Seguem-se alguns slides da sua organização internacional, que apresenta soluções contra a desertificação, com relevância para a melhoria dos solos e que confirmam os textos atrás reproduzidos :

Una parte de humus puede retener cuatro partes de agua

Cada **1%** de incremento de **Materia Orgánica** en el suelo (30 cm de profundidad y densidad de 1,4 gr/cm³), crea una absorción adicional de agua de aprox. **20 L/m²**







EXUDACION

30-40% del Carbono fijado por las plantas es exudado por las raíces para alimentar la vida de la rizosfera

A más vida en el suelo, más nutrientes esenciales del suelo se ponen a disposición de las plantas

El volumen de Carbono liberado al suelo es directamente proporcional a la masa de raíces y a la velocidad de crecimiento

J. Vieira Natividade – Subericultura

A propósito de minerais potencialmente relevantes para o desenvolvimento dos sobreiros, reproduz-se extractos do capítulo “Composição Química da Cortiça”, na pagina 171 (ultimo paragrafo) e pag.172 :

“Iniciativa Pró-Montado Alentejo” – Artigos técnico-científicos conexos

antracenas, etc.. Outras substâncias se podem obter ainda do tecido suberoso do sobreiro submetendo-o a diversos tratamentos: glicerina (2,65-6,2 ‰), coniferina, ácido esteárico, ácido oleico, etc.. Na cinza da cortiça (1-4,12 ‰), BARCELÓ (cit. FERREIRA JÚNIOR 1942) identificou os seguintes metais: cálcio,

potássio, manganês, ferro, alumínio, magnésio, sódio, bário, estrôncio, cobre, lítio, crómio e titânio, sete dos quais já haviam sido estudados por KÜGLER (1884). O cálcio e o potássio são os elementos que se encontram em maior quantidade nas cinzas.

Instalação e manutenção de novas plantações de sobreiros regados - Recomendações técnicas - Equipa de investigação Pró-FLORMED

Extractos »

A plantação deve ser realizada após a instalação do sistema de rega para evitar a perda de vigor ou mortalidade das mudas devido a períodos de deficit hídrico. O solo deverá apresentar um teor de humidade adequado, evitando condições de secura ou de excesso de água. Idealmente, a plantação deve ser realizada na sua melhor época – o Outono.

A rega gota-a-gota é a recomendada pela sua sustentabilidade (eficiência entre 80 – 95%) e precisão.

A rega de superfície é a ideal para os primeiros anos das plantas e para solos bastante arenosos com pouca matéria argilosa. Além disso, permite que se movimentem os tubos de rega conforme as necessidades, acompanhando o crescimento das plantas. Pode-se optar pelo enterramento dos tubos após 2/ 3 anos de plantação.

As necessidades de rega são determinadas pelo balanço hídrico do solo, onde, a evapotranspiração cultural (ETc) a precipitação e, no caso particular dos sobreiros, o acesso ao solo encharcado, são as componentes que assumem maior importância. Para se proceder a rega de precisão, será necessário monitorizar as condições de humidade do solo.

Recomenda-se a instalação de alguns pontos de amostragem do status hídrico do solo, a várias profundidades, com sensores do tipo Watermark, DeltaT PR2, EnviroSCAN ou similares. Este tipo de equipamentos permitem avaliar melhor

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como se distribui e varia a água no solo ao longo do tempo, produzindo assim informação útil para corrigir/ajustar as dotações.

Para a componente de monitorização climática é importante ter instalada uma estação agro-meteorológica automática equipada no mínimo com udómetro, sensor de humidade relativa temperatura do ar, velocidade do vento e radiação solar. Este equipamento permite contabilizar diariamente a contribuição da precipitação para o balanço hídrico do solo e o cálculo da evapotranspiração potencial, fornecendo assim informação útil para otimizar localmente as dotações de rega em função do clima.

A rega deve ter como principal objectivo colmatar os períodos de seca que coincidem com os de maior consumo potencial de água e, acessoriamente, funcionar como veículo de aplicação de fertilizante.

