

REVIEW

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# Tropical dry forest dynamics in the context of climate change: syntheses of drivers, gaps, and management perspectives

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## Abstract

This review attempts to synthesize the available literature on tropical dry forests and their dynamics in the context of climate change and thereby identifies possible gaps and priority areas for further research and management endeavors. Tropical dry forests (TDFs) occur in dryland environments, which are characterized by prolonged periods of dry months. They experience distinct seasonality and high inter-annual variability in climatic variables, particularly rainfall. Despite the enormous ecological and livelihood importance of TDFs, these forests are highly threatened by global changes. So far, they have received far less attention from research and development interventions as compared to the humid tropical forests. Their significance is still overlooked in many countries' national policies. Current modeling frameworks show that drought, precipitation, and temperature are highlighted as strong drivers of tree growth and/or mortality in these forests. Well-valued and sustainably managed TDFs have the potential to contribute to climate change adaptation and mitigation, buffer against erosion and desertification, and contribute to economic development, food security, and poverty alleviation. TDFs suffer notable disregard from research and development strategies. Thus, greater awareness and appropriate policies and investments are needed at various levels to counteract the increasing vulnerability of people, forest ecosystems, and species living in these fragile ecosystems. Further research is also needed to generate knowledge on the status and significances of TDFs and their responses in the face of the changing climate so as to bring their sustainable management to the attention of policymakers and managers.

**Keywords:** Climate change, Dry forests, Forest management, Livelihood resilience, Threats

## Introduction

Tropical forests are a reservoir for about 25% of the global terrestrial carbon (Bonan 2008), thus play major roles in regulating regional and global climate dynamics (Lewis et al. 2009; Zhou et al. 2013). However, recent findings show that tropical forests are subject to huge losses and are becoming a source of carbon emissions to the atmosphere rather than carbon sink (Baccini et al. 2017). In general, tropical forests are facing greater risks

both from human-induced and natural factors. This is particularly true for tropical dry forests (TDFs), which are under severe upheavals due to man-made and natural factors. Accounting for the largest proportion (about 40%) of all tropical forests (Murphy and Lugo 1986; Miles et al. 2006), TDFs are reported to have substantial roles in climate mitigation and adaptation measures by significantly contributing to the global carbon stock, and supporting and regulating various ecosystem services (Djouidi et al. 2015; Sunderland et al. 2015). These ecosystems are known to harbor diverse and multifunctional landscapes and are inextricably linked to the lives of millions of people across the globe. TDFs are particularly vital for supporting vulnerable households at

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times of hardships (including those increasingly affected by climate change and variability) (Blackie et al. 2014).

Despite their vast ecological and socio-economic significances (e.g., Campbell et al. 1997; Cunningham et al. 2008), TDFs remain overlooked from research and development interventions as compared to their wet counterparts (Miles et al. 2006; Blackie et al. 2014; Bhadouria et al. 2016). On the other hand, TDFs are disappearing at alarming rates; they are receiving severe threats from the exceptionally high rates of changes in land use and climate. Although there is lack of comprehensive and reliable data on their rates of deforestation and dynamics in the context of climate change (Blackie et al. 2014), earlier studies reported that only less than 10% of mature dry forests are left in many areas (Murphy and Lugo 1986; Bullock et al. 1995). For long, TDFs did not receive sustained attention as that of the wet tropical forests despite the general notion that TDFs are under various threats (Gillespie et al. 2012). There is lack of pertinent literature on TDFs especially in regards to their dynamics in the face of the changing climate. Therefore, there is an urgent need to understand the dynamics of TDFs in relation to environmental variability, especially in the context of climatic variability (IPCC 2001; Aubry-Kientz et al. 2015; Bhadouria et al. 2016). In addition, the frequent changes in the drivers of deforestation and in the political, environmental, and socio-economic contexts call for urgent actions. On top of climate change, population explosion, food insecurity, and increasing demand for energy sources, and among others, are adding more pressures to these fragmented resources. This review is, thus, an attempt to provide further insights into the state of knowledge of tropical dry forests and their dynamics in the light of the changing climate, and thereby identify gaps and priority areas for further research and management activities.

### Approaches

In this review, a broader literature search of all available published and unpublished scientific reports was made to address different aspects of TDFs. Even though the review was performed considering studies published recently, given the scarcity of literature specific to TDFs, an attempt was made to exhaustively review available works spanning across a wider range of years. Then, study results that are related to the dynamics of dry forests in the tropics were systematically assessed, particularly in relation to climate change. The review process was further complemented by screening the references cited by the various publications obtained (by searching for books, journals, and grey literature on TDFs). The scientific internet searcher engines (e.g., using Web of Science journals) were used to search for the various scientific articles developed in the area of tropical dry

forests. Using systematic review methods, an attempt was made to synthesize a diverse range of evidence on a wide array of topics related to TDFs. The author also relied on own expert knowledge and experiences in identifying and synthesizing relevant articles. While assessing the current status of TDFs, focus was given to themes, such as drylands and climate variability, drivers of forest change, dry forests and livelihoods, climate change mitigation and adaptation, food security, demand for energy, sustainable management of dry forests, and policies and institutional support for sustainable management of these resources.

In this review paper, the author first presented a general overview of TDFs considering their concepts, extent, and significances for livelihood resilience and the environment. Based on a synthesis of the available empirical evidence, the conservation status and the main drivers and/or threats to these resources were evaluated, with particular focus to the climatic drivers which, directly or indirectly, might modulate the dynamics of these ecosystems. Next, concise discussions were made on possible management approaches and scenarios relevant for their sustainable management options. Finally, concluding remarks were provided by presenting a synthesis of gaps and thereby suggesting future works required to improve our understanding of the state of knowledge of TDFs, particularly in the face of the changing climate scenarios.

### Tropical dry forests: an overview

#### Conceptual frameworks

The concept of “dry forests” remained debatable (Miles et al. 2006; Blackie et al. 2014). This might be attributed to a number of factors. For long, the economic value of forests was perceived to be minimal unless they are logged or converted into agricultural lands (Godoy et al. 1993). Only few forest products (e.g., timber) were valued, while little attention was given to the other multiple benefits that forests can provide (e.g., NTFPs—non-timber forest products) (Campbell et al. 2002). Drylands are generally perceived as resource-poor areas and hence attracted fewer development endeavors (Lemenih and Teketay 2004). Earlier management plans were largely associated with management of the more bio-diverse tropical humid forests (Petheram et al. 2006). Thus, dryland resources (including dry forests) are still poorly known and have not attracted the same level of interest and investment as that of the humid tropical forests despite the encouraging initiatives these days (FAO 2015, 2016). As a consequence of this pervasive misconception, TDFs continued to degrade at higher rates. They are still among the least studied ecosystems and remain undervalued in many countries, and their importance is overlooked in many national policies and development programs (Woldeamanuel 2011).

Given the fact that there is lack of clear and comprehensive understanding of the general terms, *forests* and *drylands* (Chazdon et al. 2016), it is difficult to explicitly define dry forests. Even though there are some attempts (Table 1) to define dry forests, there is still lack of agreement in developing common understanding. It has been noted that this is a complex issue and requires a further comprehensive understanding of the complexity, status, and roles of drylands in general and dry forests in particular, as well as context-specific approaches tailored to the unique conditions of the dryland eco-regions that are needed (Blackie et al. 2014).

