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Invited review

Drylands extent and environmental issues. A global approach

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ABSTRACT

Drylands, a critical terrestrial system of the Earth due to low water availability, are known for their extensive global reach, estimated by most scientific sources at approximately 41% of the world's land area, or ~60 mil km^2. However, the analysis of the global dryland areas, using new climate data, suggests a total of ~45% of the Earth's terrestrial area, almost 7 mil km^2 more than initially estimated. This new spatial dimension involves a wide range of environmental issues, some of which have yet to be associated with these critical global systems. This paper primarily aims to accurately quantify the global, continental and national extent of drylands by using a high-resolution climate database presently available at global level. Also, based on relevant scientific literature, this approach attempts to briefly highlight the main environmental issues (natural and anthropogenic) of the major continental and regional dryland areas. In this respect, special attention was given to the land degradation processes (water and wind erosion, vegetation degradation, salinization, soil compaction and nutrient loss), as it is known to be the main environmental perturbation in almost all dryland systems. Research shows that, given the fact that Africa and Asia have the most extensive dryland systems on Earth (each of them has almost 23 mil km^2, or ~15% of the global land area), these continents are especially threatened by major environmental perturbations (desertification, in addition to other ecological and climatic disturbances such as drought, dust storms, heat waves, water stress, extreme rainfall events, wildfire, dzud, or disease emergence), which are currently affecting 46 African states (37% of the 126 states affected by aridity worldwide) and 38 Asian states (30%). Given this context, anthropogenic systems are indirectly severely threatened by the crisis generated by soaring poverty, food insecurity, population migration, and escalating conflicts and regional political instability. Moreover, in the current context of large-scale aridity identified at high latitudes, another critical threat reviewed was the cryosphere's destabilization, which can potentially accelerate climate warming by means of positive feedback mechanisms that can be triggered in the global climate system. In this respect, a major concern is attributed to permafrost melting that, against the background of a significant expansion in the terrestrial northern hemisphere (in Russia, Alaska and Canada), can generate a massive acceleration of climate warming due to the potential release of large quantities of carbon dioxide (CO_2) and methane (CH_4), which are currently stored in these frozen soils in the Arctic and sub-Arctic regions.

Contents

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1. Introduction

Drylands are critical terrestrial environments, considered to be Earth's largest biome (Schimel, 2010). It is unanimously agreed that drylands total ~41% of the Earth's surface, where >2 billion people live, of which approximately 90% in developing countries (Safriel et al., 2005; UNEP, 2007). Amid constant large-scale atmospheric and oceanic circulation mechanisms, or regional geographic conditions, these lands are characterized by an overall climatic water deficit, under the 0.65 mm/mm threshold, considering the Aridity Index (AI) computed as the ratio of precipitation (P) to potential evapotranspiration (PET) over a multiannual period (Middleton and Thomas, 1997).

Given these restrictive climatic conditions, biodiversity, which is rich in many drylands contrary to popular belief (Maestre et al., 2012a), plays an essential role in maintaining the multiple ecosystem functions and services, i.e. the ecosystem multifunctionality (Maestre et al., 2012b). However, in these areas water scarcity drastically limits the ecosystem services recognized by the Millennium Ecosystem Assessment (MEA), i.e. provisioning, regulating, supporting and cultural services (MEA, 2005). The restriction of supporting and regulating services can be considered of utmost importance, as it slows down soil formation processes and the nutrients' circuit, and reduces water and climate regulation capacities.

In the latter case, considering water regulation, the main issue is related to the low fresh water availability of drylands natural ecosystems (deserts, temperate grasslands, savanna woodlands). It is estimated that these media total only 8% of the world's renewable water supply, which is not enough to ensure optimal ecosystem functionality and, more importantly, not enough for the one third of the global population drylands accommodate, which requires a minimal average of 2000 cubic meters per capita per year (for basic welfare and sustainable development), as opposed to the currently available 1300 cubic meters (MEA, 2005). In terms of climate regulation, the low organic carbon sequestration capacity represents a major problem of climate warming mitigation (FAO, 2004), although, at the same time, drylands have o global significance due to huge inorganic soil carbon reserves – it is estimated that these areas store 46% of the planet's terrestrial carbon inventory (Safriel et al., 2005).

An inevitable consequence of the prolonged decline of ecosystem functions and services consists of land degradation. This process is considered to be similar to desertification if, against the background of climatic variations and human activities, it occurs in dryland systems such as arid (AI between 0.05 and 0.2 mm/mm), semi-arid (0.2–0.5 mm/mm) and dry sub-humid (0.5–0.65 mm/mm) climate areas (UNCCD, 1994). In these three climate systems, which total about 35% of the Earth's terrestrial surface (excluding hyper-arid areas, which total an additional ~7% of global land), according to current estimations (Middleton and Sternberg, 2013), there are generally six desertification dimensions, i.e. water erosion, wind erosion, vegetation degradation/loss, salinization, soil compaction, and soil fertility decline (Dregne, 2002). In this context, it is estimated that there are severely degraded lands on 10–20% of these arid environments (medium certainty conclusion), which affects 250 million people directly, and about 1 billion people indirectly (Reynolds et al., 2007). To a large extent, this critical degradation is also present in croplands, which total approximately 25% of total drylands (Safriel et al., 2005).

A significant expansion of drylands is expected to be recorded by the end of the 21st century, amid the imminent amplification of global warming (IPCC, 2013). Recent research showed that, between 1991 and 2005 alone, global drylands increased by 4%, compared to the previous three–four decades, and by the end of the century an increase of these arid environments (considering RCP8.5 scenario) of up to 10% is expected, compared to the 1961–1990 period (Feng and Fu, 2013). Moreover, the most recent research, based on the improvement (correction) of the Fifth Coupled Model Intercomparison Project projections, initially used by Feng and Fu (2013) in a basic form, point to a much more drastic state of affairs, i.e. a 23% global drylands expansion by the year 2100, compared to the 1961–1990 baseline (considering the same pessimistic scenario, RCP8.5), which means these critical environments will total 56% of the global land area (Huang et al., 2016). The risk of this unfavorable prediction is all the higher as almost 80% of this potentially catastrophic expansion is expected to take place in developing countries (more vulnerable to aridity than developed countries), where dryland systems are likely to total ~60% of these countries' total area, under the scenario RCP8.5 (Huang et al., 2016).

Given the large-scale climate aridity amplification, coupled with population increase, land degradation acceleration (in terms of intensity and global extent) is inevitable. In this context, the challenges will be significant, seeing as the world population is estimated to reach 9.2 billion by 2050 (Bongaarts, 2009), when 70–100% more food will be required (Godfray et al., 2010). This demographic increase is predictable especially in the world's drylands, which already experienced (after 1990) the highest population growth rate of all Earth systems (MEA, 2005). In synergy with ecosystem stability decline (Ruppert et al., 2015), other major issues are predicted, i.e. accentuation of poverty, population migration, amplification of conflicts and regional political instability (UNCCD, 2011).

This paper is a review that primarily aims to realize a comprehensive global, continental and national assessment of dryland systems extent, based on high resolution spatial climate data currently available at global level. A secondary objective is to briefly highlight the main current and future environmental issues, representative for the largest dryland areas identified at continental or regional scale.

2. Drylands in the global context

Using Global Aridity Index (Trabucco and Zomer, 2009) (Fig. 1), a high-resolution climate geo-database (30 arc sec or ~1 km at equator), recently obtained based on WorldClim data (Hijmans et al., 2005), it was noticed that drylands represent 45.4% (66.7 mil km^2) of the Earth's total terrestrial area (~147 mil km^2) (Table 1), significantly more than the previous statistical estimations (41%, ~60 mil km^2) (MEA, 2005; Safriel et al., 2005). Remarkable values were also found for hyper-arid (5.9%, 8.6 mil km^2), arid (14.2%, 20.8 mil km^2), semi-arid (16.4%, 24.1 mil km^2) and dry sub-humid (9%, 13.2 mil km^2) areas (Fig. 1, Table 1), compared to previous studies (6.6%/9.8 mil km^2, 10.6%/15.7 mil km^2, 15.2%/22.6 mil km^2 and 8.7%/12.8 mil km^2 for hyper-arid, arid, semi-arid, and dry sub-humid systems) (Safriel et al., 2005).

For the most part, this spatial difference is due to the significant expansion of drylands towards northern latitudes (identified in this updated database), as opposed to the initial data (Safriel et al., 2005) that indicated an expansion of arid environments towards lower latitudes, generally to the 60°N parallel. The presence of aridity at high latitudes, according to the new high resolution climatic database, is mainly caused by the new higher PET values in P/PET ratio (compared to the same ratio used for previous aridity estimations), based on which the Global Aridity Index was computed. This is primarily due to the longer period of temperature (T) series that was used for calculating the new global PET database, i.e. 1950–2000 in Trabucco and Zomer (2009), compared to the 1951–1980 climatological baseline used by Middleton and Thomas (1997). The additional 20-year period is highly important because, after 1980, mean global temperatures (especially at northern latitudes) increased at an accelerated rate (IPCC, 2013), thus influencing the higher mean PET values in the entire 1950–2000 interval, in comparison with 1951–1980. To a lesser extent, the expansion of drylands to the north can also be attributed to the decreasing precipitation trends of the second half of the 20th century (which influence the mean values of the extended 50-year period), which were recorded in several areas in north-western North America and north-eastern Asia (IPCC, 2013), which are currently affected by aridity (Fig. 1).