Até ao momento não há dados científicos que indiquem qual o período ideal de rega dos sobreiros, de forma a maximizar o crescimento com uma eficiente utilização da água. Assim, até novas informações, sugere-se que a campanha de rega tenha aproximadamente 16 semanas de rega/ ano distribuídas durante o período de maior seca estival, dependendo da precipitação e solicitação atmosférica. As 16 semanas usadas na estimativa abrangem o período entre finais de Maio até Setembro ou até às primeiras ocorrências de precipitações significativas.

Tratando-se do primeiro ano de plantação, recomenda-se também fertirrega durante a primavera, em particular durante as semanas sem precipitação e conforme a capacidade de armazenamento de água do solo. Nos anos seguintes, na sequência de um inverno seco (indicando que o solo encharcado se encontra mais profundo) e primavera pouco chuvosa, a fertirrega poderá ter início em Abril e colmatar as semanas primaveris sem precipitação.

Em lenhosas, a dotação necessária varia conforme o tipo de solo e a área foliar das plantas, devendo ser suficiente para manter a humidade de solo no intervalo de conforto para as plantas. Por conseguinte, é necessária a monitorização contínua das necessidades de rega (ponto 5). A humidade relativa no solo tem como limite de conforto mínimo 6% em solos muito arenosos, até 25% de valor mínimo em solos bastante argilosos.

No caso particular do ensaio experimental (REGASUBER), um regossolo arenoso e profundo, a dotação semanal mínima nos dois anos iniciais foi de 30 L por sobreiro.

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Conforme os resultados dos estudos em curso, **estes valores serão actualizados para plantas de maiores dimensões**. As dotações em cada ensaio particular deverão ser analisadas em função dos dados de tipo de solo, humidade de solo e dimensões das plantas.

Devido à jovem idade das plantas, as suas raízes ainda não se desenvolveram muito, tanto em extensão como em profundidade. Por esse motivo, recomenda-se, nesta fase inicial, que se dê preferência a fertirregas de período curto, mas frequente. Por exemplo, fornecer fertirrega com frequência de 3x por semana, ajustando o período de cada rega para que a soma semanal atinja a dotação previamente estipulada. **Quanto mais arenosos forem os solos, mais importante será a frequência da fertirrega**. Com a idade das árvores, a frequência deverá ser tendencialmente reduzida e a dotação aumentada, de forma a ir ao encontro do maior volume radicular.

Enquanto realizar rega de superfície, recomenda-se a fertirrega durante o período nocturno, por forma a evitar perdas de água por evaporação. Com rega subterrânea, estas restrições são desnecessárias.

O efeito dos fertilizantes no sobreiro ainda estão em estudo.

Contudo, a fórmula deve ser adaptada às características e aos défices de nutrientes identificados no solo. Na parcela experimental, particularmente deficiente em azoto, aplicou-se o Nutrifluid NPK 12-6-6 na ordem de 9 L/ semana/ ha (em compasso 4x4). A fertilização deverá ser realizada mais próxima do final da rega, para não se perder por lixiviação, terminando com cerca de 10 minutos de rega sem fertilizantes, para limpeza dos tubos.

A estrutura radicular do sobreiro possui um sistema horizontalmente extenso à superfície do solo, estendendo-se para além da área de projecção da copa. Além disso, as árvores tendem a não lançar raízes nas direcções onde estas tenham já sido cortadas. Por este motivo deve evitar-se a prática de gradagem e optar-se pelo uso de corta-mato para controlo de matos e infestantes.

Desde os primeiros anos de crescimento aconselha-se a condução das de forma a alcançar fustes altos, para uma maior rentabilidade na tirada de cortiça. Para tal, as podas de formação de fuste deverão ser iniciadas e efectuadas sempre que se considere necessário, respeitando as épocas legais para o efeito.

“Iniciativa Pró-Montado Alentejo” – Artigos técnico-científicos conexos

É importante referir que, pela experiência já observada em campo, as plantas em fertirrega apresentam um crescimento mais rápido do que as plantas em modo de sequeiro.

Assim, é importante iniciar as podas de formação de fuste atempadamente e em plantas ainda pequenas. Desta forma evitar-se-á efectuar grandes cortes no futuro, que eventualmente prejudicariam a vitalidade da árvore e evitando ainda falhas em possíveis pranchas direitas do fuste.

Para controlo de animais, como coelhos, javalis ou gado, aconselha-se a construção de cercas reforçadas em baixo.