In order to assess the conservation status of forests in drylands, information is required on their distribution pattern and rate of change in the forest extent in relation to global environmental changes (Miles et al. 2006). Such assessments, in turn, require a clear definition of this vegetation type. Table 1 provides a summary of some of the common definitions of TDFs.

In the context of the future unprecedented climate change scenario, it would be difficult to define the biogeography of TDFs on the basis of their current state (Sunderland et al. 2015). As the climate becomes warmer and drier, the extent of dry forests may expand into areas currently occupied by humid tropical forests. On the other hand, areas considered as dry forests under current definitions may be changed into, for instance, savanna due to different disturbance factors. For instance, the Miombo woodlands in Africa and dry dipterocarp forests in Asia, which are currently classified as dry forests under the FAO definition, might be described as savanna ecosystems (Dexter et al. 2015; Lehmann et al. 2011).

Besides, the issue of what constitutes a dry forest may vary with different areas and contexts. For instance, Prance (2006) argues that there is co-existence and intermixing of TDFs and savannas; thus, it is useful to treat them together. But, the existence of dynamic yet changing processes (e.g., variations in soil, topography, and vegetation types), largely governed by climate, defines the balance between savanna, dry forest, and rainforest. Considerable variations in TDFs have also been observed in different localities and across continents in terms of floristic compositions (Dexter et al. 2015) and in terms of strategies employed to cope with water deficit conditions (Apgaua et al. 2015). Thus, there is still considerable work pending towards the development of global and ecologically cohesive characterization scheme for TDFs. These all discrepancies call for urgent action to clarify the concept and extent of dry forests under varied contexts, and thus improve the management and restoration of TDFs under the changing climate.

#### Distribution of TDFs

Accounting for nearly half of the world's tropical and sub-tropical forests, dry forests are generally distributed over an extensive geographical range, spanning large areas of Africa, Latin America, and the Asia Pacific (Miles et al. 2006). They are known to occur in an environment with a seasonal climate characterized by a prolonged period of dry months and with an inadequate amount of rainfall for tree ecological function (Murphy and Lugo 1995).

According to Miles et al. (2006), Latin America hosts about 54% of the TDFs. Similarly, FAO's (2012b) report

**Table 1** Some definitions/concepts of tropical dry forests provided by different authors

S/N	Definitions/concepts	Sources
1	In the simplest terms, TDFs may be defined as forests occurring in tropical regions characterized by pronounced seasonality in rainfall distribution, resulting in several months of drought.	Mooney et al. (1995)
2	Tropical dry forest, also known as seasonally dry tropical forest, can loosely be defined as forest in frost-free regions with 500–2000 mm of precipitation annually and a pronounced dry season of 4–7 months.	Walter (1971), Murphy and Lugo (1986), Miles et al. (2006)
3	FAO's definition describes TDFs as forests experiencing a tropical climate, with summer rains ... a dry period of 5 to 8 months [and] annual rainfall ranges from 500 to 1500 mm.	FAO (2001, 2012a)
4	Tropical dry forests are forest types that occur in an environment with a seasonal climate characterized by at least three dry months, and with an annual rainfall ranging from 250 mm to 2000 mm.	Menaut et al. (1995), Mayaux et al. (2005), Meir and Pennington (2011)
5	TDFs can be broadly defined as a vegetation type typically dominated by deciduous trees (at least 50% of trees present are drought deciduous), where the mean annual temperature is $\geq 25^{\circ}\text{C}$ , total annual precipitation ranges between 700 and 2000 mm, and there are three or more dry months every year (precipitation < 100 mm per month).	Sanchez-Azofeifa et al. (2005)
6	It should be noted that the inclusion of structural and/or functional component to the aforementioned definitions is important in distinguishing TDFs from the tropical savanna biomes, which otherwise share similar climatic conditions and vegetation structure particularly with degraded forests. Accordingly, TDFs, unlike the savanna biomes, are characterized by woody tall (> 10 m) vegetation with no C4 grass layer and have an intermediate shade-tolerant tree layer, commonly with a litter layer floor and occasional patches of herbaceous plants including C3 grasses.	Ratnam et al. (2011), Charles-Dominique et al. (2015)

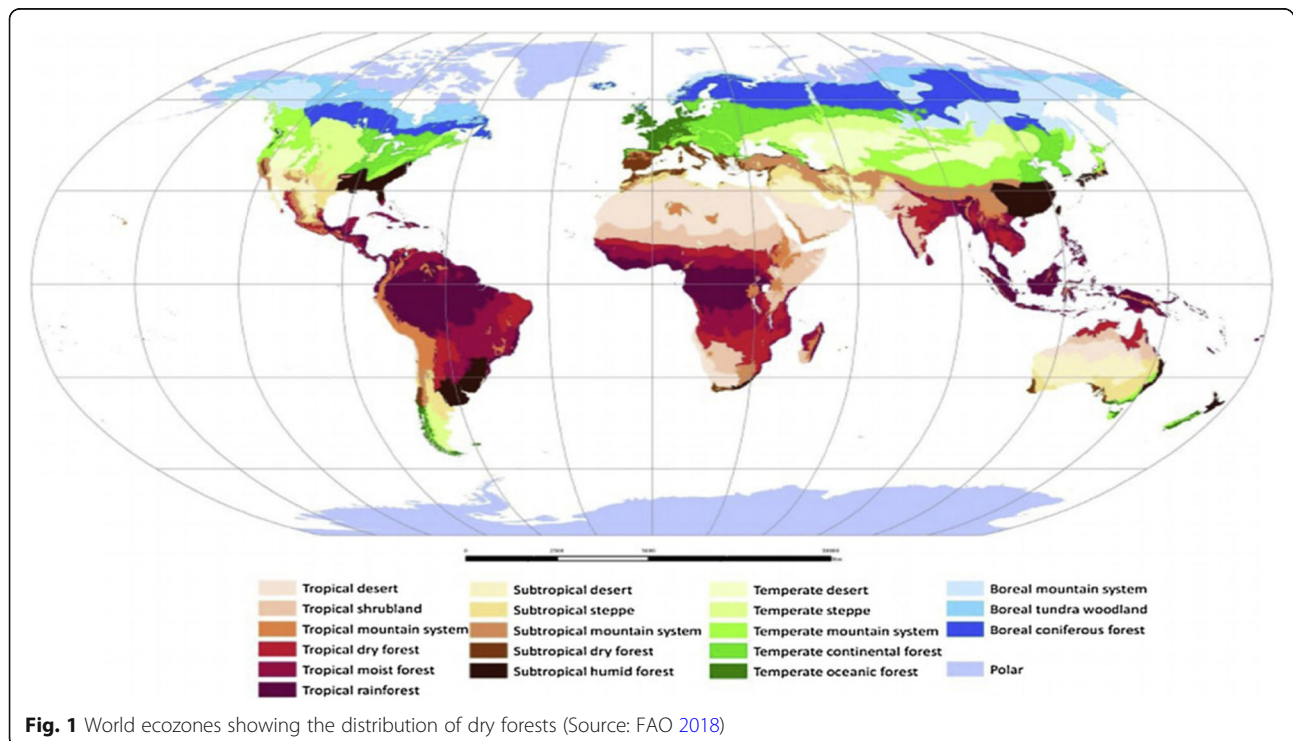
confirms that the largest areas of dry forests are found in South America, followed by Sub-Saharan Africa (SSA) and India. On the other hand, Mayaux et al. (2005) reported that Africa hosts the largest proportion (i.e., 59%) of the global tropical dry forests. Although updated figures on the extent of dry forests across different areas and scales are lacking, considerable concentrations are also found in Southeast Asia, Northern Australia, and parts of the Pacific, Central America, and the Caribbean.