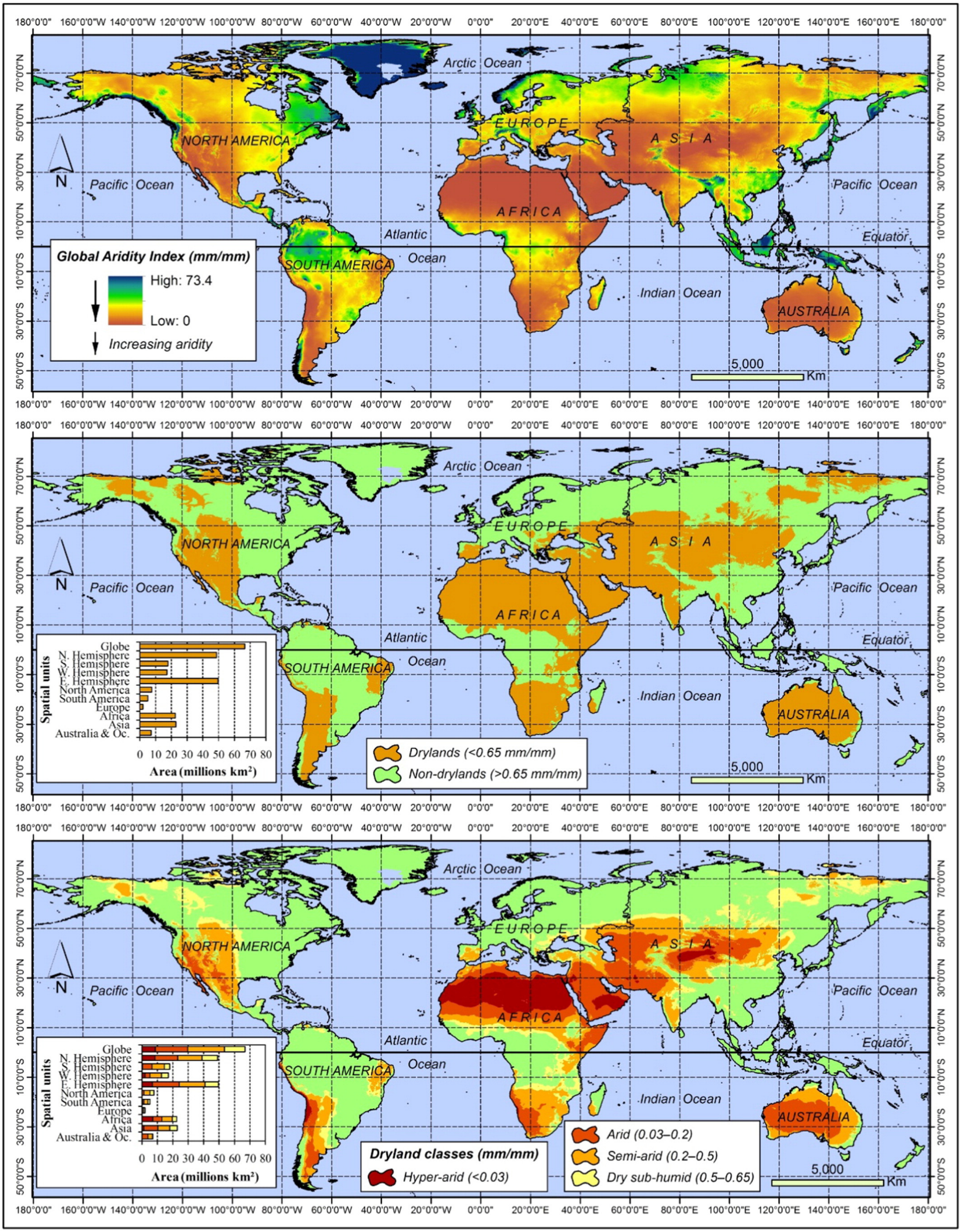

Fig. 1. Spatial representation of Global Aridity Index in unclassified (up), classified generally (middle) and classified comprehensively (down) forms. Note: absolute values of dryland areas were obtained for land polygons (purchased at the highest resolution available from http://www.naturalearthdata.com), with the Mollweide projection (Central Meridian: 0.00).

Table 1
Drylands extent at global, hemisphere and continental level.

No.	Spatial scale	Drylands' share of total continental/hemispheric/global area (%)									
		Hyper-arid		Arid		Semi-arid		Dry sub-humid		Total drylands	
		†	††	†	††	†	††	†	††	†	††
1.	Glob	5.86*		14.16*		16.38*		8.97*		45.36*	
2.	Northern Hemisphere	8.30	5.65	14.78	10.06	15.91	10.83	9.76	6.64	48.75	33.18
3.	Southern Hemisphere	0.66	0.21	12.83	4.10	17.37	5.55	7.28	2.32	38.14	12.18
4.	Western Hemisphere	3.72	1.31	6.31	2.22	14.39	5.07	8.50	2.99	32.92	11.60
5.	Eastern Hemisphere	7.02	4.55	18.43	11.94	17.46	11.31	9.22	5.97	52.13	33.76
6.	North and Central America	0.02	<0.01	4.46	0.73	16.32	2.69	10.38	1.71	31.17	5.14
7.	South America	1.48	0.18	5.92	0.72	13.54	1.64	7.76	0.94	28.71	3.47
8.	Europe	0.00	0.00	0.02	<0.01	7.99	0.54	9.49	0.64	17.50	1.17
9.	Africa	23.37	4.78	19.62	4.01	21.72	4.44	10.28	2.10	74.99	15.33
10.	Asia	2.97	0.90	19.88	6.03	17.27	5.24	10.81	3.28	50.92	15.46
11.	Australia and Oceania	0.00	0.00	48.09	2.66	33.02	1.83	5.30	0.29	86.42	4.78

Note: † and †† represent the percentage of drylands systems (the four classes and the total) of the total surface of the reference unit (hemisphere/continent), and of the total global surface; * – the percentage of drylands systems (the four classes and the total) of the total global area.

Secondly, the differences are due to the superior PET estimation method based on T, Hargreaves (compared to Thornthwaite method used in the initial dryland estimations), which performs almost as well as the best FAO-PM method (Hargreaves and Allen, 2003; Trabucco and Zomer, 2009). The Thornthwaite PET value assessment method is therefore considered to be inferior to the Hargreaves method, given the fact that the former generally underestimates this climate parameter's values (Bandoc and Prăvălie, 2015; Prăvălie and Bandoc, 2015), especially in highly arid regions. This is in fact the reason why hyper-arid areas were adjusted upward to 0.05 in the initial database (Safriel et al., 2005), as opposed to the 0.03 threshold used in the current aridity database (Trabucco and Zomer, 2009).

Upon investigation of the mean values of the two climate parameters of the Global Aridity Index, for instance in the areas affected by aridity expansion to northern latitudes above the 60°N parallel (Fig. 2), it was noticed that the presence of semi-arid and dry sub-humid systems in north-western North America and north-eastern Asia is due to multiannual P amounts that generally range between 150 and 300 mm in the continents' dryland areas, coupled with mean multiannual PET values that particularly range between 350 and 550 mm in both instances (except for island areas where P and PET values are generally lower). These regions' aridity is therefore essentially a projection of low precipitation in relation with the lost humidity due to evapotranspiration, which is undoubtedly higher, based on research data recorded in the period 1950–2000. On the other hand, the lack of semi-arid/dry sub-humid areas in other regions located at the same high latitudes (western Siberia, northern Europe), is attributed, for the most part, to higher precipitation amounts, even though PET values are also quite high in these Eurasian regions (Fig. 2).

Returning to the spatial dimension assessment of these restrictive environments, in terms of hemispheres drylands cover latitudinally approximately half of the northern continental hemisphere (almost 50 mil km^2), and more than one third of the southern hemisphere (~18 mil km^2) (Fig. 1, Table 1). Similarly to the global context, semi-arid regions occupy the largest areas in both hemispheres, and are followed by the arid regions (Fig. 1, Table 1). Longitudinally, drylands are prevalent in the eastern hemisphere, both overall and separately, for each type (Fig. 1, Table 1).

The continental analysis highlighted extensive dryland areas in Asia and Africa (each of them with almost 23 mil km^2), which total ~31% of the Earth's terrestrial area (Fig. 1, Table 1). Africa is the continent that is most heavily affected by aridity, considering that drylands cover almost three quarters of its surface, while hyper-arid areas, the most critical type of this terrestrial system, cover almost one quarter (7 mil km^2, about 5% of the Earth's surface) (Table 1). Asia is also critically affected by this environmental issue, as it holds the highest absolute value of the arid climate (8.9 mil km^2, 20% of the continent or 6% of the Earth's surface) of all dryland systems on all continents (Table 1).

In terms of states, drylands are found in 126 UN member states (65% of 193), or 128 countries, including 2 states partially recognized, i.e. Kosovo, in Europe, and Palestine, in Asia (Tables 2-7). Africa has the highest number of countries affected by aridity (37% of 126), and is followed by Asia (30%), Europe (13%), North and Central America (10%), South America (9%), and Australia and Oceania (2%). Most of the countries with >50% of their territories affected by aridity conditions are found in Africa (28% of 126), Asia (20%) and Europe (5%).

This global spatial dimension of drylands entails a wide range of environmental disturbances that strongly affect about one billion poor people living mostly in Africa and Asia (Middleton et al., 2011). According to a recent paper review, these disturbances can be synthesized as natural hazards, of which direct (drought, heat waves, extreme rainfall events, dust storms, wildfire, dzud) and indirect (desertification) climate hazards are of particular interest for these dry environments (Middleton and Sternberg, 2013). Drought is one of the most critical natural hazards, considering that over the past two decades alone (1994–2013) it affected >1 billion people worldwide, especially through agricultural crop failures, drinking water supply decline, livestock mortality and epidemic diseases amplification (CRED, 2015). Most of these negative effects occurred in dryland systems, and the highest occurrence of droughts (41%) was recorded in Africa (CRED, 2015), 75% of which is affected by aridity.

Amid this century's climate change context, it is highly likely these environmental issues will intensify, along with global drying expansion. According to the most rigorous recent studies, based on aridity data analysis simulated under scenario RCP8.5, by the year 2100 the Earth land areas covered by hyper-arid, arid, semi-arid, and dry sub-humid systems are expected to reach shares of 12.6%, 14.9%, 20.3% and 8.3%, respectively (Huang et al., 2016). Given this new critical spatial dimension of aridity, a strong increase is expected in natural hazard occurrences, especially those of climatic nature (especially droughts, heat waves and wildfire activity), which will become increasingly widespread, frequent and severe (IPCC, 2012; Middleton and Sternberg, 2013). Subsequently, vegetation cover reduction will have negative ecological consequences such as the disruption of the biogeochemical cycles of carbon (C), nitrogen (N) and phosphorus (P), which are essential elements for ecosystem processes, i.e. primary production, respiration and decomposition (Finzi et al., 2011; Delgado-Baquerizo et al., 2013). Recent studies already suggested decoupling these nutrients in dryland ecosystems (reducing soil organic C and total N concentrations, along with the vegetation decline, but increasing the concentration of inorganic P, amid the intensification of the mechanical rock weathering process in more arid conditions), and accelerating this stoichiometry disturbance with increasing aridity in the near future (Delgado-