O uso de protectores e tutores individuais é desaconselhado e apenas deverá aplicado caso não exista um meio alternativo de protecção contra animais de médio /grande porte. O uso destes, para além do investimento ser elevado, não traz benefícios relevantes ao crescimento. Por outro lado, induz à falta de investimento energético, por parte da planta, em formar um suporte lenhoso vertical na formação do fuste, ficando mais “preguiçosas”. Sendo expectável que a fertirrega favoreça o crescimento em altura, é necessário que o caule tenha rigidez necessária para suportar a planta. A rigidez deste está relacionada com a “necessidade”. Plantas expostas as condições atmosféricas, nomeadamente ao vento, apresentarão mais rigidez de suporte.

Os roedores associados a estragos nas plantações em Portugal, incluindo espécies lenhosas, são basicamente duas espécies de ratos cegos: *Microtus lusitanicus* ; *M. duodecimcostatus*. O primeiro tem a sua distribuição no norte e o segundo é mais comum no Sul, podendo ocorrer áreas de simpatria entre as duas espécies no Centro. Podem-se distinguir pela variação na presença de montículos de terra ou aberturas.

Havendo a possibilidade de perigo de praga por ratos cegos, recomenda-se que, durante a plantação, sejam colocadas “guardas mecânicos” à volta do torrão das mudas. Por exemplo, redes metálicas como as redes de galinheiro, com malha fina e maleável de 1.5 x 2.0 cm, não galvanizada. As redes, cortadas em rectângulos com as dimensões dos torrões das mudas de sobreiros, são envolvidas no torrão e plantadas com este. Pretende-se proteger as raízes enquanto a planta for jovem, mas espera-se que a malha se degrade em poucos anos em contacto com o solo, não limitando o desenvolvimento destas.

“Iniciativa Pró-Montado Alentejo” – Artigos técnico-científicos conexos

O controlo das ervas daninhas e arbustos reduz os estragos causados pelas pragas. Em áreas irrigadas há grande proliferação de vários tipos de vegetação espontânea que produzem bolbos, sementes, ou raízes não lenhificadas que servem de alimento para os ratos cegos. A eliminação da fonte de alimento é a estratégia mais eficiente no controlo destas pragas.

Recomenda-se que seja feita, de forma periódica, uma manutenção do sistema de rega detectando possíveis falhas (verificação de caudais, manutenção de condutas, desentupimento de gotejadores, colmatar fugas de água nas fitas à superfície, etc.) e solucionando de forma rápida o problema. Uma manutenção cuidada do sistema de rega evitará possíveis custos acrescidos no futuro. Se as águas são pouco calcárias, é suficiente ácido fosfórico com concentração no caudal de rega de 0.5%, durante 30 minutos para as limpezas dos tubos.

