Dryland forests and agrosilvopastoral systems: water at the core

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A water-centred approach is essential for maintaining the resilience of forested drylands in the face of climate change.

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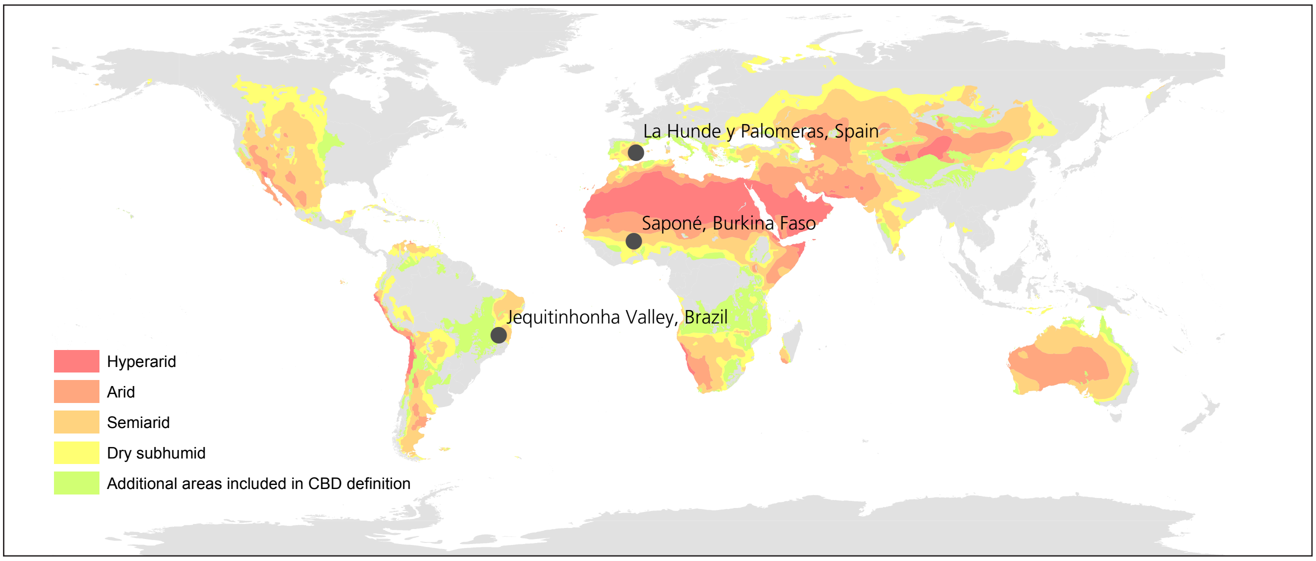
Dryland systems occur on all continents and cover about 41 percent of the Earth's land surface, with little variation in this figure in recent decades (Cherlet *et al*., 2018). Drylands differ in their moisture deficit and can be classified in four subtypes according to the United Nations Environment (UNEP) aridity index (AI)[1] as dry subhumid (0.65–0.5), semiarid (0.5–0.2), arid (0.2–0.05) or hyperarid (<0.05) (Figure 1).[2] Forests and grasslands are the dominant biomes in the dry subhumid and semiarid subtypes, respectively (more than 60 percent of the subtype areas). On the other hand, the arid and hyperarid subtypes are mostly treeless (FAO, 2016) and thus beyond the scope of this article.

Based on their underlying definition (i.e. by AI), annual potential evapotranspiration (PET) in dry subhumid and semiarid lands is considerably higher than annual precipitation, with frequent meteorological droughts. These atmospheric drivers lead to low soil moisture and this, in turn, means slow tree growth and low productivity, resulting in a socio-ecological context of water scarcity. Marked rainfall seasonality, with torrential events followed by long dry periods, and the combination of high intra- and interannual variability, put such regions within the "difficult" hydrology framework, which hampers water security, sustainable development and poverty reduction (Grey and Sadoff, 2007).

[1] AI is calculated as precipitation (P) divided by PET.
[2] Additionally, the Convention on Biological Diversity's delineation includes some areas with presumed dryland features in which P/PET > 0.65 (CBD Secretariat, 2010).



1
World dryland areas

Note: Dryland categories are as per definitions by the United Nations Convention to Combat Desertification and the Convention on Biological Diversity (CBD). Black dots show the locations of the case studies.

Source: UNEP-WCMC (2007).