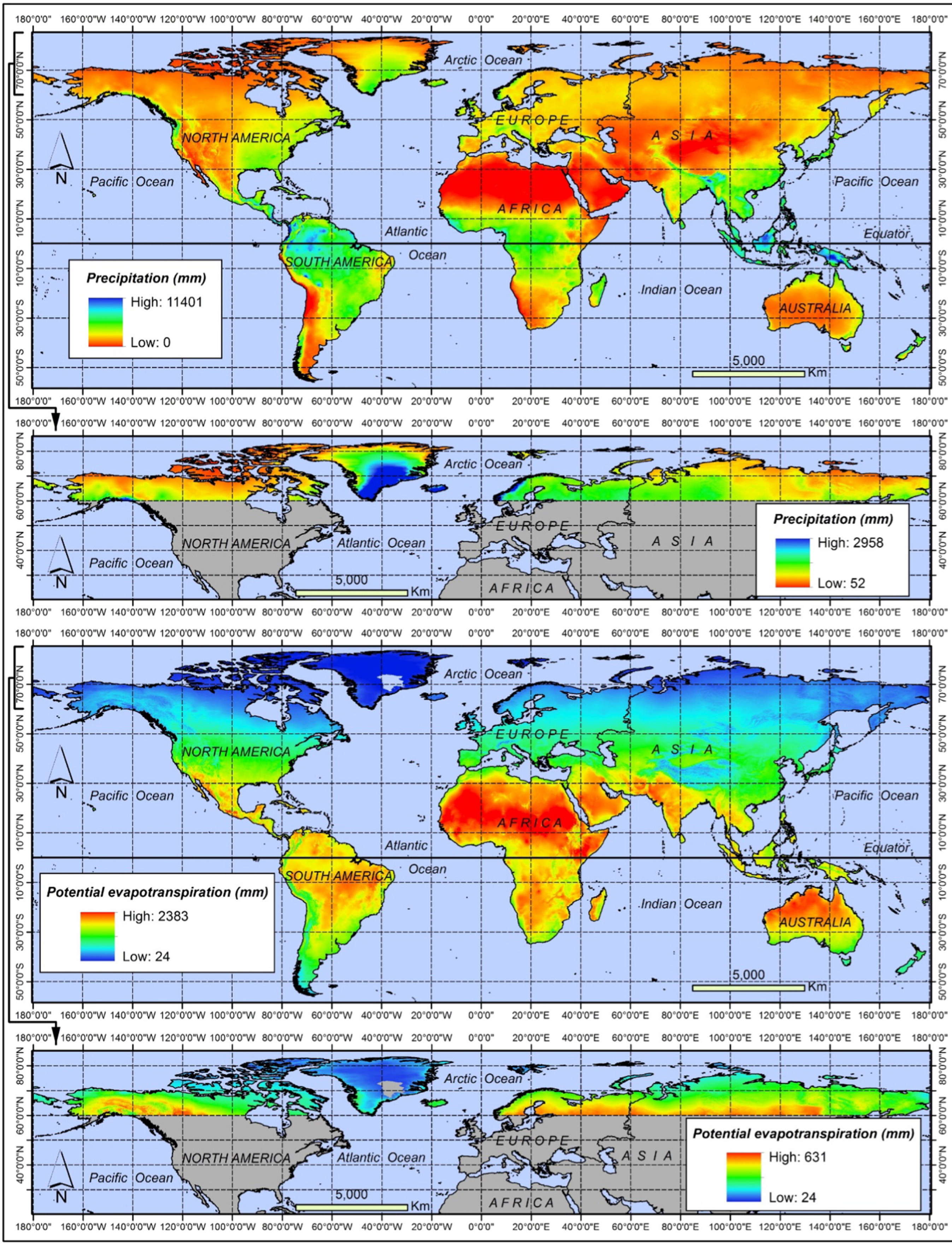

Fig. 2. Spatial representation of mean multiannual values (1950–2000) for precipitation (up) and potential evapotranspiration (down), globally and regionally (above the 60°N parallel). Note: the raster data of the two parameters were delimitted separately regionally in order to ensure a more precise identification of the climate value range in high latitude regions, above the 60°N parallel; the sources of the mapped data are Hijmans et al. (2005) for precipitation, and Trabucco and Zomer (2009) for potential evapotranspiration.

Baquerizo et al., 2013). Eventually, the imbalance of ecosystem stoichiometry can have a significant impact of the soil formation and organic matter decomposition processes, which will result in wide-scale land degradation.

However, there are also future potential benefits of dryland systems. Atmospheric dust aerosol enhancement, associated to the expansion of arid conditions, can contribute to significant climate cooling especially in the northern hemisphere, where this process is already being noticed particularly in regions such as Northern Africa and Central and South-Western Asia (Islam and Almazroui, 2012; Zhao et al., 2014). This cooling effect, caused directly by reflecting sunlight particles back into space, or indirectly through cloud albedo raising (when aerosols act as cloud condensation nuclei) (Youlin et al., 2001), is a rare example of negative feedback of climate warming (Paasonen et al., 2013). On the other hand, it is noteworthy that this aspect represents the positive side of the land-atmosphere interaction in terms of climate warming regulation mechanism, as it is generally acknowledged that soil erosion and the decrease of primary vegetation productivity, processes linked to land degradation, emit carbon into the atmosphere and trigger positive feedback in climate warming (Lal, 2004; Delgado-Baquerizo et al., 2013; Huang et al., 2016).

For the global economic system, drylands can be a major advantage by increasing energy security. A relatively recent study estimates that if only 4% of the planet's deserts were covered with photovoltaic systems, enough energy would be produced to meet the current global demand (Kurokawa et al., 2007). However, considering the current area of desert regions of approximately 30 million km^2 (~20% din Earth land) (Table 1), given the climatic definition of the sum of all hyper-arid and arid areas (Ezcurra, 2006), the hypothetical installment of solar energy systems on >1 million km^2 would be an unparalleled challenge for humanity. Trends are however encouraging, seeing as in the past decade photovoltaic energy went up globally by >50% per year (GEA, 2012).

3. Drylands in the continental context

3.1. North and Central America

Almost one third (7.6 mil km^2) of this extensive region (~24 mil km^2) is covered by drylands, which are found in 12 states, 3 of which in North America (Canada, United States – US, Mexico) and 9 in Central America (Fig. 3, Table 2). Semi-arid systems are the most representative (~4 mil km^2, 16% of the region or almost 3% of the Earth's surface), as they are widespread in the western half of the US (2.8 mil km^2, ~30% of US territory) and in most of Mexico (0.8 mil km^2, 41%). The 2 states also have extensive arid lands, totaling over 1 mil km^2, most of which in the Great Basin, Mojave (US), Sonoran and Chihuahuan (US and Mexico) deserts. Canada is also notable due to the high percentage of dry sub-humid areas (14%, almost 1.4 mil km^2) (Table 2, Fig. 3).

The main environmental problems in the US/Mexico largest drylands are related to drought, insect outbreak, wildfire, and, in part, to deforestation (Dregne, 2002; van Mantgem et al., 2009; Middleton and Sternberg, 2013). Over the past decades, intense recurrent droughts have become an increasingly apparent feature of southwestern North America, which implies, amongst others, wind erosion intensification coupled with vegetation loss (Cook et al., 2009). The recent history of the US was marked by related consequences, such as the Dust Bowl event of 1930, when, amid extreme drought and land use changes (extensive replacement of drought-resistant prairie lands with drought-sensitive wheat crops), almost unprecedented economic loss, large-scale agricultural abandonment and human migration were recorded (Cook et al., 2009). While wind erosion is still a main cause of dryland degradation in US and Mexico, negative effects on communities are not only connected with the affected agricultural systems. For instance, a less known, but important, consequence is the fungal disease Coccidioidomycosis, which sometimes becomes deadly to 100,000 people estimated to get infected every year in the two states, especially due to contaminated wind sand dispersion (Middleton and Sternberg, 2013).

Recent warming and extreme droughts are also directly responsible of forest mortality due to the so-called "forest die-off events" (Anderegg et al., 2012), triggered in southwestern North America forests by the rising of water deficit and thermal stress on the trees (van Mantgem et al., 2009). Indirectly, these climatic phenomena are closely connected with large scale outbreak eruptions, which over the past decades have devastated southwestern US forest drylands, endangering essential ecosystem services such as carbon sequestration, as a result of widespread tree mortality (Williams et al., 2010). It is estimated that bark beetles (mainly *Dendroctonus ponderosae* mountain pine beetle) affected 17 million hectares of western US forests after 1996, destroying 5.2 million hectares of trees (Carswell, 2014). Similar problems are found in western Canada, British Columbia (but with less drylands extent), where it is estimated that forest ecosystems have already transformed from a small net carbon sink into a large net carbon source (Kurz et al., 2008).

In drier climatic conditions, another inherent problem consists of increasing wildfire activity. Although fires are considered to be a natural process, essential for ensuring the normal functioning of terrestrial ecosystems by controlling biomass, a significant increase was noticed after 1980 (in terms of frequency, extent and severity) that caused a substantial forest decline in southwestern North America (Williams et al., 2010). Although there are claims that support the synergistic cause of climate warming and insect outbreaks (perceived as a factor that favors fire severity due to tree withering), recent studies say pine beetles do not necessarily cause more severe fires (Carswell, 2014). Direct climate conditions still are the main driving forces of wildfire activity. Given this

Table 2
Drylands extent at state level in North and Central America.

No.*	Country	Drylands' share of total country/continental/global area (%)														
		Hyper-arid			Arid			Semi-arid			Dry sub-humid			Total drylands		
		†	††	†††	†	††	†††	†	††	†††	†	††	†††	†	††	†††
1.	Canada	0.00	0.00	0.00	0.00	0.00	0.00	3.70	1.52	0.25	13.79	5.66	0.93	17.49	7.17	1.18
2.	USA	0.02	0.01	<0.01	6.85	2.68	0.44	29.24	11.44	1.89	8.97	3.51	0.58	45.08	17.64	2.91
3.	Mexico	0.12	0.01	<0.01	21.98	1.78	0.29	41.09	3.32	0.55	13.61	1.10	0.18	76.80	6.21	1.02
4.	Bahamas	0.00	0.00	0.00	0.00	0.00	0.00	8.46	<0.01	<0.01	18.33	0.01	<0.01	26.79	0.01	<0.01
5.	Cuba	0.00	0.00	0.00	0.00	0.00	0.00	0.08	<0.01	<0.01	6.72	0.03	0.01	6.80	0.03	0.01
6.	Haiti	0.00	0.00	0.00	0.00	0.00	0.00	4.99	0.01	<0.01	8.06	0.01	<0.01	13.05	0.01	<0.01
7.	Dom. Rep.	0.00	0.00	0.00	0.00	0.00	0.00	9.40	0.02	<0.01	13.15	0.03	<0.01	22.56	0.04	0.01
8.	Jamaica	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.47	<0.01	<0.01	1.47	<0.01	<0.01
9.	Guatemala	0.00	0.00	0.00	0.00	0.00	0.00	1.17	0.01	<0.01	2.68	0.01	<0.01	3.84	0.02	<0.01
10.	Honduras	0.00	0.00	0.00	0.00	0.00	0.00	0.59	<0.01	<0.01	3.41	0.02	<0.01	4.00	0.02	<0.01
11.	Nicaragua	0.00	0.00	0.00	0.00	0.00	0.00	0.17	<0.01	<0.01	3.67	0.02	<0.01	3.83	0.02	<0.01
12.	Panama	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.29	<0.01	<0.01	0.29	<0.01	<0.01

Note: * the states are listed in a descending order considering the maximum latitude values of northern limits; †, †† and ††† refer to the drylands systems percentage (the four classes and the total) of the total state, continental (North and Central America), and global areas; abbreviations: USA – United States of America, Dom. Rep. – Dominican Republic.