These variations in the extent of TDF coverage worldwide may partly be attributed to the differences in methods employed for the assessment and also variations in the definition of dry forests (Mooney et al. 1995; Sánchez-Azofeifa and Portillo-Quintero 2011). The extent and distribution of dry forests are generally depicted in the following FAO's map of Global Ecological Zones (GEZ) (Fig. 1).

The graphic illustration shows the relative coverage of dry forests as compared to other ecological zones. While most extensive areas of TDFs are apparent in South America, in most other areas where these forests are found, they are distributed in a rather scattered or fragmented pattern. The same is true with dry forests in Africa, they cover an extensive geographical range, but without forming large continuous areas. In Africa, the two main centers where dry forests are located include (i) in western Ethiopia, southern Sudan, and the Central African Republic and (ii) in Zambia, Zimbabwe, and Mozambique (Miles et al. 2006).

### TDFs for livelihood resilience

Dry forests play a pivotal role in rural livelihoods, particularly for the forest-dependent poor. Their invaluable roles have been confirmed by many studies elsewhere (e.g., Shackleton et al. 2007; Cunningham et al. 2008; Waeber et al. 2012; Djoudi et al. 2015). In addition to their roles in maintaining resilient and multi-functional landscapes, dry forests and woodlands also contribute in the direct provision of various products, including timber and non-timber forest products (Sunderlin et al. 2005; Chidumayo and Gumbo 2010; Djoudi et al. 2015). These products are known to supplement livelihoods and contribute to poverty alleviation; especially, they play vital roles as safety-net during hardships when other economic activities are constrained by the frequent drought events. A wide variety of these products is collected either for household consumption or sold to generate a modest cash income. For instance, the African Miombo woodland was reported to support the livelihoods of about 100 million people (Campbell et al. 2007; Syampungani et al. 2009; Dewees et al. 2011; Ryan et al. 2016). According to Worku et al. (2014), income from the dry forest in the drylands of Southeastern Ethiopia constituted the second most important component of the total household income, next to the income from livestock. The same study revealed that income from the dry forest contributed up to 63% of the total income of the very poor households. They are also important sources of employment opportunities for local forest-



dependent people (Gebremeddhin 1997; Eshete et al. 2005). Several other studies (also see Table 2) elsewhere reported that many households earn a significant amount of income for their livelihoods from the dry forests and woodlands (e.g., Lemenih et al. 2003; Shackleton et al. 2008).

Furthermore, TDFs significantly contribute to the economy of nations, particularly in the developing world (Lemenih and Teketay 2003; Sunderland and Ndoye 2004; Chikamai et al. 2009). The existence of such vegetation resources in the drier regions is important in maintaining resilient landscapes in the face of shocks through the provision of many ecosystem services (ES), including watershed protection, soil amelioration, and drought mitigation. This, in turn, supports agricultural systems upon which millions of subsistence farmers depend (Chidumayo and Gumbo 2010). In general, these myriad ES offered by TDFs can be categorized as provisioning (food, water, timber, biofuels, and fiber), regulating (air quality, water availability, carbon sequestration, nutrient cycling, and soil erosion regulation), supporting (maintenance of genetic diversity and habitat for species), and cultural (recreation, tourism) services (Chidumayo and Gumbo 2010; Ryan et al. 2016; Andrade et al. 2020).

The economic importance of dry forests is, however, being recognized very recently, and their marketing system is not yet well developed (e.g., Lemenih et al. 2003; Worku 2006; Shackleton et al. 2008; Paumgarten and Shackleton 2009). Given that the majority of forest users extract products mainly for subsistence and an important part of the trade happens informally (Shackleton et al. 2007; Jumbe et al. 2008), the contribution of dry

forests to the formal gross domestic product remains relatively low in many dry forest countries (Kalame et al. 2009). Therefore, further research and development endeavors need to be undertaken in various drylands of the tropics to show their values and thereby call upon the promotion of sustainable management of dry forests for integrated livelihood adaptation, biodiversity conservation, and combating desertification.

### Threats to and conservation status of TDFs

Despite their extensive coverage and manifold significances, TDFs are currently facing severe upheavals from global changes. The threats to dry forests and woodlands are multiple and complex, largely emanating from the interplay of anthropogenic and natural factors. These threats include pressures from agricultural encroachment, climate change, fire, overgrazing, and population explosion (Miles et al. 2006; Abiyu et al. 2010; Chidumayo and Marunda 2010; Wright 2010; Sánchez-Azofeifa and Portillo-Quintero 2011). It has been reported that about 95% of the TDFs are threatened by one or a combination of these factors (Miles et al. 2006), and conversion to other land use (mainly agriculture) remains the major threat to TDFs, particularly in the drylands of Sub-Saharan Africa (SSA) (Timberlake et al. 2010). TDFs are continuously deforested to meet the increasing energy demands. In the absence of viable modern energy source, reliance on traditional energy sources (firewood, charcoal, and organic wastes) will remain high in the majority of dryforest and woodland countries (Malimbwi et al. 2010). This energy crisis is therefore expected to continue adding more pressures on the remnant dry forest resources in these regions.

Drylands, in general, cover extensive areas (about 41% of the earth's surface) and are home to more than 2.5 billion people (Mortimore, 2009). A greater portion (about 72%) of the global drylands is found within developing countries (MEA (Millennium Ecosystem Assessment), 2005). A greater density of human population was reported in these ecosystems due to a relatively suitable climate and soils that can support agriculture (Sánchez-Azofeifa and Portillo-Quintero 2011). Consequently, the largest threats are still expected to emanate from anthropogenic fire, overgrazing, and ill-informed agricultural expansions (Hayden and Greene 2009). Billions of people farm for survival and degrade these environments, and this is expected to get worse with global climate change and population growth. Increased fire risks are also expected with the increasing scenario of warming and drying (Timberlake et al. 2010; Meir and Pennington 2011) coupled with increased fuel loads (Golding and Betts 2008) due to higher degradation rates in the dry tropical areas (Mayaux et al. 2005; Chidumayo and Marunda 2010). Nevertheless, studies that integrate the

**Table 2** Contributions of TDFs to household income, examples from selected case studies

Country	Contributions of dry forest products to household income	Sources
Botswana	20%	Chipeta and Kowero (2004)
Ethiopia	20–63%	Abteu et al. (2014); Lemenih et al. (2003); Yemiru et al. (2010); Worku et al. (2014); Ermias et al. (2014)
India	> 50%	Belcher et al. (2015)
Malawi	40%	Fisher (2004)
Nigeria	20–60%	Suleiman et al. (2017)
South Africa	19–95%	Clarke et al. (1996); Campbell et al. (2004); Dovie (2004); Shackleton and Gumbo (2010)
South Sudan	20–65%	WFP (World Food Programme) (2013); Adams et al. (2014)
Tanzania	70%	Makonda and Gillah (2007)
Zimbabwe	15–20%	Cavendish (2000)
Zambia	21%	Jumbe et al. (2008)

effects of land use change, fire, and climate change are still lacking in these ecosystems (Meir and Pennington 2011).