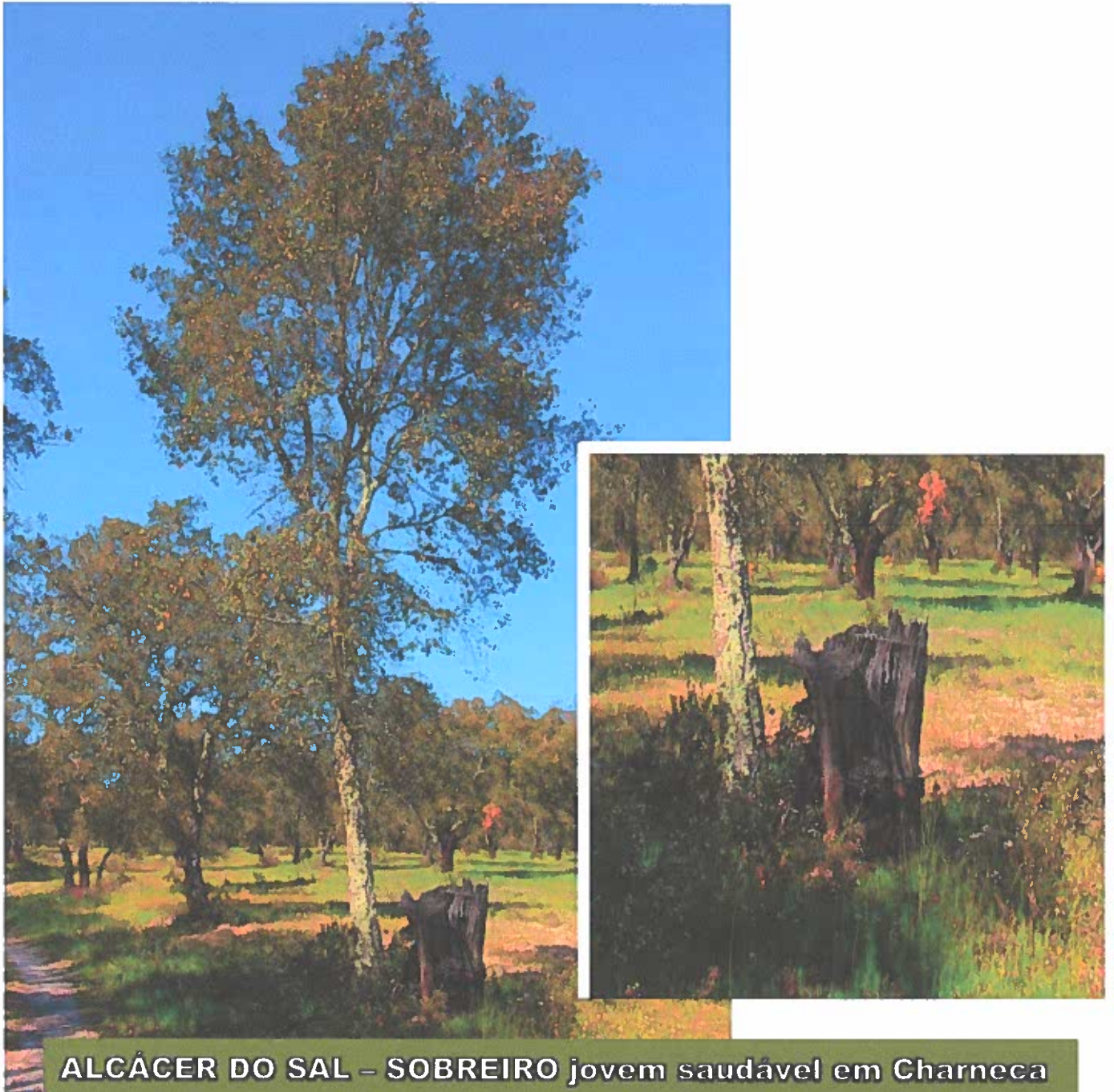
*Importância da **Matéria Orgânica** – Arvoredo jovem
(Localizada e Profunda)*



**SERRA DE GRÂNDOLA – SOBREIRO jovem saudável
Alimentando-se do Cepo de um Pinheiro jovem abatido**

“Iniciativa Pró-Montado Alentejo” – Demonstração empírica - fotos ilustrativas de Postulados para “Adaptação Climática” do Montado

*Importância da **Matéria Orgânica** – Arvoredo jovem
(Localizada e Profunda)*



ALCÁCER DO SAL – SOBREIRO jovem saudável em Charneca Alimentando-se do Cepo de um Pinheiro adulto abatido

“Iniciativa Pró-Montado Alentejo” – Demonstração empírica - fotos ilustrativas de Postulados para “Adaptação Climática” do Montado

*Importância da **Matéria Orgânica** – Arvoredo adulto
(Profunda na entre-linha)*



GRÂNDOLA – MONTADO DE SOBRO em Charneca
Condição razoável - Instalado em zona muito Arenosa
após o corte raso de Pinhal Bravo



“Iniciativa Pró-Montado Alentejo” – Demonstração empírica - fotos ilustrativas de Postulados para “Adaptação Climática” do Montado