Table 3
Drylands extent at state level in South America.

No.*	Country	Drylands' share of total country/continental/global area (%)														
		Hyper-arid			Arid			Semi-arid			Dry sub-humid			Total drylands		
		†	††	†††	†	††	†††	†	††	†††	†	††	†††	†	††	†††
1.	Columbia	0.00	0.00	0.00	0.14	0.01	<0.01	1.02	0.07	0.01	1.80	0.12	0.01	2.95	0.19	0.02
2.	Venezuela	0.00	0.00	0.00	0.01	<0.01	<0.01	3.92	0.20	0.02	11.59	0.60	0.07	15.53	0.80	0.10
3.	Guyana	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.17	<0.01	<0.01	0.17	<0.01	<0.01
4.	Brazil	0.00	0.00	0.00	0.00	0.00	0.00	8.50	4.09	0.49	5.48	2.64	0.32	13.99	6.72	0.81
5.	Ecuador	0.00	0.00	0.00	0.85	0.01	<0.01	9.64	0.14	0.02	7.83	0.11	0.01	18.32	0.27	0.03
6.	Peru	7.18	0.53	0.06	5.54	0.41	0.05	5.92	0.43	0.05	9.15	0.67	0.08	27.79	2.03	0.25
7.	Bolivia	0.00	0.00	0.00	9.07	0.56	0.07	25.37	1.55	0.19	13.27	0.81	0.10	47.71	2.92	0.35
8.	Chile	22.06	0.94	0.11	15.98	0.68	0.08	7.19	0.31	0.04	3.21	0.14	0.02	48.43	2.07	0.25
9.	Paraguay	0.00	0.00	0.00	0.00	0.00	0.00	38.99	0.88	0.11	14.33	0.32	0.04	53.32	1.20	0.15
10.	Argentina	0.07	0.01	<0.01	27.17	4.25	0.51	37.53	5.88	0.71	15.05	2.36	0.29	79.83	12.50	1.51
11.	Uruguay	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.11	<0.01	<0.01	0.11	<0.01	<0.01

Note: * the states are listed in a descending order considering the maximum latitude values of northern limits; †, †† and ††† refer to the drylands systems percentage (the four classes and the total) of the total state, continental (South America) and global areas.

context, other types of ecosystems become increasingly vulnerable, as is the case of the dry chaparral shrublands of California, highly frequently affected by fires. In the future, the intensification of all these environmental disturbances is to be expected in this region, amid the imminent transition to an increasingly arid climate (Seager et al., 2007).

The expansion of dryland systems to high latitudes in Canada and the United States (Alaska) (Fig. 3), exceeding the 60°N parallel, generally known until now as the northern limit of arid environments (Safriel et al., 2005), can point to additional, highly sensitive environmental problems. As previously noted, new aridity identified in these northern regions is a projection of higher PET, amid the higher temperatures recorded in the second half of the 20th century. Given this context, the potential to destabilize the cryosphere is an issue of utmost importance, due to the possible positive feedback effects in climate warming. The decreasing land albedo due to snow cover decrease, permafrost thawing, and the river and lake ice melting, can lead to an acceleration of the warming process by increasing the absorption of solar radiation (by up to 90%) by darker surfaces (Callaghan et al., 2011a). Permafrost thawing can also generate additional warming by freeing CO_2 and, more importantly, CH_4, which has a greenhouse effect that is 25 times higher than that of CO_2 (Callaghan et al., 2011b). With a total surface of ~22.8 mil km^2 in the terrestrial northern hemisphere (almost half of which is continuous permafrost, with higher carbon content), of which 37% is located in Canada and Alaska (a significant share overlaps drylands) (Zhang et al., 2008), these frozen soils can be a tremendous danger to global warming, seeing as they contain twice as much carbon as the global atmosphere (Schuur et al., 2015). In the future, this danger is all the greater as, in northern North America, climate projections generally indicate the largest expansion and the most significant escalation of arid conditions at high latitudes (over 60°N), both in the middle and at the end of the 21st century (Huang et al., 2016).

At lower latitudes, in Central America, water erosion is known to be a major environment deterioration problem (Dregne, 2002). According to recent research (Hansen et al., 2013), the extensive deforestation of the last decade is another serious concern, especially in Guatemala, Honduras, Nicaragua and the Dominican Republic. However, drylands do not cover massive surfaces in these countries, except for the relatively notable case of the Dominican Republic, where more than one quarter of the territory (~11,000 km^2) is affected by aridity (Fig. 3).

3.2. South America

Of the total area of ~18 mil km^2 of South America, almost 30% (5.1 mil km^2) consists of drylands, most of which are found in Argentina (2.2 mil km^2, 80% of the country's area), Brazil (1.2 mil km^2, 14%), Bolivia (~0.5 mil km^2, 48%), Chile and Peru (both under 0.4 mil km^2, but with percentages of 48% and 28%) (Fig. 4, Table 3). Semiarid systems are most common (2.4 mil km^2, 14% of the continent), especially in Argentina (over 1 mil km^2, 38% of the country's area) and Brazil (0.7 mil km^2, 9%) (Fig. 4, Table 3). The most critical drylands, hyper-arid (~260,000 km^2, of which over 60% in Chile, mostly in the Atacama Desert, and 35% in Peru, in the Sechura coastal desert) and arid (~1 mil km^2, of which over 70% in Argentina, for the most part overlapping the Monte and Patagonia deserts) systems also cover vast territories.

Salinization and water and wind erosion are the main environmental issues of drylands in Andean countries, especially in Argentina (Dregne, 2002). Agricultural soil salinization due to irrigation is a major threat, as this process is generally irreversible in drylands because fresh water is not enough to eliminate the accumulated salts (Rozema and Flowers, 2008).

Amid agricultural intensification over the past decades, another rising environmental threat was found in large-scale nutrient loss, especially in northern Argentina and north-eastern Brazil (UNEP, 2007). At the same time, intensive agriculture (expansion of agricultural crops such as soy) accounts for the widespread deforestation of dry forests of Caatinga and eastern drylands Cerrado (Brazil), but also in Chaco of Brazil, Paraguay, Argentina and Bolivia (Maestre et al., 2012a; Hansen et al., 2013). Furthermore, the drylands vegetation of north-eastern/eastern Brazil (Caatinga, partially Cerrado) has been subjected to degradation over the past decades, as the occurrence of wildfire events increased. A recent global study showed that after 1979 the fire weather season length increased noticeably in north-eastern Brazil (as noticed in at least two other global regions significantly affected by aridity, south-western North America and eastern Africa), as a result of an increase in maximum temperatures, wind speed and rain-free days, and of a decrease in atmospheric humidity (Jolly et al., 2015).

While wind erosion is an important cause of coastal environment degradation in Peru and Chile, especially in the Atacama Desert (one of the driest and oldest deserts on Earth, given that the region experienced hyper-arid conditions as far back as ~15–10 million years ago) (Armijo et al., 2015), the most severe form of this process is found in the sandy areas of Argentina (Dregne, 2002). This environmental problem can have complex, large-scale effects. For instance, it is estimated that Argentina's loess region, totaling over 1 mil km^2 (the largest one in the Southern Hemisphere), is primarily responsible for doubling, in the 20th century, the aluminosilicate dust concentration in the local atmosphere of the northern Antarctic Peninsula (McConnell et al., 2007). It is possible that dust mobility and export enhancement in Argentina (especially in Patagonia) to account, to a considerable extent, for the climate changes in the northern Antarctic Peninsula (by modifying the albedo), which is currently known to be the most rapidly warming region of the Southern Hemisphere (McConnell et al., 2007).

Another major issue consists of cryosphere changes in the dryland mountains of South America. The accelerated climate warming in the Andean region, estimated at ~0.33 °C/decade after 1980, more than twice as high as the global trend, caused a strong retreat of glaciers, especially in the Central Andes (Rangecroft et al., 2013). Bolivia is particularly important in this respect, given the limited adaptive capacity related to its being one of the poorest countries in Latin America. It is estimated that Bolivian glaciers have already lost almost 50% of their ice mass over the past half century, and in the following decades a much faster glacier retreat is expected, compared to other dryland mountains of the world, i.e. 80% (in the Bolivian Cordillera Real mountains, the southern region of which overlaps the country's dry sub-humid and semi-arid areas) (Rangecroft et al., 2013). The ecological and socio-economic systems' vulnerability to water security decrease in the region is therefore clear.

The threat of water security can also be a sensitive issue for another Latin America drylands area – the Guarani aquifer region in northern Argentina. It is one of the world's largest aquifers, with a total area of ~1.2 mil km^2 (which however mostly consists of non-drylands in southern Brazil, eastern Paraguay and northwestern Uruguay) (UNEP, 2007), and is currently facing obvious rates of groundwater depletion, similarly to the other worldwide major aquifers (Famiglietti, 2014). Major threats of the 21st century include increasing pressure on water resources and accelerated land degradation especially in eastern Bolivia, central Paraguay, southern Peru, central Chile and eastern Brazil, where drylands expansion is expected under a warming climate (Huang et al., 2016). However, reducing these imbalances is possible in central-southern Argentina (Patagonia), under lower aridity conditions simulated for this region (Huang et al., 2016).

3.3. Europe

The European Continent, with a total area of almost 10 mil km^2, is 17.5% (~1.7 mil km^2) affected by aridity, in 18 states (including the partially recognized state of Kosovo) located in the southern, central and eastern regions (Fig. 5, Table 4). Dryland systems are almost entirely found in dry sub-humid (over 0.9 mil km^2, 9.5% of the continent) and semi-arid (almost 0.8 mil km^2, 8%) climates, with the exception of a small arid area north of the Caspian Sea (Fig. 5, Table 4). In addition to the Russian Federation, which totals 7% of European aridity, Spain has the largest drylands area (over 350,000 km^2, >70% of the country's area), followed by Ukraine (almost 200,000 km^2, 32%), Romania (over 100,000 km^2, 44%) and Greece (~70,000 km^2, 52%) (Fig. 5, Table 4).