Climate change is expected to cause an increase in the global area of drylands of 10–23 percent, depending on dryland subtype, by the end of the twenty-first century, particularly in areas of North and South America, the Mediterranean, southern Africa, Australia, the Middle East and Central Asia (Cherlet *et al*., 2018). The intensification of precipitation and other climatic extremes under warmer conditions is likely to increase water scarcity and moisture deficits in drylands and beyond.

Climatic constraints increase the role of soil processes and properties in the regulation and magnitude of water-related issues in drylands, especially those concerned with resource storage (e.g. soil depth, infiltrability, deep-water storage

A combination of land uses (e.g. agriculture, woodlands, pastures and barren land shown here) and management practices (e.g. soil treatments and the check dam) interact with climate and soil processes and affect the regulation and magnitude of water-related issues

and erosion). Thus, land-use and management practices, especially nature-based solutions, are extremely important for the soil–water–productivity complex.

This article uses case studies in drylands on three continents to show the importance of a water-centred approach to dryland management for increasing resilience and adaption to climate change.

FOREST ECOSYSTEM PROCESSES AND TREE FUNCTIONAL TRAITS

Dryland forests and agrosilvopastoral systems (DFASs) face specific challenges compared with other vegetation types. Low water availability, low growth and unprecedented disturbance regimes (e.g. wildfires and pest outbreaks), aggravated by climate change, make them less resilient and more prone to shifts toward less-productive states (desertification) (Johnstone *et al*., 2016). Anthropogenic pressures (such as those imposed by grazing, browsing, forest overexploitation and deforestation) add complexity and feedbacks.

Ecohydrology in drylands is mostly captured by the strong relationship between soil cover and water; that is, forest structure – both physical (e.g. tree density, canopy cover and basal area) and biological (species composition) – has a direct impact on water-resource availability (Bosch and Hewlett, 1982), affecting variables such as infiltration, evapotranspiration, surface runoff (and erosion) and groundwater recharge. On the one hand, decreasing canopy cover increases net precipitation, which in turn can increase soil moisture and related water flows such as groundwater recharge and water yield, as well as soil evaporation. On the other, high tree cover increases interception and transpiration while maximizing soil protection and enhancing soil infiltration capacity. The explicit consideration of trade-offs between various hydrological processes and vegetation is essential in drylands when dealing with resource storage (i.e. soil and water). Moreover, the water-related traits of tree species (e.g. canopy and root architecture, wood density, and leaf area index) are important drivers affecting the redistribution and subsequent use of water in the soil profile.

TARGETING WATER IN OBJECTIVES AND MANAGEMENT OPTIONS

Drylands provide a wide array of goods and ecosystem services, but their potential is often underestimated because they are wrongly perceived to be unproductive (White and Nackoney, 2003). Drylands support the livelihoods of more than one-third of the global human population by supplying food, forage for livestock and drinking water. They also provide habitats for species uniquely adapted to variable and extreme environments, which, in turn, constitute sources of genetic material for developing drought-resistant varieties. Because of their great extent, drylands can store large amounts of carbon (Lal, 2004).

The provision of all these goods and ecosystem services is essentially dependent on water availability, which is often limited, variable and unpredictable but also fundamental for supporting flora and fauna. Vegetation dynamics, soil-water flows and climate are strongly coupled in drylands; the capacity to cope with temporal water shortages is essential for both people's livelihoods and the ecosystems themselves. Thus, water is the key element for the socio-ecological resilience of drylands and must constitute a quantitative basis of any management approach (Falkenmark, Wang-Erlandsson and Rockström, 2019).

In more humid environments, water yield has long been quantified as part of ecosystem management (Bosch and Hewlett, 1982). In dryland ecosystems, water should not just be quantified, it should be central to land planning and management. More specifically, the emphasis should be on soil water and aquifer recharge rather than on increasing total runoff or streamflow. Groundwater is the primary water resource in drylands because surface water resources are generally scarce and highly unreliable; maximizing its recharge should therefore be targeted as a means to increase the socio-ecological resilience of drylands.

CASE STUDIES

Below, three case studies from drylands on three continents demonstrate how water-centred management can improve water budgets and local livelihoods, increase climate-change resilience and adaptation, and reduce the risk of disaster.

Pine reforestation in drylands

Monte La Hunde y Palomera (950 metres above sea level) is a publicly owned dryland forest in eastern Spain (Figure 2). The forest covers 4 700 ha, and it includes 887 ha of homogeneous Aleppo pine (*Pinus halepensis*) planted between 1945 and 1970 as part of a national afforestation programme. The Aleppo pine forest has high tree density (more than 1 500 trees per ha, to increase soil protection) and little silvicultural intervention. The lack of intervention is common in many protective forests in the Mediterranean.