The climate-induced impacts are even worse in drylands of developing countries with a large number of forest-dependent populations, such as the SSA. Dryland resources (especially the dry forests) in these regions are among the most exploited systems and are being transformed to agricultural lands at an alarming rate (Bongers and Tennigkeit 2010). The forest resources in these areas are facing high rates of degradation and deforestation (DD) due to the above-mentioned factors (Hosonuma et al. 2012; Rudel 2013). Inhabitants of these areas are generally poor; in the absence of other livelihood options, they often overexploit the remnant resources. The decreased rainfall and recurrent drought events are also expected to further exacerbate the current exploitation levels, thus resulting in more pressures on the remnant vegetation resources or total conversion to persistent agricultural lands. This would, in turn, impose additional stresses on the inhabitants whose livelihood is dependent on products (e.g., NTFPs) gathered from the dry forests. Under such circumstances, if immediate interventions are not taken to reverse the situation, the dry forest fragments would enter a state of total depletion with far-reaching consequences to the more fragile ecosystems and people's livelihood in the foreseeable future.

In general, it is evident that TDFs are threatened globally (Stern et al. 2002; Miles et al. 2006; Chidumayo and Marunda 2010) and will continue to face tremendous challenges as they are not receiving the attention they deserve from research and management interventions (Blackie et al. 2014; Bhadouria et al. 2016). Consequently, they are caught in a spiral of deforestation, fragmentation, degradation, and desertification (FAO 2010). Projections also show that these ecosystems may even be at greater risk than humid forests (Portillo-Quintero and Sánchez-Azofeifa 2010; Aide et al. 2012; Gillespie et al. 2012). Figure 3 tries to demonstrate the current ecological scenario of tropical dry forest ecosystems, along with the major disturbances. As illustrated in Fig. 3, TDFs are exposed to various threats, largely resulting from anthropogenic activities. Climate change is also a huge concern in the drylands; it is expected to worsen degradation caused by human-induced activities. Reports show that climate-related changes will continue adding further stress to these fragile ecosystems, with significant implications on the lives of billions of people (Corlett 2011; Feeley et al. 2012). This urges for management measures to reduce their vulnerability and facilitate their adaptation to climate change.

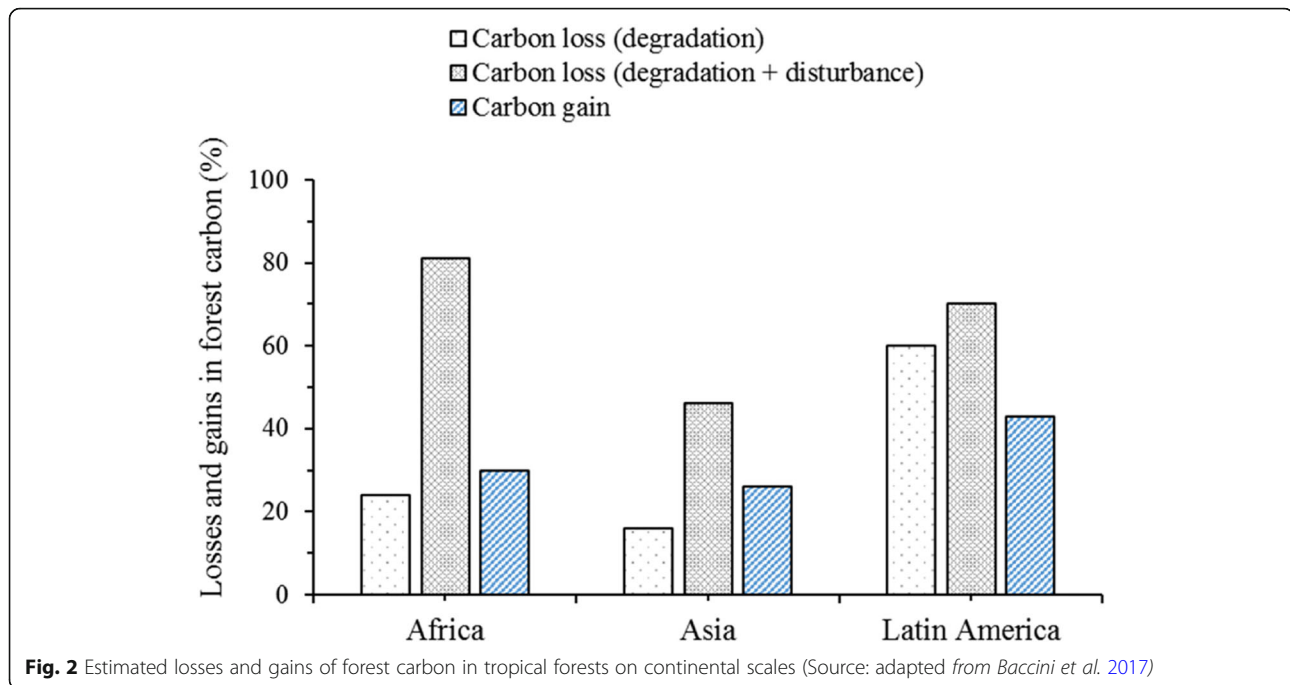
### **Climate change and TDFs dynamics**

Tropical forests play a vital role in regulating the global climate by capturing large amounts of carbon (Bonan 2008). However, there are emerging controversies whether

tropical forests are still significant contributors to the terrestrial carbon balance. TDFs, in particular, are at greater risk globally, mainly due to threats from a combination of climatic changes (global warming) and human-induced land use changes. In view of this, researchers recently revealed that deforestation is more responsible for the loss of dry forests than predicted impacts by climate change (Baccini et al. 2017; Manchego et al. 2017). Accordingly, the potential of tropical forests in sequestering carbon is being negated by forest degradation. According to Baccini et al. (2017), tropical forests are rather becoming net contributors (source) of carbon emitted to the atmosphere than storage (sink). Unlike previous studies, which relied largely on deforestation to estimate forest carbon losses, the current study (Baccini et al. 2017) considered changes attributed to subtle natural and human-induced losses (e.g., degradation and disturbances) to estimate carbon losses. This shows the attempts being made to account for the possible forest losses emanating from both degradation and disturbances (human-induced and natural). Manchego et al. (2017) also compared the relative impact of climate change and deforestation on tropical dry forests and found out that the impact of deforestation is significantly higher than those attributed to climate change. These emerging results highlight the need to account for changes in disturbance factors as well when dealing with the interactions between these factors and climate change.

McNicol et al. (2018) also reported higher estimates of carbon losses than the previously thought when the biomass and carbon losses due to degradation and deforestation that were accounted for. Even though the high rates of degradation and deforestation in these regions are significant contributors for the carbon losses, biomass gains were also reported due to re-growth of the woodlands, offsetting the carbon losses from deforestation and degradation. Thus, the dynamics and uncertainties in the carbon stock fluxes and the extent of deforestation, degradation, and vegetation re-growth need to be substantiated by providing further evidence (McNicol et al. 2018). The magnitude of losses and gains of forest carbon may vary considerably across the tropical regions, implying that similar studies should be carried out across varied geographic ranges before provision of concrete conclusions. The following figure (Fig. 2) tries to demonstrate these variations on a continental basis.