Although it is the least arid continent, Europe is marked by different environmental disturbances, especially in the semi-arid Mediterranean region, where the most related studies have been conducted so far. The large-scale decline of ecological and economic land productivity, mainly as a result of intense water (Panagos et al., 2015) and wind (Borrelli et al., 2014) erosion, constitutes the general consensus of the environmental problems identified in this southern European region. It is estimated that water and wind erosion affects 115 mil ha, and 42 mil ha, respectively, of European territory, most of which in the Mediterranean region (EEA, 1998). Soil erosion is amplified by other related perturbations such as wildfires (Caon et al., 2014), as 75% of the burnt areas are located in dryland Mediterranean countries, of which Spain and Portugal are the most heavily affected (Middleton and Sternberg, 2013; Panagos et al., 2015).

The Mediterranean region can be considered the continent's most important climate change hotspot, due to the significant decrease in precipitation and to the increasing climate warming recorded over the past decades (IPCC, 2013). Given this context, a notable consequence is the perturbation of terrestrial carbon sequestration. A recent study interestingly highlighted the fact that, after the second half of the 20th century, the approximately global 30–40°N latitudinal belt exceeded the mean annual temperature threshold of 16 °C, which is considered to be a dryness-control of terrestrial carbon uptake (Yi et al., 2014). These global areas with temperatures above 16 °C, which expanded poleward by 6% between 1948 and 2012, have experienced a carbon uptake that was 27% lower, which indicated the danger of a strong positive feedback in climate warming, amid the substantial reduction of the carbon transfer from the atmosphere to the biosphere (Yi et al., 2014). Southern Europe was significantly affected by this environmental perturbation, as were extensive areas in the northern hemisphere, in the United States, the Near and Middle East, and China. This century's outlook is bleak, considering the expansion of climate aridity towards central Europe (Gao and Giorgi, 2008; Feng and Fu, 2013; Huang et al., 2016), which will determine an increase of dryness-controlled areas by at least another 8% as early as 2050 (Yi et al., 2014).

Table 4
Drylands extent at state level in Europe.

No.*	Country	Drylands' share of total country/continental/global area (%)														
		Hyper-arid			Arid			Semi-arid			Dry sub-humid			Total drylands		
		†	††	†††	†	††	†††	†	††	†††	†	††	†††	†	††	†††
1.	Russia**	0.00	0.00	0.00	0.06	0.02	<0.01	10.14	4.05	0.27	8.28	3.31	0.22	18.48	7.38	0.49
2.	Germany	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.19	0.01	<0.01	0.19	0.01	<0.01
3.	Ukraine	0.00	0.00	0.00	0.00	0.00	0.00	6.08	0.37	0.02	25.68	1.57	0.11	31.76	1.94	0.13
4.	France	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.78	0.04	<0.01	0.78	0.04	<0.01
5.	Czech Rep.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.56	0.02	<0.01	2.56	0.02	<0.01
6.	Slovakia	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	9.88	0.05	<0.01	9.88	0.05	<0.01
7.	Hungary	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	59.54	0.56	0.04	59.54	0.56	0.04
8.	Moldova	0.00	0.00	0.00	0.00	0.00	0.00	0.28	<0.01	<0.01	47.39	0.16	0.01	47.67	0.16	0.01
9.	Romania	0.00	0.00	0.00	0.00	0.00	0.00	3.45	0.08	0.01	40.05	0.96	0.06	43.51	1.05	0.07
10.	Italy	0.00	0.00	0.00	0.00	0.00	0.00	5.80	0.18	0.01	13.36	0.41	0.03	19.17	0.58	0.04
11.	Serbia	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	25.43	0.20	0.01	25.43	0.20	0.01
12.	Bulgaria	0.00	0.00	0.00	0.00	0.00	0.00	1.12	0.01	<0.01	56.63	0.64	0.04	57.75	0.66	0.04
13.	Spain	0.00	0.00	0.00	0.60	0.03	<0.01	54.05	2.78	0.19	17.61	0.90	0.06	72.26	3.71	0.25
14.	Kosovo***	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5.85	0.01	<0.01	5.85	0.01	<0.01
15.	Macedonia	0.00	0.00	0.00	0.00	0.00	0.00	28.52	0.07	<0.01	30.21	0.08	0.01	58.73	0.15	0.01
16.	Portugal	0.00	0.00	0.00	0.00	0.00	0.00	17.53	0.16	0.01	21.75	0.20	0.01	39.28	0.37	0.02
17.	Greece	0.00	0.00	0.00	0.00	0.00	0.00	23.43	0.32	0.02	28.58	0.38	0.03	52.01	0.70	0.05
18.	Malta	0.00	0.00	0.00	0.00	0.00	0.00	75.34	<0.01	<0.01	11.99	<0.01	<0.01	87.33	<0.01	<0.01

Note: * the states are listed in a descending order considering the maximum latitude values of northern limits; ** area of Russia in relation to the European continent; *** states with disputed sovereignty; †, †† and ††† refer to the drylands systems percentage (the four classes and the total) of the total state, continental (Europe) and global areas; abbreviations: Czech Rep. – Czech Republic.

3.4. Africa

The large area of the African continent, which totals 30 mil km^2, consists of 75% drylands, or ~22.5 mil km^2 (Table 1). It is the continent that has the most restrictive climate conditions in the world, seeing as, according to the new Global Aridity Index (Trabucco and Zomer, 2009), aridity is present on three quarters of its area, while hyper-arid areas, characterized by the highest climatic water deficit, total almost one quarter (an extensive area, of almost 7 mil km^2, which almost entirely overlaps the Sahara Desert) (Table 1, Fig. 6). Arid and semi-arid areas are also considerable, i.e. 5.9 mil km^2 (20% of the continent), and 6.5 mil km^2 (22%) (Table 1).

While the 46 states have various aridity degrees, 18 countries comprise large areas of the most restrictive dryland systems (hyper-arid and arid areas, which correspond to deserts), the most remarkable examples of which are Saharan countries (Western Sahara, Mauritania, Morocco, Algeria, Mali, Niger, Tunisia, Libya, Chad, Egypt, Sudan), and the ones spanning across the Namib, Kalahari and Karoo deserts (Namibia, Botswana, South Africa) (Fig. 6, Table 5). Of these, considering the 75% hyper-arid climate threshold within national limits, the most arid countries in Africa and worldwide are Western Sahara (91%, ~245,000 km^2), Egypt (89%, ~880,000 km^2), Libya (82%, ~1.3 mil km^2) and Algeria (75%, ~1.7 mil km^2) (Table 5, Fig. 6).

Under these circumstances, the ecological and socio-economic implications are monumental. Amid large areas of dry unconsolidated substrates with low vegetation cover, dust particles are one of the main characteristics of the vast Saharan region, which is estimated to emit between 50 and 70% of the global atmospheric dust amount (Ezcurra, 2006). For Saharan states, dust storms are therefore an essential problem due to the wide range of associated negative effects such as soil erosion acceleration, mechanical damaging of crops, air pollution, drinking-water contamination, human disease transmission, etc. (Middleton and

Table 5
Drylands extent at state level in Africa.