The Monte La Hunde y Palomera forest region has an AI of 0.62, a mean annual temperature of 13.7 °C, and precipitation of 465 mm (1960–2007). The soils are shallow, with high concentrations of carbonate, a basic pH, and a sandy-silty loam texture.

The lack of forest management, combined with the climatic characteristics of drylands, has produced a dense forest in which growth is stalled; it intercepts about 40 percent of gross precipitation and severely competes for the other 60 percent (del Campo *et al*., 2017, and references therein). As a result, the forest is highly susceptible to climatic fluctuations (i.e. rainfall variability), thus increasing its vulnerability to climate change. Water infiltration and percolation is essential not only for the forest itself but also for feeding two complex aquifer systems, Mancha Oriental (7 000 km^2) and Alpera (400 km^2). The two aquifers comprise the main water source of 127 000 ha of field crops, but they have suffered recurrent drought episodes in the last 20 years.

In this context, the aim of forest management must be to enhance tree growth and vigour (thus reducing the forest's climatic vulnerability) and soil protection, while also increasing the catchment water budget and its contribution to downstream users. Thus, thinning from below at different intensities (higher on flat sites, and moderate to light on steeper sites) was performed in a crowded forest, achieving an alternation of firebreak and groundwater recharge areas (tree density <170 trees per ha) together with zones of moderate tree density (450–700 trees per ha), enough to promote tree vigour and infiltration without decreasing soil protection. This management approach focuses on soils, trees, water and climatic factors and can be considered as ecohydrological-based forest management. It has proved capable of coping with trade-offs among multiple objectives: canopy interception and stand transpiration have been reduced; soil water infiltration, deep percolation, tree transpiration and water contributions to the aquifers have all increased; and fuel models have been altered. The management changes have produced a forest with less climatic vulnerability and lower fire risk (del Campo *et al*., 2017, and references therein) and, which, therefore, is more capable of facing climate-change-related disturbances.

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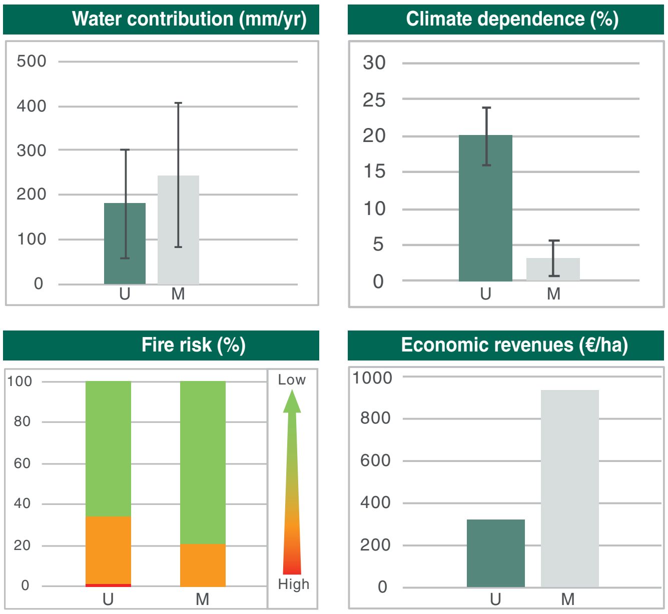
Aleppo pine forest, Monte La Hunde y Palomera forest, eastern Spain

Ecohydrological forest management also has social and economic benefits throughout the catchment. For example, increasing the water budget increases the capability of users to cope with drought. Reducing the fire hazard both decreases the public sense of insecurity, which is especially important in the urban–forest interface, and potentially avoids the costs of damage caused by wildfire and the expense of forest restoration. Such benefits arise when water is put at the core of the management approach.

2
Results of ecosystem management, Monte La Hunde y Palomera



Notes: Forest water contribution (mm/yr); climate dependence (growth dependence on previous monthly precipitation in %); fire risk (percentage of days/year with very high [red], high [orange] and low [green] fire risk); economic revenues (euros per ha), (see del Campo *et al*., 2017 for specific references).
U = unmanaged, M = managed.