Even though the effects of anthropogenic disturbances seem to outweigh the climate-induced impacts, projections into future scenario also show serious repercussions of climate change in the dry tropics (Serdeczny et al. 2016). Therefore, climate, besides the human-induced land use changes, will continue to play an important role in the dynamics of dryland systems (Olson et al. 2004; Bongers and Tennigkeit 2010). The effects



from climate change are expected to be even pronounced in the SSA and related dry tropical regions in particular given their high sensitivity to the climate anomalies, such as frequent occurrences of extreme heat, increasing aridity, and erratic rainfall patterns. Climate change may directly affect the growth and population dynamics of trees growing in drylands (e.g., Bogino et al. 2009; Scheiter and Higgins 2009), mainly through variations in rainfall and temperature regimes (Chidumayo and Marunda 2010). The variations in rainfall and temperature regimes are expected to influence tree growth, leaf phenology, and survivorship through their impacts on photosynthesis, respiration, and nutrient dynamics (Wright 2010; Feeley et al. 2012). Allen et al. (2017) have also confirmed the sensitivity of TDFs to the predicted changes in rainfall regimes across the dry tropical regions.

On the other hand, constituents of TDFs are known to have peculiar structural and functional traits that enable them to sustain under various disturbance levels. Evidences show that TDFs are especially resilient to specific disturbances, mainly to seasonal water deficits and forest fires (Pulla et al. 2015). Under seasonal water deficit conditions, plants either tolerate drought or avoid drought by, for example, dropping leaves and thus limit transpiration during the dry season, to survive these dry environments. However, in certain areas, for instance, in the African dry woodlands, rainfall intensity and frequency may vary considerably within the short-wet season itself, implying that even the deciduous trees may face drought stress (Murphy and Lugo 1995; Bullock

et al. 1995). Such strong variability in rainfall and the existence of extended dry spells (water stress) have significant effects on the annual carbon gain and allocation patterns of plants challenging their survival in the dryland systems (Mengistu 2011). Thus, the future of these ecosystems remains uncertain in the backgrounds of the changing climate and its complex interactions with various disturbance factors (both human-induced and natural factors).

According to the predictions of the Intergovernmental Panel on Climate Change (IPCC), the climate in the tropics and sub-tropics will get warmer and drier, with some exceptions in East Africa, the Sahel, the Guinean coast, and southern Sahara where there is a likelihood of increment in rainfall, but with high level of uncertainty (IPCC 2007). This will likely result in various drastic transformations, including losses of biodiversity components, species range shifts, altered tree productivity, and an overall extinction risks to the already endangered species living in the highly fragmented environments (FAO 2010; Feeley et al. 2012; Yin et al. 2018). There may also be many unknown consequences associated with such changes (Manchego et al. 2017). This will possibly alter the balance and functioning of the ecosystem, with subsequent negative impacts on the livelihoods of the forest-dependent people.

Even though it is generally stated that TDFs are facing severe threats from climate change, we found no agreement on this claim; persistent uncertainties are still prevailing in these regions as far as impacts from climate change are concerned. Some studies (e.g., Cox et al.

2004; Feeley et al. 2007; Battles et al. 2008; Allen et al. 2010; Poulter et al. 2010; Midgley and Thuiller 2011; Yin et al. 2018) reported increased climate-induced tree mortality or decline in productivity owing to the repeated incidences in extreme droughts and temperatures. Others (e.g., Sabaté et al., 2002; Herrmann et al. 2005; Ow et al. 2008; McMahon et al., 2010; Wigley et al. 2010; Dong et al. 2012; Higgins and Scheiter 2012) claimed positive feedbacks on tree growth and vegetation cover favored by the elevated atmospheric CO<sub>2</sub> concentrations. Such variations may be attributed to differences in methods employed during estimations (Zhou et al. 2013). The response of trees to changes in climate variables is also both species—and site-specific (Enquist and Leffler 2001; Worbes 2002; Couralet et al. 2010; Corlett 2011). More specifically, it can be attributed to factors related to species genetic diversity, interactions with other human-induced disturbances, such as insect outbreaks and wildfires (Cunningham and Read 2003; Poulter et al. 2010; Good et al. 2011; Feeley et al. 2012) and other agro-ecological variability, including local differences in climate variables, soil texture, and nutrient availability (Bazzaz and Fajer 1992; Diaz et al. 1993; Lo et al. 2010; Timberlake et al. 2010). These contradicting evidence signals a pressing need to better understand the changes and/or dynamics in the tropical forest systems, particularly that of the dry forests.

In general, the impacts from climate change may vary from positive to negative according to regions; climate change may increase tree productivity in some areas while decreasing it elsewhere (Shugart et al. 2003; Sedjo 2010). Sleen et al. (2014) also confirm that there is no concrete evidence for consistent long-term growth stimulation of tropical tree growth induced by CO<sub>2</sub> fertilization, but witnessed an increase in water-use efficiency. Predicting the consequences of climate change on tropical dry forests has, thus, emerged as one of the grand challenges for global change scientists. If the responses and feedbacks of tropical forests to climate change are not adequately addressed, it is difficult to gauge myriad mitigation strategies and to develop adaptive approaches to alleviate climate change damages. It is important to understand the potential response of tree species from the TDF ecosystems to the anticipated changes in climate (Wright 2010; Corlett 2011; Dong et al. 2012). In general, in the context of climate change, identifying and predicting the impacts of climatic drivers on tropical forest dynamics are becoming a matter of urgency (Aubry-Kientz et al. 2015). In order to fully understand the impacts of climate change, we need to address the interactions and/or feedbacks from both climate-induced effects and other disturbance factors at different levels. Recent evidence shows that the inclusion of disturbance factors while modeling climate-induced effects

may elevate estimates of productivity losses or cancel out productivity gains attributed to climate change (Reyer et al. 2017). On the contrary, the same study also reported few cases of higher productivities in the presence of disturbance factors. Therefore, in order to plan adaptation measures, it is vital to properly address such discrepancies by replicating similar studies across different geographic scales.

### **Managing dry forests under a changing climate**

There exist a broad range of ecological, economic, and cultural reasons that underlie the need for backing sustainable management of dry forests and woodlands. Under the harsh and changing climatic conditions, the presence of such vegetation resources in drylands provides viable livelihood diversification options (Chidumayo and Gumbo 2010). Dry forests are endowed with diverse vegetation types that have the ability to produce various NTFPs during dry seasons even when other dominant economic activities are constrained by frequent drought. The non-destructive nature of NTFPs extraction also adds a conservation benefit for these ecosystems (Lemenih et al. 2003). In addition to the roles in sustaining the lives of millions of vulnerable households, TDFs have a huge potential in capturing large amounts of carbon, maintaining diverse and resilient landscapes, and water conservation (Portillo-Quintero et al. 2015). Therefore, their sustainable management would mean a lot for the local communities, national economies, and the environment at large. That is, if well-valued and sustainably managed, TDFs have the potential to contribute to climate change adaptation and mitigation, buffer against erosion, and desertification, and contribute to economic development, food security, and poverty alleviation.

The sustainable utilization of forest products and services is closely attached to how successful a country manages its forest resources (dry forests in this particular case). Nevertheless, in spite of significant contributions of the dry forests in the drier part of tropical regions, only a few countries, if any, are making adequate investment in their management. There is a general lack of laws and regulations and/or their enforcement, absence of programs, and political commitment to encourage the participation of stakeholders, especially the private sector and local communities, in the sustainable management of these resources (Malimbwi et al. 2010). This has often been attributed to the lack of appropriate institutional arrangements and policies that regulate the use and management of the resources (Chidumayo and Gumbo 2010).