Importância da Fertilidade Geral – Arvoredo adulto

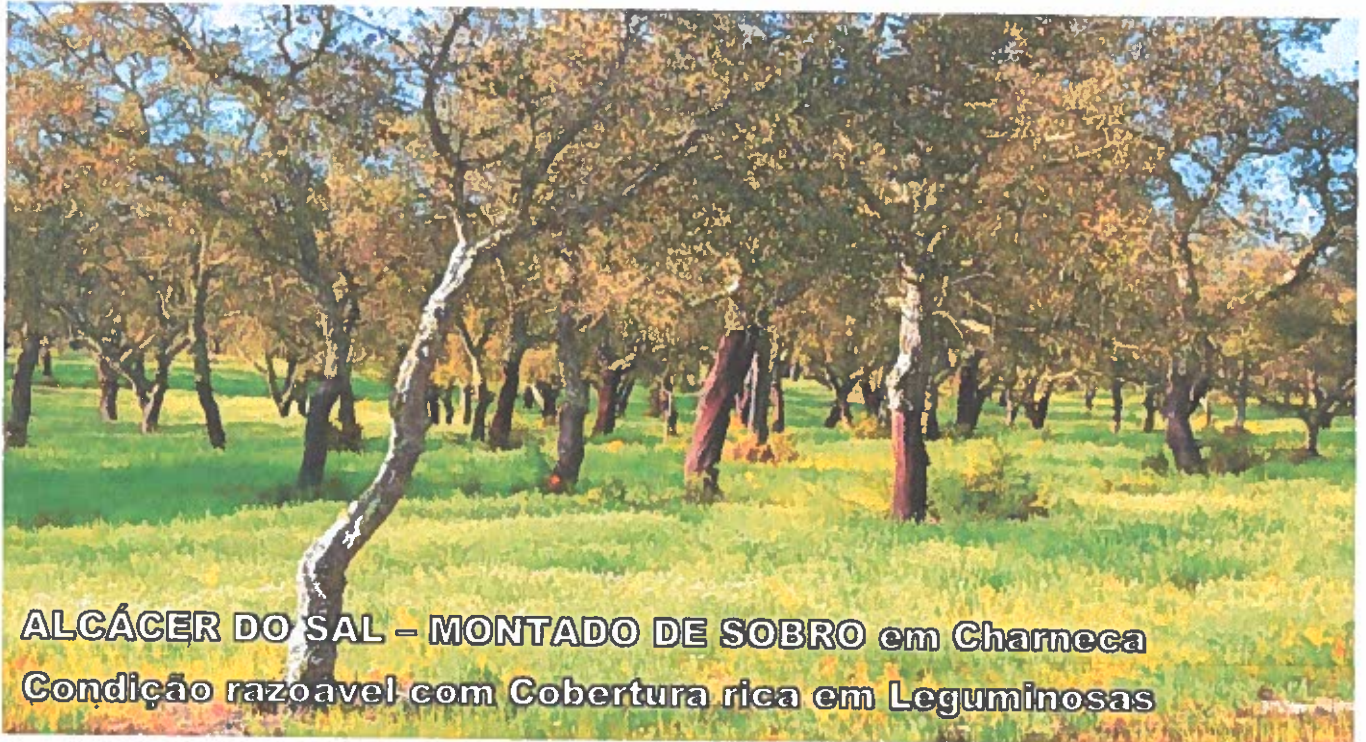
(Matéria Orgânica, Leguminosas e Limpeza)



“Iniciativa Pró-Montado Alentejo” – Demonstração empírica - fotos ilustrativas de Postulados para “Adaptação Climática” do Montado

Importância da Fertilidade Geral – Arvoredo adulto

(Matéria Orgânica, Leguminosas e Limpeza)



“Iniciativa Pró-Montado Alentejo” – Demonstração empírica - fotos ilustrativas de Postulados para “Adaptação Climática” do Montado

Importância da Fertilidade Geral – Arvoredo adulto

(Matéria Orgânica, Leguminosas e Limpeza)



ALCACER DO SAL – MONTADO DE SOBRO em Charmeca
Estado razoável com Programa de Fertilidade associado