Agroforestry parklands: coping with multiple objectives but only "one water"

Saponé is a rural municipality in central Burkina Faso in West Africa. The dominant soils are ferric lixisols, with low nutrient content and sandy-clay and sandy-loam textures. Mean annual precipitation at Ouagadougou (30 km north of Saponé) was 790 mm in 1952–2014 (in the range of 570–1 189 mm). Most rainfall occurs in a single rainy season, which runs from April to October. Mean annual potential evapotranspiration and mean AI (1974–2003) are 1 900 mm and 0.38, respectively.

The landscape is characterized by open tree cover (30 trees per ha) dominated by *Vitellaria paradoxa* (shea), with annual crops such as pearl millet, sorghum, groundnut and cowpea grown under and among the scattered trees. These cultivated

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Harvesting aleppo pine, Monte La Hunde y Palomera forest, eastern Spain

open woodlands are referred to as agroforestry parklands, and they constitute the predominant farming system in the Sudano-Sahelian region of West Africa, covering large areas (Boffa, 1999). Trees are actively conserved and promoted on farms because of the benefits they provide to local communities – including the provision of fruits, nuts, shading, medicines, and fodder for livestock.

Rainfall is highly variable in Saponé. The relatively short rainy season is characterized by a few intense events unevenly distributed over time, and there is large spatial and interannual rainfall variability. The soils have low structural stability and are highly vulnerable to physical degradation, such as decreases in soil infiltration capacity, resulting in limited soil and groundwater recharge opportunities and a higher prevalence of infiltration-excess overland flow. This, in turn, increases the risk of agricultural drought, erosion and flooding, placing considerable constraints on water supply and food production, particularly given the dominance of rainfed crops. Physical degradation is typically a result of land use, land-cover conversions and human pressure in general; thus, management approaches designed to improve local livelihoods should aim to increase soil and groundwater recharge.

Trees consume more water than shorter vegetation types such as crops and grasses (Zhang, Dawes and Walker, 2001). Based on this understanding, increasing tree cover is often discouraged in drylands because it might jeopardize precious water resources (Jackson *et al*., 2005). But results from studies conducted in the agroforestry parklands of Saponé reveal a more nuanced story. Soil water drainage collected at a depth of 1.5 m was highest in the area below the edge of the tree canopy and decreased both towards the tree stem and towards the centre of adjacent open areas among trees (Ilstedt *et al*., 2016). Thus, little water was available for groundwater recharge both close to tree stems and in the open areas far away from trees. Interception and transpiration losses are higher in the area around tree stems, which explains the reduced deep drainage in this area. The decrease in water drainage observed with increasing distance from the canopy edges of trees towards open areas, on the other hand, can be attributed to the observed concurrent decrease in infiltration capacity and preferential flow (Bargués-Tobella *et al*., 2014). Thus, trees should not be seen only as water consumers but also as key ecosystem engineers that enable soil and groundwater recharge.

In Saponé, groundwater recharge is maximized at an intermediate canopy cover (Ilstedt *et al*., 2016). At tree cover below the optimum, more trees result in increased groundwater recharge because the improvement in soil hydraulic properties conferred by these trees outweighs additional evapotranspiration losses. The opposite is the case, however, at tree-cover percentages above the optimum (Figure 3).

Although more research is needed, from a management perspective it is vital to

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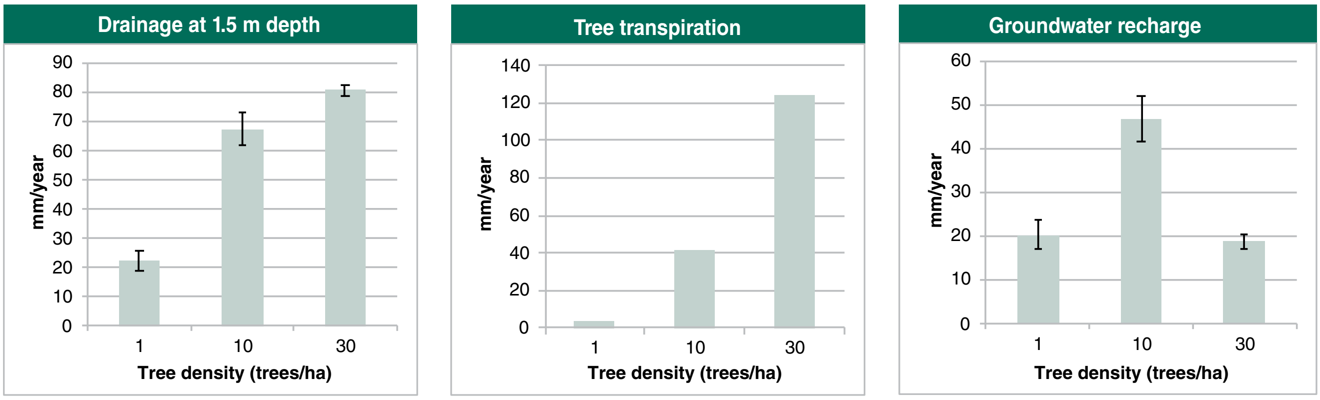
Agroforestry parklands, Saponé, Burkina Faso