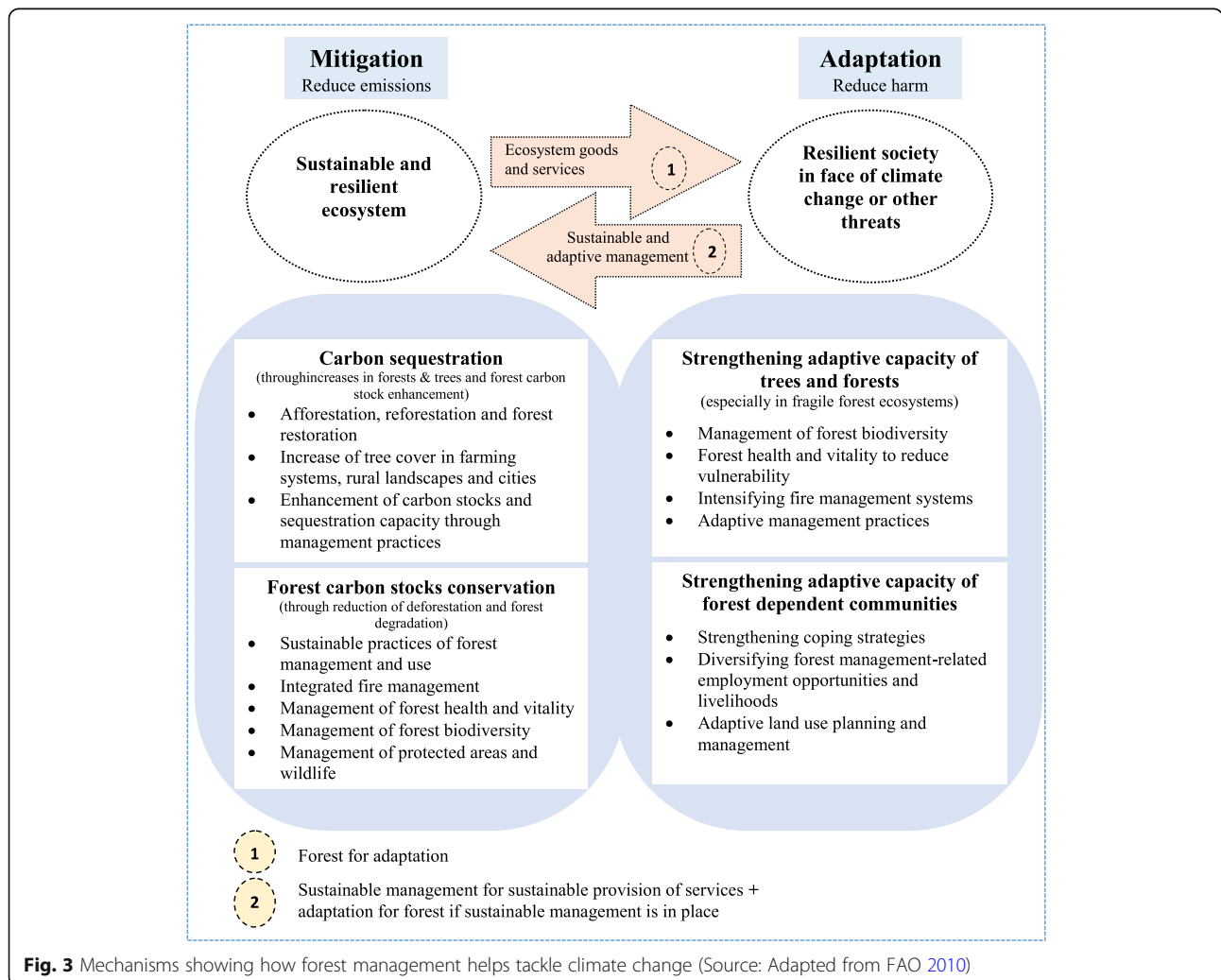
According to FAO's (2005) report, a successful forest management deals with both technical (silvicultural activities) and social aspects (policy/legal, administrative and economic) of forests and aims at keeping a balance between consumption and conservation, i.e., sustaining the resource base while supporting livelihood and providing



services. Thus, sustainable forest management (SFM) is all about maintaining and enhancing long-term health of forest ecosystems, while providing economic, social, and cultural opportunities for the benefit of present and future generations. The concept of SFM considers ecological, economic, and social aspects, aiming for development by acknowledging their interplay (FAO 2010). To ensure SFM, there is an urgent need to address the agents responsible for degradation with the corresponding undesirable consequences. This, in turn, requires appropriate and timely interventions from all stakeholders before the damage to the remnant dryland resources proceeds beyond the possibility of their rehabilitation. In view of this, there is urgent need for multi-disciplinary research and conservation programs tailored towards TDF conservation and/or sustainable management at various levels, from local to continental scales.

In general, SFM has been reported to be a viable framework for simultaneously reducing carbon emissions, sequestering carbon, and enhancing adaptation to

climate change. In addition, it helps to supply various forest products, protect biodiversity, secure fresh water supplies, and provide other manifold ecosystem services. Figure 3 illustrates the mechanisms (including the measures to be taken and the benefits to be shared) how SFM can provide an effective framework for forest-based climate change mitigation and adaptation. Likewise, the management of TDFs should be handled within the umbrella of sustainable forest management. Proper management of dry forests can both maximize their contribution to climate change mitigation and enhances their environmental, socio-cultural, and economic functions, thereby helping the forest-dependent people adapt to new conditions caused by climate change. Therefore, if dry forests are to continue to play their multi-functional role, their management needs to take climate change scenarios into account and the improved forest management practices should be planned and implemented in an integrated fashion as suggested in FAO (2010). Managers need to plan to build resilient dryland forest ecosystems. Greater awareness and appropriate policies and



**Fig. 3** Mechanisms showing how forest management helps tackle climate change (Source: Adapted from FAO 2010)

investments are needed at country, regional, and global levels to counteract the increasing vulnerability of people, forest ecosystems, and species living in these fragile ecosystems. In view of this framework, new research approaches need to be proposed for studying the links between tropical forests and environmental changes, and thereby improve predictions of tropical forest responses to global changes, with particular focus to the undervalued TDFs. But, since the continued loss of TDFs is caused by a complex set of drivers at various levels, actions targeting at reversing this trend need to account for the complexity of the various driving forces.

According to Lehtikoinen (2014), the DPSIR (drivers, pressures, state, impacts, and responses) framework is the essential ecosystem-based approach for environmental management analysis. This framework can be adopted for the sustainable management of TDF ecosystems as well. The DPSIR framework could help map the complex picture of issues linked to the system (which combines the identified components) and make the complexity more understandable and manageable. This needs to be complemented by defining concrete and potential policy recommendations (the “responses” in the DPSIR framework) to help tackle the different problems.

Despite TDFs offering a wide range of benefits to the poor, the various environmental changes occurring in the dry forest regions are likely to alter the growth rates of the flora, impacting species composition and productivity. Some of the potential major environmental changes in the region include changes in amount and seasonality of rainfall, rising concentrations of atmospheric CO<sub>2</sub>, rising temperatures, and altered fire and other disturbance regimes. These changes will result in adverse impacts on TDF biodiversity, carbon sequestration and storage, and other ecosystem services, and thus there is a dire need to understand how these changes will alter the ES that support the livelihoods of the poor (Chidumayo and Gumbo 2010; Ryan et al. 2016).