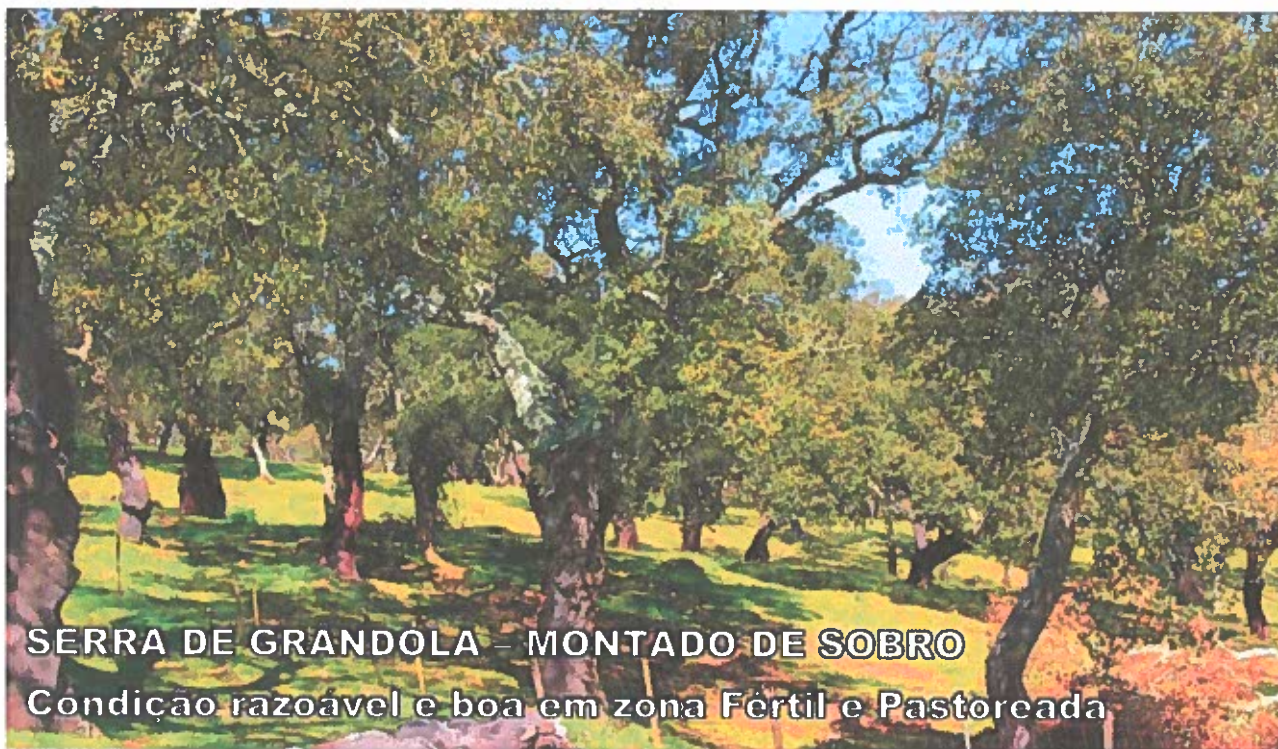


SERRA DE GRANDOLA – MONTADO DE SOBRO
Condição razoável em zona Resguardada de maior Fertilidade

“Iniciativa Pró-Montado Alentejo” – Demonstração empírica - fotos ilustrativas de Postulados para “Adaptação Climática” do Montado

Importância da Fertilidade Geral – Arvoredo adulto

(Matéria Orgânica, Leguminosas e Limpeza)



SERRA DE GRANDOLA – MONTADO DE SOBRO
Condição razoável e boa em zona Fértil e Pastoreada

“Iniciativa Pró-Montado Alentejo” – Demonstração empírica - fotos ilustrativas de Postulados para “Adaptação Climática” do Montado