3
Results of ecosystem management, Saponé; three tree densities

promote practices that maximize the positive impacts of trees on soil hydraulic properties and minimize tree water use and interception. Thus, tree species selection, tree pruning and livestock control offer opportunities to increase groundwater recharge (Ilstedt *et al*., 2016).

Cerrado: the hydrological consequences of vegetation biomass increment

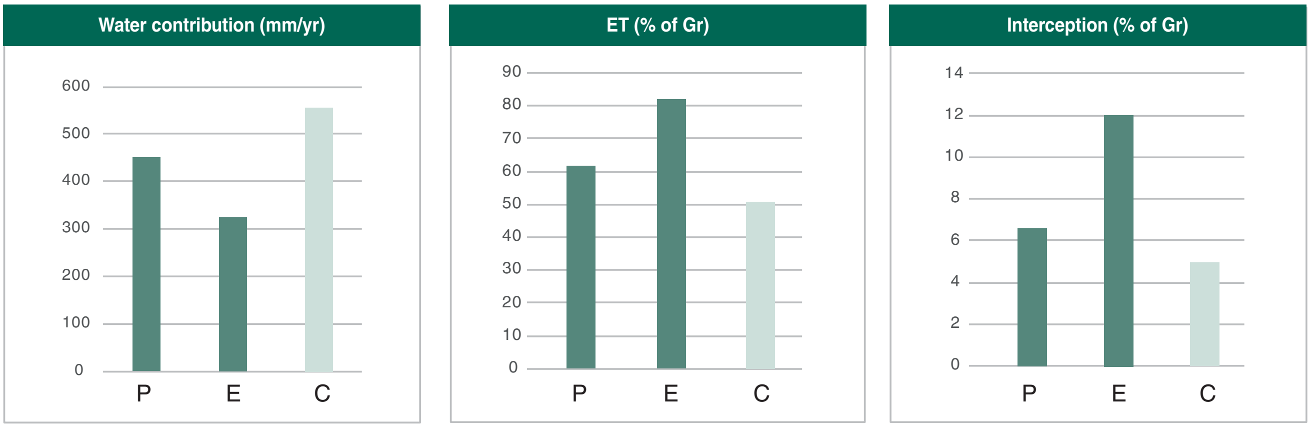
The Cerrado is the second-largest biome in Brazil, occupying 204 million ha (24 percent of the country's total land area); it is subject to considerable land-use pressure (Sano *et al*., 2019). Vegetation types vary along a regional climatic gradient depending on local soil and geographical characteristics and include dry forests, scrub woodland, open scrub (*sensu stricto* Cerrado) and grasslands. Annual precipitation is in the range of 1 200–1 800 mm, presenting high seasonality (with a six-month dry season) and the AI is slightly lower than 1. The predominant soils are deep, highly weathered and acidic, and they have low nutrient concentrations. Because nutrient deficiency can be corrected, and other soil characteristics are highly favourable, some lands in the Cerrado have been converted to agriculture; production is high when fertilizers are used. The Cerrado, therefore, has become one of the world's most threatened biodiversity hotspots (Klink and Machado, 2005).

The Cerrado concentrates the headwaters of rivers draining to the north, northeast, southeast and south of the country. The natural vegetation in the biome has low biomass density and low interception. This, added to the well-drained soils, means there is a hydric excess responsible for recharging aquifers and maintaining stream flows (Honda and Durigan, 2017). Degradation due to land-use change (mostly to agriculture) is altering this dynamic, however, leading to contaminated streams and reducing water availability.