TDF ecosystems are characterized by extended water deficit conditions. Besides, the high variability of rainfall together with the increasing temperatures, evaporation, and evapotranspiration rates result in reduced ecosystem productivity in these regions. Thus, management activities should concentrate on conservation and restoration of the remnant vegetation to effectively use the scarce water resources. The resilience and continuous provision of ecosystem services of TDFs in the face of the changing climate can be improved by adopting best management practices—practices that help reduce soil erosion, increase soil moisture and carbon content, and biomass production. For instance, Andrade et al. (2020) suggested that TDFs need to be thinned to improve the resilience of their ecosystem services to climate change as vegetation thinning promotes underbrush development

which increases water retention and carbon storage of the soil, among others. Other various soil and water conservation techniques and vegetation management activities have been suggested to enhance TDF resilience to climate change.

Nevertheless, the management interventions should be carefully applied for different ecosystem types. There are always trade-offs among different management interventions and ecosystem services. For instance, in savanna ecosystems, given that water is seasonally scarce resource, an increase in tree biomass with woody encroachment or afforestation may threaten ecosystem services related to water resources, posing an indirect effect on ecosystem functioning and biodiversity. However, such management interventions may have positive effect on carbon sequestration whilst negatively affecting the water provisioning (Honda and Durigan 2016). To address such conflicts, it is important to adopt specific management practices for specific ecosystem types. Management interventions, such as prescribed burning, maintaining historical vegetation structure through avoiding woody encroachment/afforestation are among the recommended strategies to maintain the hydrological regimes and associated ecosystem functioning in savanna ecosystems where water is a key determining factor. Nevertheless, this may not be the case in other forested ecosystems where there is a relatively conducive soil and climatic conditions. While fire is the most relevant disturbance conditioning the existence of savannas and grasslands in most regions of the world (Honda and Durigan 2016), tropical dry forests should be protected from fire as the flora is not adapted to fire (Dexter et al. 2018), and limited post-fire recovery has been reported for TDFs as compared to the dry savanna biomes (Ratnam et al. 2011).

Relying only on structural and climatic definitions of TDFs leads to inappropriate management policies and practices. For instance, misclassifying savanna as dry forests would mean support for afforestation and fire suppression policies which may compromise the unique biodiversity and ecosystem functioning in savannas. On the other hand, misclassifying degraded forests as savanna (e.g., the dry forests of Latin America which lack adequate protected areas) can equally hamper their conservation goals (Banda-R 2016). Thus, when recommending best management practices for a particular biome, we should first carefully identify and classify the type and unique attributes of the biome as conservation goals that differ significantly with biomes. In this regard, we need an improved understanding of the savanna-forest dynamics and their responses and feedback mechanisms to various disturbance regimes and environmental controls (Hoffmann et al. 2012). Without such information, it is difficult to properly project the distribution and extent of TDFs under the changing climate, and thereby recommend appropriate management interventions.

In general, as it stands, we are now at a critical moment as far as the conservation status of TDFs is concerned owing to the enormous threats (both proximate and underlying drivers) from human-induced factors coupled with impacts from climate change. Overcoming the challenges calls for improvements in our knowledge tailored towards producing and sustaining their diversity and predicts how these ecosystems will respond to emerging (man-made and natural) global changes. The various challenges facing the dry tropical regions can only be tackled by preparing and implementing appropriate management plans that can ensure the development, sustainable utilization, and conservation of the resources, in addition to addressing the various causes and consequences of deforestation and degradation (DD). In conclusion, political decisions are among the main underlying forces that affect the management of TDFs. Therefore, political frameworks and policy arrangements should focus increasingly on reducing the pressure on these resources while integrating recommendations made by scientists and researchers. These recommendations should also help politicians to become more aware of the role of policy as a factor in the conservation of dry forests. To achieve this, more emphasis needs to be placed on the economic, cultural, and intangible resources provided by these resources.

### Gap analyses and the way forward

As discussed earlier in this review, existing evidence shows that the future of TDFs is highly uncertain as they continue to face mounting threats. The impacts of climate change and anthropogenic activities are reinforcing each other. While they are expected to strongly be vulnerable to the changing patterns and amounts in rainfall, a huge impact is still anticipated from the inappropriate use of these remnant resources. Hence, there is a dire need to fill the gaps through the provision of baseline information addressing different aspects of TDFs across varied geographic scales, to generate knowledge and thereby inform global, regional, and national policy processes regarding TDFs. Underpinning the REDD+ programme, there is a need to capitalize on measures aimed at curbing deforestation and forest degradation (DD) and intensify afforestation and reforestation activities. Albeit its potential across dryland regions remains insufficiently explored, and evidence from climate models (GCM) showed that afforestation is a viable approach to enhance precipitation and mitigate global warming in semi-arid regions, and thus is expected to be effective across the dry tropical regions (Yosef et al. 2018). However, its complex interactions with the climate system make it controversial.

In general, analysis of the state of knowledge on TDFs suggests the existence of considerable gaps and inconsistencies. These various gaps can fall into conceptual,

methodological, and empirical gaps. Firstly, drylands in general and TDFs in particular lack reliable and consistent definitions, and there has been a pervasive misconception that rated these areas as resource-poor areas and less attractive for development. Besides, there is lack of appropriate approaches that can facilitate long-term climate-vegetation dynamics in the dry tropics. Hence, there is a need to work on methods and tools that can help us understand the long-term relationship between climatic conditions and tree growth and forest dynamics in the dry tropics, and thereby enabling the development of models that help estimate carbon sequestration and forest yield. In this regard, however, there are already encouraging initiatives in the tropics which employed tree-ring analysis to quantify the long-term growth dynamics of tropical trees in response to climate change even though it is far from complete. There are also prospects of integrating tree-ring analysis with other approaches, such as remote sensing, to better understand the dynamics of tropical dry forests in the context of climate changes (Wang et al. 2004; Southworth et al. 2013). However, such approaches (i.e., the integration of tree-ring studies and remote sensing) need to be replicated and tested across different regions. Even the existing limited studies show contradicting results. Some scholars argued that climate change may increase tree productivity in some areas (due to CO<sub>2</sub> fertilization effect), while others found a decreasing trend elsewhere, implying that the impacts may vary from positive to negative according to regions. This contradicting evidence is indications for a pressing need to better understand the dynamics of the dryland forest systems.