No.*	Country	Drylands' share of total country/continental/global area (%)														
		Hyper-arid			Arid			Semi-arid			Dry sub-humid			Total drylands		
		†	††	†††	†	††	†††	†	††	†††	†	††	†††	†	††	†††
1.	Tunisia	7.47	0.04	0.01	63.82	0.33	0.07	25.04	0.13	0.03	2.18	0.01	<0.01	98.51	0.51	0.10
2.	Algeria	75.39	5.81	1.19	15.31	1.18	0.24	7.40	0.57	0.12	1.06	0.08	0.02	99.16	7.64	1.56
3.	Morocco	3.78	0.05	0.01	43.93	0.61	0.12	46.02	0.63	0.13	4.25	0.06	0.01	97.98	1.35	0.28
4.	Libya	82.15	4.43	0.91	16.91	0.91	0.19	0.93	0.05	0.01	0.00	0.00	0.00	99.99	5.40	1.10
5.	Egypt	89.15	2.93	0.60	10.65	0.35	0.07	0.00	0.00	0.00	0.00	0.00	0.00	99.80	3.28	0.67
6.	W. Sahara	91.12	0.81	0.17	8.76	0.08	0.02	0.00	0.00	0.00	0.00	0.00	0.00	99.87	0.89	0.18
7.	Mauritania	52.87	1.84	0.38	46.59	1.62	0.33	0.47	0.02	<0.01	0.00	0.00	0.00	99.94	3.48	0.71
8.	Mali	31.22	1.31	0.27	39.45	1.65	0.34	21.82	0.91	0.19	7.26	0.30	0.06	99.77	4.17	0.85
9.	Niger	50.48	2.00	0.41	43.43	1.72	0.35	6.09	0.24	0.05	0.00	0.00	0.00	99.99	3.96	0.81
10.	Chad	37.99	1.61	0.33	31.29	1.33	0.27	26.19	1.11	0.23	4.37	0.19	0.04	99.83	4.24	0.87
11.	Sudan	36.26	2.27	0.46	40.45	2.53	0.52	23.17	1.45	0.30	0.11	0.01	<0.01	99.99	6.26	1.28
12.	Eritrea	0.11	<0.01	<0.01	63.26	0.25	0.05	35.95	0.14	0.03	0.07	<0.01	<0.01	99.38	0.40	0.08
13.	Cape Verde	0.00	0.00	0.00	40.06	0.01	<0.01	50.64	0.01	<0.01	2.10	<0.01	<0.01	92.80	0.01	<0.01
14.	Senegal	0.00	0.00	0.00	20.70	0.14	0.03	62.56	0.41	0.08	15.25	0.10	0.02	98.52	0.65	0.13
15.	Burkina Faso	0.00	0.00	0.00	5.31	0.05	0.01	77.84	0.72	0.15	16.85	0.15	0.03	99.99	0.92	0.19
16.	Ethiopia	0.00	0.00	0.00	27.46	1.04	0.21	34.15	1.29	0.26	12.88	0.49	0.10	74.50	2.82	0.58
17.	Nigeria	0.00	0.00	0.00	3.23	0.10	0.02	32.79	1.00	0.20	23.64	0.72	0.15	59.65	1.81	0.37
18.	Gambia	0.00	0.00	0.00	0.00	0.00	0.00	91.01	0.03	0.01	8.64	<0.01	<0.01	99.64	0.04	0.01
19.	Cameroon	0.00	0.00	0.00	0.85	0.01	<0.01	8.30	0.13	0.03	4.97	0.08	0.02	14.12	0.22	0.05
20.	Djibouti	0.00	0.00	0.00	97.35	0.07	0.01	2.49	<0.01	<0.01	0.00	0.00	0.00	99.84	0.07	0.01
21.	Guinea-Bissau	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6.26	0.01	<0.01	6.26	0.01	<0.01
22.	Guinea	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	10.94	0.09	0.02	10.94	0.09	0.02
23.	Benin	0.00	0.00	0.00	0.00	0.00	0.00	17.72	0.07	0.01	76.82	0.30	0.06	94.55	0.37	0.07
24.	South Sudan	0.00	0.00	0.00	0.03	<0.01	<0.01	64.96	1.37	0.28	22.23	0.47	0.10	87.22	1.84	0.38
25.	Somalia	5.12	0.11	0.02	67.31	1.43	0.29	27.51	0.58	0.12	0.00	0.00	0.00	99.93	2.12	0.43
26.	Ghana	0.00	0.00	0.00	0.00	0.00	0.00	1.84	0.01	<0.01	39.58	0.32	0.06	41.42	0.33	0.07
27.	Togo	0.00	0.00	0.00	0.00	0.00	0.00	1.63	<0.01	<0.01	51.70	0.10	0.02	53.33	0.10	0.02
28.	Central Afr. R.	0.00	0.00	0.00	0.00	0.00	0.00	7.54	0.16	0.03	22.30	0.46	0.09	29.84	0.62	0.13
29.	Ivory Coast	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	33.08	0.36	0.07	33.08	0.36	0.07
30.	D.R. of Congo	0.00	0.00	0.00	0.00	0.00	0.00	0.44	0.03	0.01	7.34	0.57	0.12	7.78	0.61	0.12
31.	Kenya	0.00	0.00	0.00	38.14	0.74	0.15	43.49	0.85	0.17	8.22	0.16	0.03	89.86	1.75	0.36
32.	Uganda	0.00	0.00	0.00	0.00	0.00	0.00	9.30	0.08	0.02	29.60	0.24	0.05	38.90	0.31	0.06
33.	Tanzania	0.00	0.00	0.00	0.00	0.00	0.00	27.31	0.86	0.18	39.45	1.24	0.25	66.76	2.10	0.43
34.	Rwanda	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	41.27	0.03	0.01	41.27	0.03	0.01
35.	Burundi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	17.54	0.02	<0.01	17.54	0.02	<0.01
36.	Angola	0.14	0.01	<0.01	3.04	0.13	0.03	30.24	1.26	0.26	19.38	0.81	0.17	52.79	2.20	0.45
37.	Zambia	0.00	0.00	0.00	0.00	0.00	0.00	28.84	0.72	0.15	36.51	0.92	0.19	65.35	1.64	0.34
38.	Malawi	0.00	0.00	0.00	0.00	0.00	0.00	5.94	0.02	<0.01	45.71	0.18	0.04	51.65	0.20	0.04
39.	Mozambique	0.00	0.00	0.00	0.03	<0.01	<0.01	30.84	0.81	0.17	36.36	0.96	0.20	67.23	1.77	0.36
40.	Madagascar	0.00	0.00	0.00	0.01	<0.01	<0.01	21.09	0.42	0.09	7.23	0.14	0.03	28.33	0.56	0.11
41.	Zimbabwe	0.00	0.00	0.00	0.95	0.01	<0.01	81.77	1.07	0.22	14.81	0.19	0.04	97.53	1.27	0.26
42.	Namibia	5.63	0.15	0.03	55.26	1.52	0.31	39.06	1.08	0.22	0.00	0.00	0.00	99.94	2.75	0.56
43.	Botswana	0.00	0.00	0.00	27.94	0.54	0.11	72.06	1.39	0.28	0.00	0.00	0.00	99.99	1.93	0.40
44.	South Africa	0.01	<0.01	<0.01	31.15	1.27	0.26	49.84	2.03	0.41	11.45	0.47	0.10	92.45	3.76	0.77
45.	Swaziland	0.00	0.00	0.00	0.00	0.00	0.00	41.04	0.02	<0.01	24.42	0.01	<0.01	65.47	0.04	0.01
46.	Lesotho	0.00	0.00	0.00	0.00	0.00	0.00	13.31	0.01	<0.01	50.98	0.05	0.01	64.30	0.07	0.01

Note: * the states are listed in a descending order considering the maximum latitude values of northern limits; †, †† and ††† refer to the drylands systems percentage (the four classes and the total) of the total state, continental (Africa) and global areas; abbreviations: W. Sahara – Western Sahara, Central Afr. R. – Central African Republic, D.R. of Congo – Democratic Republic of the Congo.

Table 6
Drylands extent at state level in Asia.

No.*	Country	Drylands' share of total country/continental/global area (%)														
		Hyper-arid			Arid			Semi-arid			Dry sub-humid			Total drylands		
		†	††	†††	†	††	†††	†	††	†††	†	††	†††	†	††	†††
1.	Russia**	0.00	0.00	0.00	<0.01	<0.01	<0.01	4.25	1.23	0.37	18.45	5.35	1.62	22.70	6.58	2.00
2.	Kazakhstan	0.00	0.00	0.00	32.76	2.00	0.61	61.33	3.75	1.14	3.75	0.23	0.07	97.84	5.98	1.82
3.	China	5.08	1.07	0.32	16.97	3.57	1.08	22.87	4.82	1.46	11.56	2.43	0.74	56.48	11.89	3.61
4.	Mongolia	<0.01	<0.01	<0.01	40.70	1.43	0.43	50.51	1.77	0.54	6.07	0.21	0.06	97.28	3.41	1.04
5.	Uzbekistan	0.00	0.00	0.00	79.83	0.80	0.24	16.25	0.16	0.05	1.20	0.01	<0.01	97.28	0.98	0.30
6.	Georgia	0.00	0.00	0.00	0.00	0.00	0.00	4.15	0.01	<0.01	9.61	0.02	<0.01	13.77	0.02	0.01
7.	Kyrgyzstan	0.00	0.00	0.00	0.41	<0.01	<0.01	45.58	0.20	0.06	24.39	0.11	0.03	70.38	0.31	0.10
8.	North Korea	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	<0.01	<0.01	0.04	<0.01	<0.01
9.	Turkmenistan	0.00	0.00	0.00	93.32	1.03	0.31	6.67	0.07	0.02	0.01	<0.01	<0.01	99.99	1.10	0.33
10.	Turkey	0.00	0.00	0.00	0.00	0.00	0.00	38.74	0.68	0.21	32.53	0.57	0.17	71.27	1.25	0.38
11.	Azerbaijan	0.00	0.00	0.00	0.00	0.00	0.00	63.54	0.12	0.04	19.59	0.04	0.01	83.13	0.16	0.05
12.	Armenia	0.00	0.00	0.00	0.00	0.00	0.00	26.98	0.02	0.01	35.08	0.02	0.01	62.06	0.04	0.01
13.	Tajikistan	0.00	0.00	0.00	8.44	0.03	0.01	29.48	0.09	0.03	10.40	0.03	0.01	48.32	0.15	0.05
14.	Iran	0.74	0.03	0.01	74.50	2.71	0.82	23.00	0.84	0.25	0.93	0.03	0.01	99.17	3.61	1.10
15.	Afghanistan	3.59	0.05	0.02	45.53	0.66	0.20	35.99	0.52	0.16	3.74	0.05	0.02	88.86	1.29	0.39
16.	Iraq	0.00	0.00	0.00	85.49	0.86	0.26	8.88	0.09	0.03	4.50	0.05	0.01	98.87	0.99	0.30
17.	Syria	0.00	0.00	0.00	73.64	0.31	0.09	21.57	0.09	0.03	1.36	0.01	<0.01	96.57	0.40	0.12
18.	Pakistan	1.51	0.03	0.01	71.82	1.41	0.43	17.32	0.34	0.10	3.13	0.06	0.02	93.77	1.84	0.56
19.	Cyprus	0.00	0.00	0.00	0.00	0.00	0.00	75.59	0.02	<0.01	13.55	<0.01	<0.01	89.14	0.02	0.01
20.	India	0.00	0.00	0.00	6.96	0.49	0.15	31.90	2.26	0.69	18.55	1.32	0.40	57.41	4.07	1.24
21.	Lebanon	0.00	0.00	0.00	0.00	0.00	0.00	18.44	<0.01	<0.01	16.16	<0.01	<0.01	34.60	0.01	<0.01
22.	Israel	3.26	<0.01	<0.01	53.25	0.03	0.01	37.21	0.02	0.01	4.21	<0.01	<0.01	97.93	0.05	0.01
23.	Jordan	26.35	0.05	0.02	66.86	0.13	0.04	6.79	0.01	<0.01	0.00	0.00	0.00	99.99	0.20	0.06
24.	Palestine***	0.00	0.00	0.00	28.24	<0.01	<0.01	71.59	0.01	<0.01	0.00	0.00	0.00	99.83	0.01	<0.01
25.	Saudi Arabia	29.39	1.26	0.38	70.53	3.03	0.92	0.01	<0.01	<0.01	0.00	0.00	0.00	99.94	4.29	1.30
26.	Nepal	0.00	0.00	0.00	0.00	0.00	0.00	1.37	<0.01	<0.01	4.70	0.02	<0.01	6.07	0.02	0.01
27.	Kuwait	0.00	0.00	0.00	99.04	0.04	0.01	0.00	0.00	0.00	0.00	0.00	0.00	99.04	0.04	0.01
28.	Myanmar	0.00	0.00	0.00	0.00	0.00	0.00	5.45	0.08	0.02	5.65	0.09	0.03	11.10	0.17	0.05
29.	Bhutan	0.00	0.00	0.00	0.00	0.00	0.00	15.78	0.01	<0.01	10.12	0.01	<0.01	25.90	0.02	0.01
30.	Oman	57.94	0.40	0.12	41.58	0.29	0.09	0.36	<0.01	<0.01	0.00	0.00	0.00	99.88	0.70	0.21
31.	Bahrain	0.00	0.00	0.00	84.88	<0.01	<0.01	0.00	0.00	0.00	0.00	0.00	0.00	84.88	<0.01	<0.01
32.	Qatar	0.00	0.00	0.00	97.36	0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.00	97.36	0.02	0.01
33.	U.A.E.	11.14	0.02	0.01	87.58	0.16	0.05	0.00	0.00	0.00	0.00	0.00	0.00	98.73	0.18	0.05
34.	Vietnam	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.46	<0.01	<0.01	0.46	<0.01	<0.01
35.	Thailand	0.00	0.00	0.00	0.00	0.00	0.00	0.06	<0.01	<0.01	12.35	0.14	0.04	12.42	0.14	0.04
36.	Yemen	4.88	0.05	0.02	91.29	0.93	0.28	3.73	0.04	0.01	0.00	0.00	0.00	99.90	1.02	0.31
37.	Cambodia	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.34	<0.01	<0.01	0.34	<0.01	<0.01
38.	Indonesia	0.00	0.00	0.00	0.00	0.00	0.00	0.03	<0.01	<0.01	0.18	0.01	<0.01	0.20	0.01	<0.01
39.	East Timor	0.00	0.00	0.00	0.00	0.00	0.00	0.35	<0.01	<0.01	2.26	<0.01	<0.01	2.60	<0.01	<0.01

Note: * the states are listed in a descending order considering the maximum latitude values of northern limits; ** area of Russia in relation to the Asian continent; *** states with disputed sovereignty; †, †† and ††† refer to the drylands systems percentage (the four classes and the total) of the total state, continental (Asia) and global areas; abbreviations: U.A.E. – United Arab Emirates.