The area of short-rotation forest plantations has increased in the region, with *Eucalyptus grandis* the most important species. The biomass of these forests increases rapidly, with the trees exploring water resources using their deep root systems and presenting high evapotranspiration, potentially altering the soil water balance. Lima *et al*. (1990) compared the soil water balance in Cerrado vegetation with *Pinus* and *Eucalyptus* plantations in northeastern Minas Gerais (Jequitinhonha Valley, annual precipitation = 1 121 mm) and showed that the conversion of natural Cerrado vegetation (36 m^3 per ha) to *Pinus caribaea* (210 m^3 per ha) and *Eucalyptus grandis* (366 m^3 per ha) increased interception losses by 74 mm per year for *Pinus* and 134 mm per year for *Eucalyptus* (Figure 4). The soil water balance decreased from 556 mm per year in natural Cerrado vegetation to 450 mm in *Pinus* and 326 mm in *Eucalyptus*. The reduction in water availability by plantations increases the effects of natural seasonality (i.e. lower availability during dry seasons) and reduces stream flows. In this case, forest management should be adjusted to water availability, such as by reducing the area of plantations, increasing rotation lengths (because water use declines with tree age; Perry and Jones, 2017), mixing stand ages (to create a mosaic), and reducing management intensity.

Another aspect under discussion regarding the Cerrado biome, mostly in protected areas and remaining fragments, is the reduction of fire – considered a natural element of Cerrado ecology (Durigan and Ratter, 2016) – brought about by a policy of fire suppression (Durigan and Ratter, 2016). Fire reduction is leading to an increase in vegetation biomass, which in turn results in higher interception and modified evapotranspiration dynamics (Passos *et al*., 2018), causing changes in the hydrological regime and in plant communities. Oliveira *et al*. (2017) monitored piezometric wells in various Cerrado vegetation types over a two-year period and showed that the increase in vegetation density reduced watertable recharge from 363 mm per year (grasslands) to 315 mm per year (Cerrado). Differences in evapotranspiration rates and soil water content were also observed among vegetation types (Miranda *et al*., 2003).

Land-use change in the Cerrado, and in other drylands worldwide, requires taking into account the hydrological constraints (made clear by the characteristics of the natural vegetation) to maintain hydrological processes and the provision of ecosystem services.



4
Comparison of plantations and natural Cerrado vegetation, Jequitinhonha Valley, Brazil
Note: Water contribution (mm/yr); evapotranspiration (% of gross precipitation – Gr); interception (% of Gr). C = Cerrado, E = *Eucalyptus*, P = *Pinus*.

CHALLENGES IN THE GOVERNANCE AND MANAGEMENT OF DRYLAND FORESTS AND AGROSILVOPASTORAL SYSTEMS

Water plays a fundamental role in socio-ecological resilience (Falkenmark, Wang-Erlandsson and Rockström, 2019), particularly in drylands. Forward-looking governance and management policies in dryland forests and agrosilvopastoral systems, therefore, need to consider water as a crucial supporting element for the production of goods and services, at least at the same level as biomass and carbon.

Water-oriented land management can contribute to several Sustainable Development Goals (SDGs), including SDG 2 (Zero hunger), SDG 6 (Clean water and sanitation) and SDG 15 (Life on land). But it is a highly complex challenge, with economic, social, environmental and climatic dimensions. The need for multiple goods and services increases the complexity of the challenge because their quantity, typology and valuation (in economic terms) vary with ecosystem type (La Notte *et al.,* 2015) and hamper the potential for a generalized approach applicable to all dryland forests and agrosilvopastoral systems. Also, many of the products produced in dryland forests and agrosilvopastoral systems are not clearly marketable, discouraging potential investment in management. Decision-support systems capable of handling complexity and multiple interactions, and which might encompass economic valuation (Tecle, Shrestha and Duckstein, 1998), present a potential means for negotiating the complexity of water-oriented land management in drylands.

The Cerrado, Brazil

CONCLUSION

The water-oriented management of dryland forests and agrosilvopastoral systems may increase water availability and therefore socio-ecological resilience. As the case studies presented above show, strategies such as canopy opening, pruning and species selection can be effective in combating water scarcity (by increasing soil and groundwater recharge) while also increasing climate-change resilience and adaptation. The optimum management intensities and strategies are likely to vary with ecosystem characteristics, even within the same catchment or region.

The need to provide multiple goods and ecosystem services increases the management challenge but also the potential benefits and therefore management possibilities. The complexity of multi-objective management approaches, and the ecological variability of dryland forests

A patch of Cerrado surrounded by farm fields on the access road to Caverna Aroe Jari, Mato Grosso, Brazil

and agrosilvopastoral systems, means that more effort is needed to quantify and value the goods and ecosystem services of dryland forests and agrosilvopastoral systems and to incorporate this information in management.

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