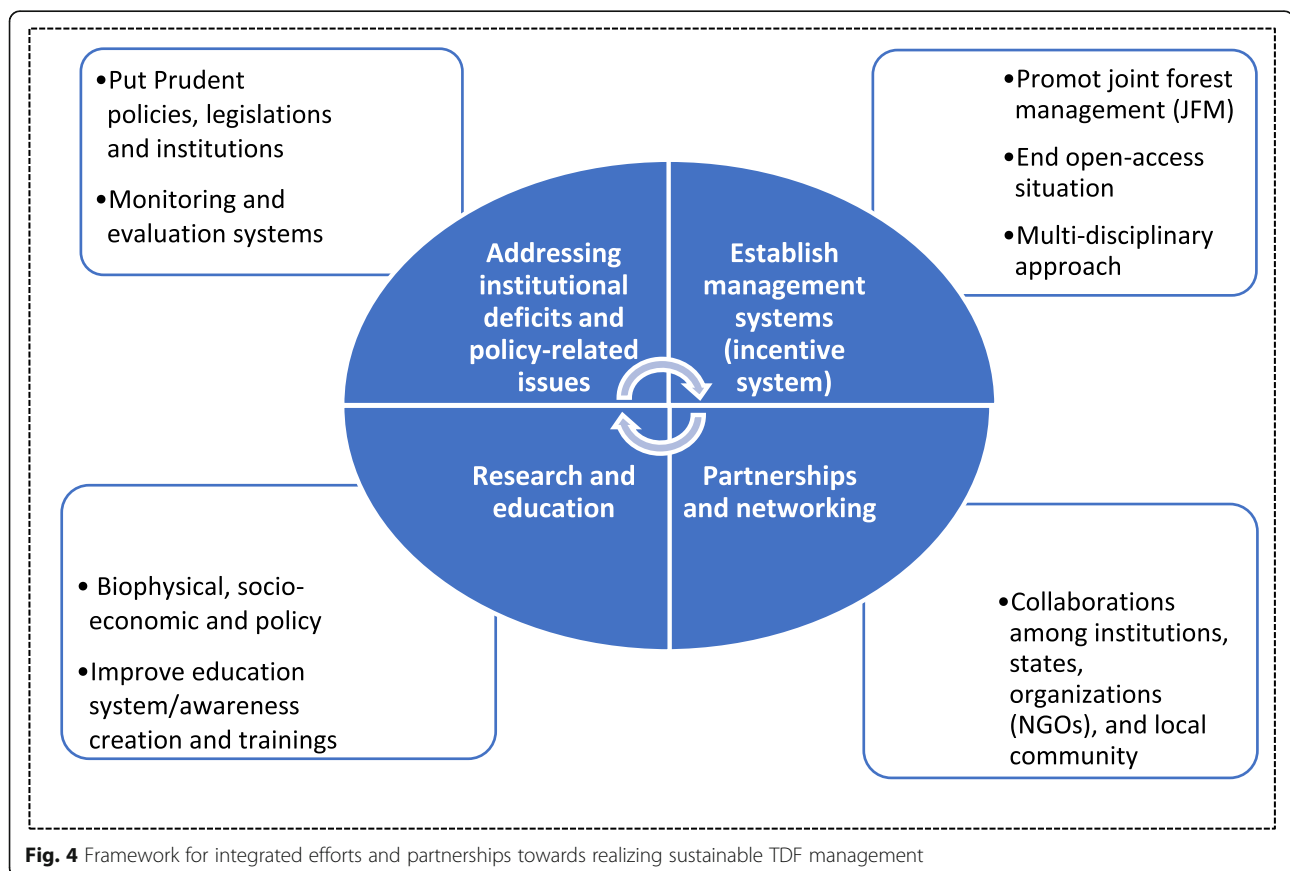
There are still empirical gaps and uncertainties on the long-term potential responses of dryland tree species to the anticipated changes in climate and their potential interactions with other, largely anthropogenic, drivers (Pulla et al. 2015; Reyer et al. 2017). Besides, there is only limited understanding of the extent, distribution, conservation status and productivity of TDF ecosystems, and their associated services (Maass et al. 2005). Recent findings showed that changes in atmospheric CO<sub>2</sub> and temperature, and changes in total and seasonal precipitation, can have reinforcing or canceling effects on the physiology of TDF plants, leading to changes in their growth, survival, and reproductive output (Pulla et al. 2015). Thus, studies should pay attention to eco-physiological aspects, phenological responses, climate change-driven changes in the ecosystem and ecosystem services, degradation of TDFs and implications for the ecosystem and ecosystem services, and effects from various drivers. Further research is needed to quantify the contribution of dry forests on people's livelihoods and to develop options that will guide the policy-making process to generate additional economic incentives for

communities and countries to be engaged in sustainable management and use of dry forests (Worku et al. 2014). This urges for more regional and landscape-specific studies to understand the dynamics of TDFs and their responses to various disturbances. In doing so, more focus should be given to areas previously unexplored, especially to the Asian and African dry forests, to fill the geographical gaps in the prevailing evidence (Derroire et al. 2016). Such studies are reported to be important in designing strategies aimed at the restoration and conservation of these important and threatened forests (Ceccon et al. 2014).

Another grim reality regarding TDFs is that they remained in an open-access situation, with large tracts of land being under state-ownership, making it difficult to put a thriving forest management system by state agencies alone. Under such circumstances (i.e., forest governance crisis), forest products are being extracted recklessly. Sustainable forest management by its nature presumes clear and secure long-term tenure (property rights). Bromley (1991) also confirmed that most environmental problems arise due to problems associated with property rights. This necessitates the need to establish an incentive system for dry forests where different stakeholders (state, community, private individuals) share management and ownership

responsibilities as well as benefits. This all has to be supported by creating awareness among the wider community and by formulating appropriate policies and institutional frameworks (Fig. 4). Creating partnerships among various stakeholders on a participatory basis is, thus, a viable option to ensure sustainable management of dry forests and woodlands.

Each of the stakeholders could play significant roles in addressing, directly or indirectly, the causes and consequences of DD as well as unforeseen challenges in future dryland forest management endeavors. There are already evidences on initial success stories of joint forest management (JFM) approaches in saving the remnant dry forests and woodlands in Africa (e.g., Lemenih and Bekele 2008; Blomley 2013; Siraj et al. 2016). Therefore, the multidisciplinary approach remains a viable option to solve the multi-dimensional and heterogeneous dryland forest problems, i.e., integrated approach combining components focusing on sector development and those targeting on specific areas (Fig. 4). Organizations such as research and education, and similar GOs and NGOs should contribute towards research and formulation of prudent policies and laws targeting TDFs. However, as stated in Bekele and Girmay (2014), promulgating prudent policies alone cannot be a solution for every



problem; governments should also be keen in recognizing dry forests as a viable livelihood option and invest in their sustainable management. To win the attention of policymakers and development agents, it requires strong empirical evidence of the economic benefits and environmental significances of these resources. Therefore, in all tropical dry forest regions, there is a need to further increase research and understanding of the sustainable management of dry forests and undertake an analysis of forestry and other policy areas that affect them in one or another way.

## Conclusion

In conclusion, forests in drylands play an important role in terms of biodiversity conservation, harboring unique and endemic species that are particularly adapted to the extreme environmental conditions (Banda-R 2016). They also provide essential ecosystem goods and services, livelihoods, and well-being of its residents. Despite these and other related significances, virtually all of the remnant TDFs are currently exposed to various threats, largely resulting from anthropogenic activities. Consequently, these ecosystems are caught in a spiral of deforestation, fragmentation, degradation, and desertification. It is also believed that the lack of education and training at university and technical and vocational level greatly contributed to these dismal pictures associated with TDFs. Studies warn that the future of dryland resources in general and that of TDFs, in particular, is uncertain as they are under mushrooming threats. The impacts from anthropogenic activities are being compounded by those impacts from global climate change. These valuable ecosystems remained overshadowed by the historical preoccupations of the more humid forest ecosystems.

The scientific literature showed that there are many reasons that urge us to give due attention to these ecosystems, particularly in the face of the changing climate. Beyond supporting the livelihoods of millions of people worldwide, they are among the biodiversity hotspot centers in the world and have pivotal roles in climate change mitigation and adaptation (Blackie et al. 2014). However, little focus has been given to these resources, and their long-term responses to climate change and the feedbacks thereof are poorly known. Under “business-as-usual scenario”, these remnant dry forest resources would enter a state of total depletion with far-reaching consequences to the more fragile dryland ecosystem and communities’ livelihood in the not too distant future. Thus, in our efforts to mitigate the impacts of climate change and to realize the sustainable development goals, we need to pay more attention to these most fragile and least understood ecosystems. To this end, an integrated effort from researchers, scientists, and policymakers are required.

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## Authors’ contributions

ZGS carried out the review and prepared the manuscript. The author(s) read and approved the final manuscript.

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