Sternberg, 2013). It was found that the Algerian Sahara dust affects the population even due to human inhalation and ingestion of radioactive contaminated particles (with $^{239-240}$Pu, ^{137}Cs and ^{90}Sr radionuclides), originating from certain sites (Reggane and Ekker) where France tested nuclear weapons between 1960 and 1966 (Prăvălie, 2014).

There are however certain notable positive aspects of Saharan dust. Climate cooling by reducing the incoming solar radiation is a well-known such effect (Zhao et al., 2014). Another positive example is the Bodélé Depression in Chad, which, seeing as it produces ~50% of the mineral aerosols emitted by Sahara (one of the world's largest dust sources), it supplies essential nutrients to certain terrestrial (Amazon rainforest) and marine (Atlantic phytoplankton ecosystems, Caribbean coral reefs) ecosystems located at far distances (Washington et al., 2009). This mechanism can also limit climate warming. By means of atmospheric transport, the Bodélé Depression supplies iron to the Atlantic Ocean surface waters, a vital nutrient stabilizing phytoplankton, thus indirectly contributing to the biological storage of carbon into the deep ocean, when these microscopic organisms that assimilate CO_2 by photosynthesis die (Washington et al., 2009). Moreover, iron fertilization is crucial due to the fact that, over the past decades, global phytoplankton

Table 7
Drylands extent at state level in Australia and Oceania.

No.*	Country	Drylands' share of total country/continental/global area (%)														
		Hyper-arid			Arid			Semi-arid			Dry sub-humid			Total drylands		
		†	††	†††	†	††	†††	†	††	†††	†	††	†††	†	††	†††
1.	Australia	0.00	0.00	0.00	50.73	48.09	2.66	34.81	32.99	1.83	5.54	5.25	0.29	91.08	86.34	4.78
2.	Kiribati	0.00	0.00	0.00	0.00	0.00	0.00	29.29	<0.01	<0.01	28.53	<0.01	<0.01	57.82	0.01	<0.01
3.	New Zealand	0.00	0.00	0.00	0.00	0.00	0.00	0.18	0.01	<0.01	1.43	0.05	<0.01	1.61	0.05	<0.01

Note: * the states are listed in a descending order considering the maximum latitude values of northern limits; †, †† and ††† refer to the drylands systems percentage (the four classes and the total) of the total state, continental (Australia and Oceania) and global surfaces.

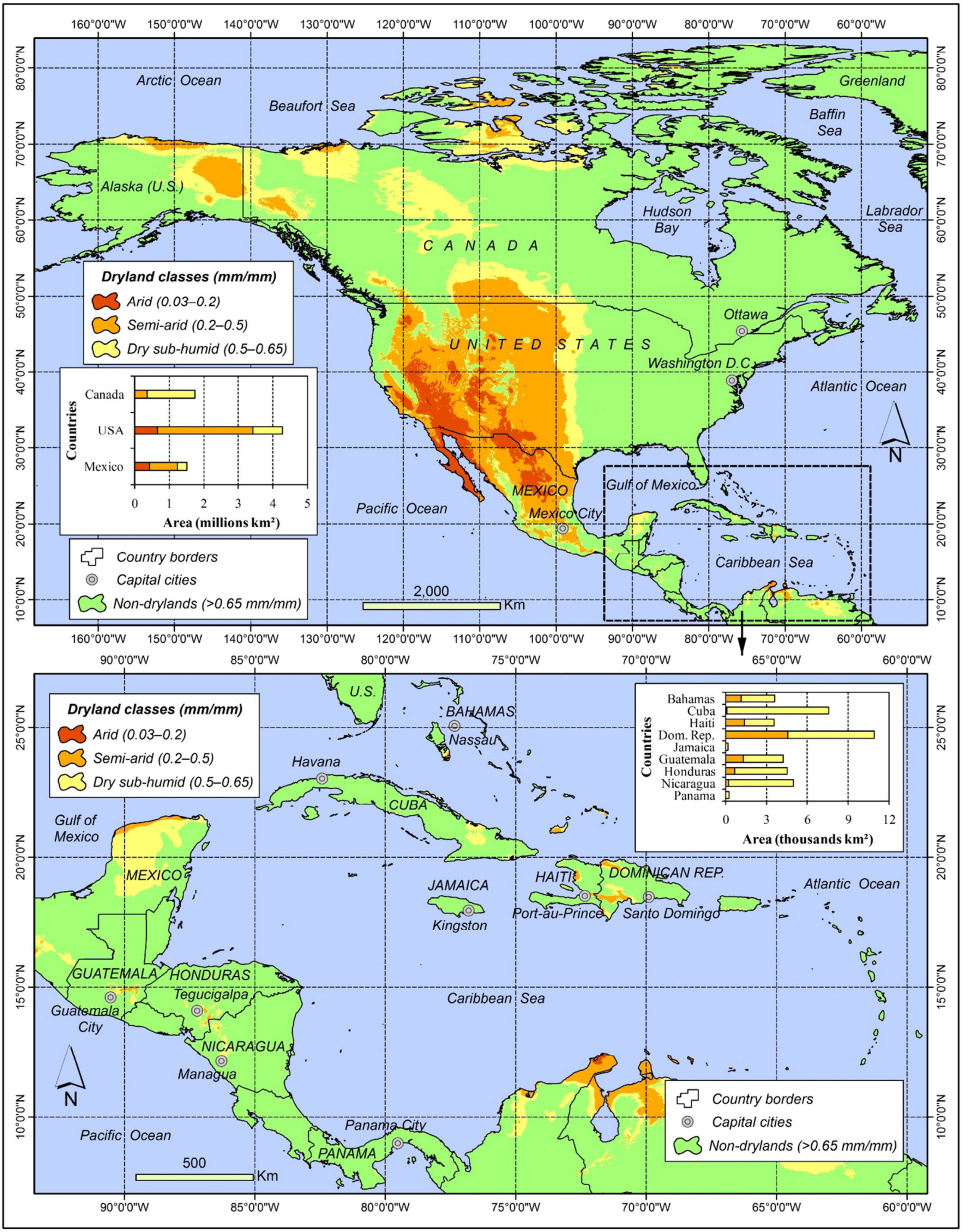

Fig. 3. Spatial representation of dryland systems in North and Central America. Note: absolute values of drylands area were obtained for country polygons (provided by http://www.gadm.org), by using the Mollweide projection (Central Meridian: 0.00).

Fig. 4. Spatial representation of dryland systems in South America. Note: absolute values of drylands area were obtained for country polygons (provided by http://www.gadm.org), using the Mollweide projection (Central Meridian: 0.00).

concentrations have declined dramatically (especially in the Atlantic) – by ~1% of the global mean chlorophyll concentration per year, amid sea surface temperature increase (Boyce et al., 2010).

Land degradation is generally present in all African drylands, in every multidimensional form (except for soil salinization), and may be the continent's most severe environmental problem. This issue was thoroughly analyzed by Dregne (2002), who highlighted the large-scale, long lasting anthropogenic causes of land degradation in the continent's northern, southern, western and eastern regions, i.e. overgrazing, deliberately set fires, fuelwood cutting and poor agricultural practices. Some of these anthropogenic pressures are still ongoing at alarming rates, as is the case of the massive deforestation

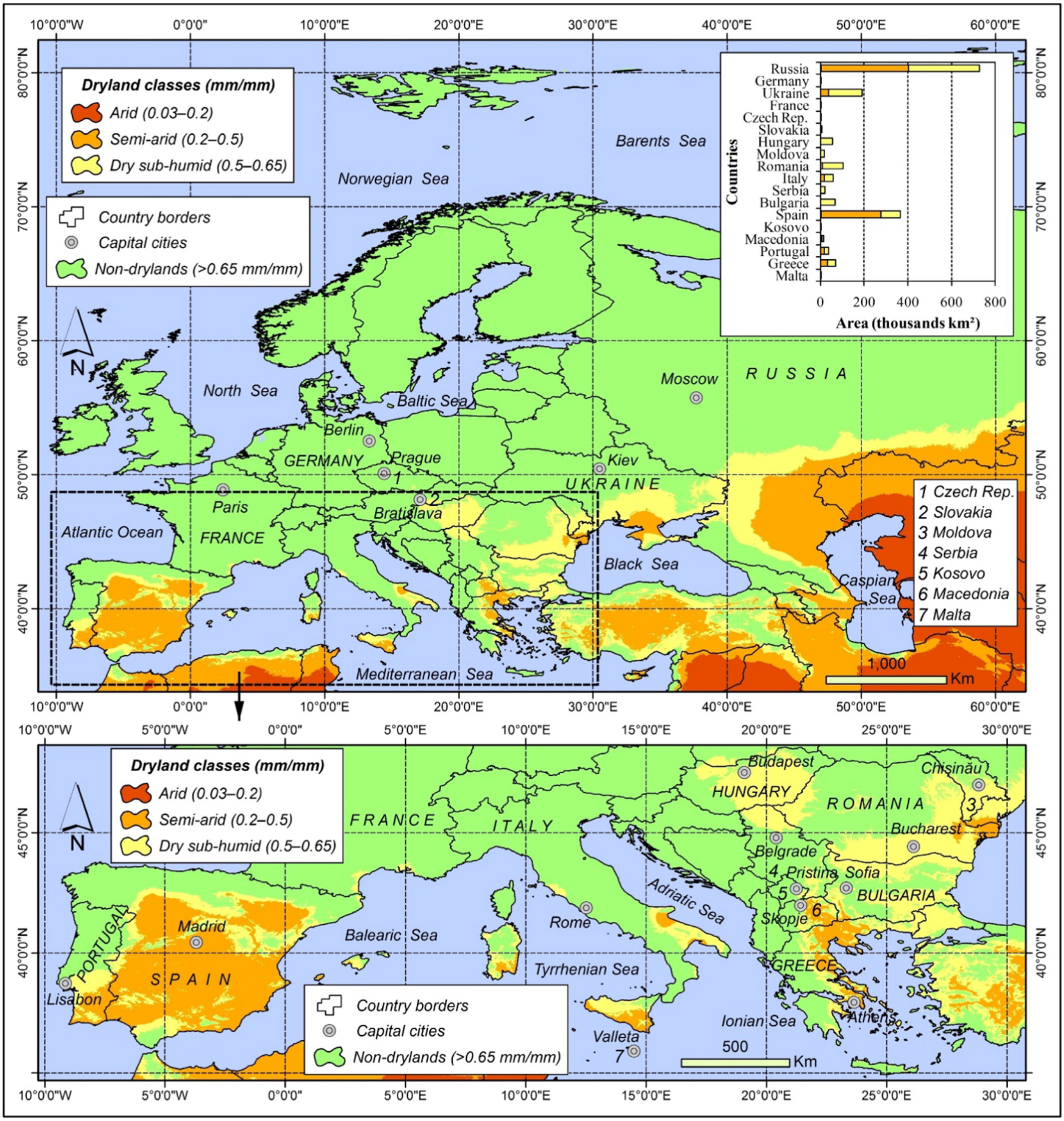

Fig. 5. Spatial representation of dryland systems in Europe. Note: absolute values of drylands area were obtained for country polygons (provided by http://www.gadm.org), using the Mollweide projection (Central Meridian: 0.00).