= *Importância da Densidade/Ensombramento* =



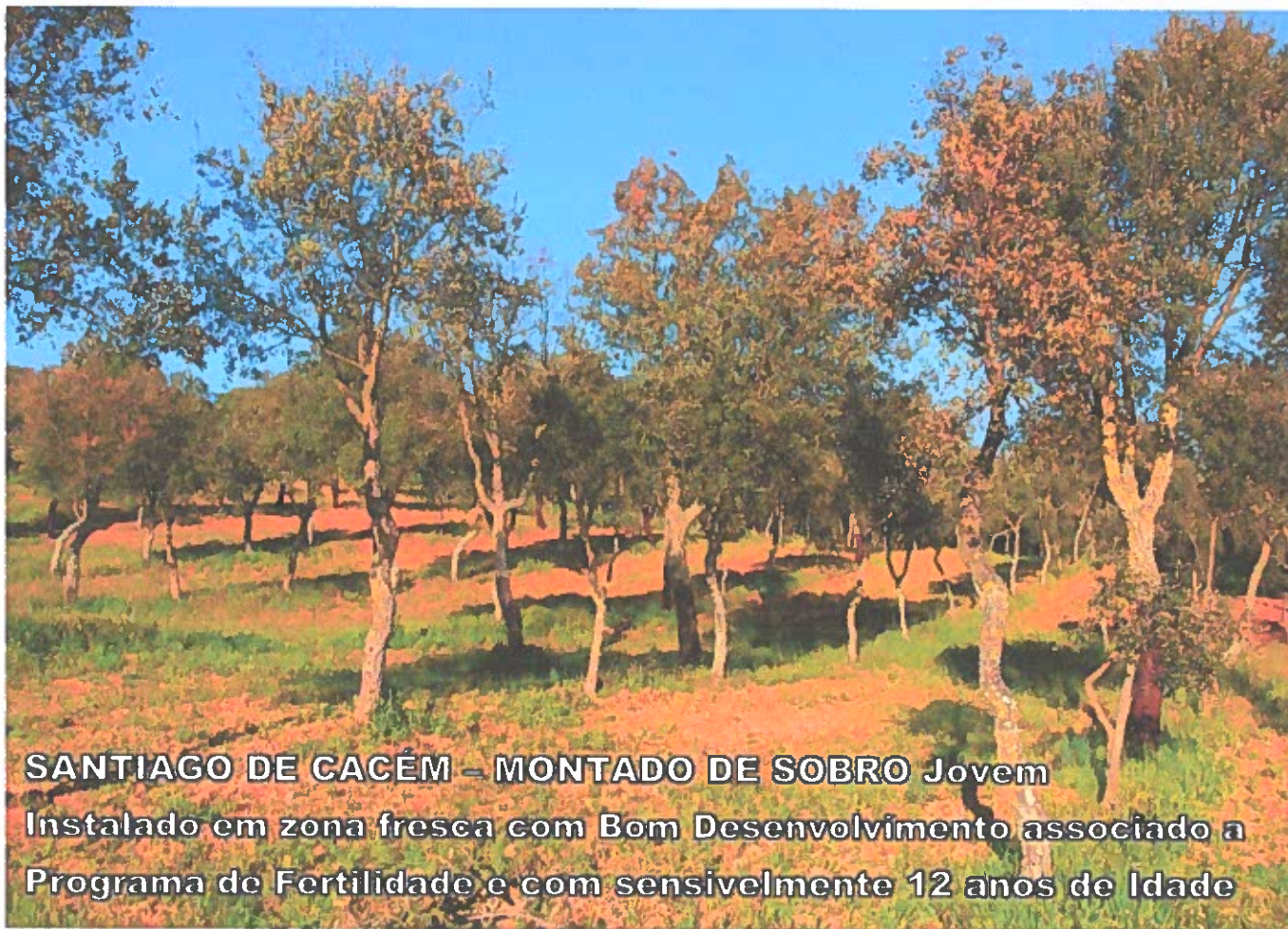
“Iniciativa Pró-Montado Alentejo” – Demonstração empírica - fotos ilustrativas de Postulados para “Adaptação Climática” do Montado

= *Importância da Densidade/Ensombramento* =



“Iniciativa Pró-Montado Alentejo” – Demonstração empírica - fotos ilustrativas de Postulados para “Adaptação Climática” do Montado

= Importância da Disponibilidade de Água em Adensamentos e Florestações =



“Iniciativa Pró-Montado Alentejo” – Demonstração empírica - fotos ilustrativas de Postulados para “Adaptação Climática” do Montado

= Importância da Disponibilidade de Água em Adensamentos e Florestações =



SERRA DE SANTIAGO – MONTADO Recente

Instalado (Encosta Baixa, Fértil e Sombria)

Instalação/Adensamento do Montado de Sobro em Vale e Cômoro em zona naturalmente Fértil



“Iniciativa Pró-Montado Alentejo” – Demonstração empírica - fotos ilustrativas de Postulados para “Adaptação Climática” do Montado

= Importância da Disponibilidade de Água em Adensamentos e Florestações =



SERRA DE SANTIAGO – MONTADO Recente

Instalado (Encosta Baixa, Fértil e Sombria)

Instalação/Adensamento do Montado de Sobro em Vale e Comoro em zona naturalmente Fértil