practices in countries such as Angola, Zambia, Zimbabwe, Mozambique or Tanzania (Hansen et al., 2013). As a result, water erosion is by far the most severe form of land degradation (especially in eastern and southern Africa, but also in the Maghreb countries, where gully, rill, and sheet erosion are dominant), followed by wind erosion (particularly intense in Sahel countries, from Mauritania/Senegal to Sudan) (Dregne, 2002). These effects had serious implications in severe nutrient depletion, as seen in sub-Saharan Africa, generally marked by poor conditions of agricultural practices (<3% of total cropland is under sustainable land and water management practices) and soil fertility (Nkonya et al., 2011). All these problems have intensified over the past decades by extreme drought phenomena, particularly in sub-Saharan and eastern Africa drylands (Middleton et al., 2011; Middleton and Sternberg, 2013).

Water stress is another one of the continent's major problems, which peaks in northern Africa, the Sahel region, eastern and southern Africa (Vörösmarty et al., 2005). The major northwest Sahara aquifer, which crosses the borders of Algeria, Libya and Tunisia over an area of 1.2 mil km^2 (Abotalib et al., 2016), is currently undergoing an apparent decline, as a result of unsustainable use of groundwater by deep drilling,

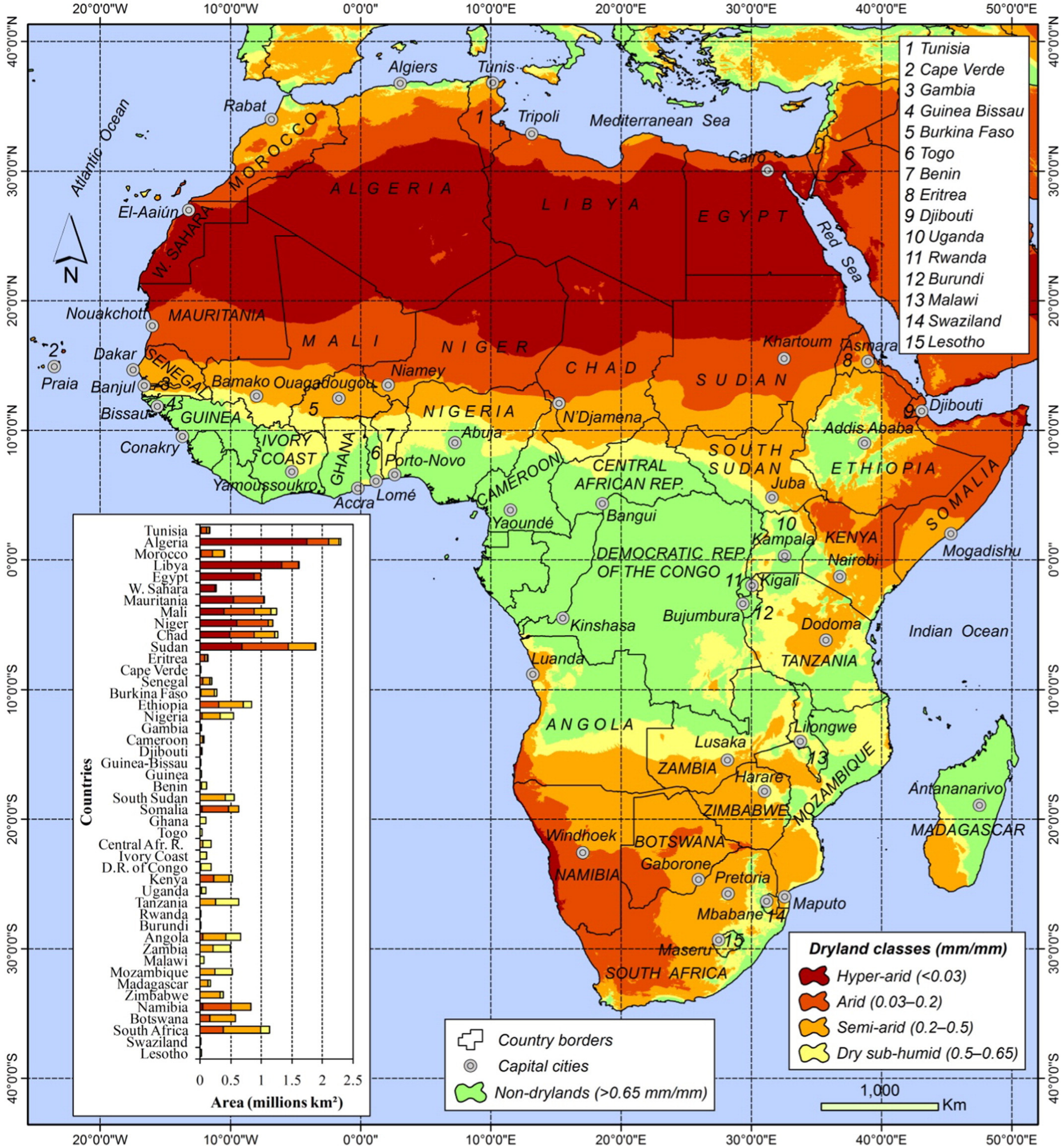

Fig. 6. Spatial representation of dryland systems in Africa. Note: absolute values of drylands area were obtained for country polygons (provided by http://www.gadm.org), using the Mollweide projection (Central Meridian: 0.00).

which can even exceed 2 km (Famiglietti, 2014). However, its retreat rate is considerably lower than those of the other large global aquifers (Famiglietti, 2014).

Also, sub-Saharan countries are extremely vulnerable in that rain-fed agriculture accounts for 35% of the gross domestic product, and for >70% of employment (Rockström and Karlberg, 2010). Considering the overall precipitation decline that is expected (IPCC, 2013), it appears that the increase in the region's water security instability in this century will be inevitable. Under these circumstances, significant demographic changes are also expected in sub-Saharan African drylands, as a result of an increase in human migration (Kniveton et al., 2012). At the same time, due to food crises, drought is a determining factor of socio-economic destabilization in other African regions as well. Eastern Africa is an illustrative example, seeing as, in the past two decades, it totaled almost 60% of all African drought events, including the extreme event of 2005, which caused food insecurity for >11 million people (CRED, 2015).

Moreover, the entire continent is expected to see a 54% increase in armed conflict incidence by 2030 alone, due to the climate warming that will dramatically affect agricultural systems by increasing the climatic water deficit (Burke et al., 2009). This conclusion is based on the fact that the economic wellbeing of African dryland poor countries, the main triggering factor of war conflicts on the continent, mainly depends on agricultural yields (60–100% of the African communities' income is based on agriculture, especially in poor rural areas), which generally decrease by 10%–30% per °C of temperature rise (Burke et al., 2009). However, other research found the role of temperature rise in African civil wars to be less substantial, highlighting certain noteworthy additional causes such as interethnic conflicts and geopolitical international events (Buhaug, 2010).

Another alarming aspect is disease emergence, of which the most important is malaria. It is estimated that between one and three million people die of malaria each year in the world, mainly in sub-Saharan Africa (Chaves and Koenraadt, 2010). The most important hotspot of malaria incidence increase in recent decades is found in East African highlands (Ethiopia, Kenya, Uganda, Tanzania), due to certain driving patterns such as climate change (climate warming, atmospheric humidity increase as a result of evapotranspiration increase), demographic aspects (population increase, migration, health services decline), land use changes or antimalarial drug resistance (Chaves and Koenraadt, 2010; Alonso et al., 2011).

It is highly probable that by the end of the century these problems will escalate, considering that most of the climate simulations indicate a significant expansion of the most critical climates, arid (in the south, especially towards the eastern regions of Namibia and Botswana, but also in the Sahel region) and hyper-arid (mostly in sub-Saharan Africa) (Huang et al., 2016). Although all dryland systems will expand in Africa to some extent, the expansion of the arid climate (i.e. the transition from semi-arid to arid climate) is of particular interest, primarily in terms of biogeochemical imbalances. It was found that biogeochemical cycles are most fragile in the areas of transition from semi-arid to arid climates, where the decline in organic C and total N, and the increase in inorganic P are the steepest, thus resulting nonlinear disturbances of C, N and P cycles (Delgado-Baquerizo et al., 2013). These issues are particularly important for Africa, as it is the continent that has the most extensive transition to an arid climate (expected by 2100), alongside Asia (especially in north-eastern China) and, partially, North America (generally, large parts of Mexico) and Australia (eastern areas) (Huang et al., 2016). On the opposite end, an amelioration of aridity conditions is expected especially in some areas of eastern Africa (Feng and Fu, 2013; Huang et al., 2016).

3.5. Asia

Approximately half of the Earth's largest continent area, Asia (~45 mil km^2), is made up of drylands, which consist of over 70% arid (~8.9 mil km^2, 20% of the continent) and semi-arid (7.7 mil km^2, 17%) systems (Fig. 7, Table 1). Of the 39 states that have dryland systems, China is by far the most heavily affected by aridity (5.3 mil km^2, more than half its area of ~9.4 mil km^2), with absolute drylands that are twice as large as the other 38 countries (except for Russia and Kazakhstan, where aridity affects ~2.9 mil km^2, and ~2.7 mil km^2) (Fig. 7, Table 6). While extensive absolute areas, exceeding 1.5 mil km^2, are also found in other countries such as Saudi Arabia, India, Iran and Mongolia, Saudi Arabia is a particular case of the Asian continent in that it comprises the largest hyper-arid climate area (>0.5 mil km^2) (Fig. 7, Table 6).

As it was to be expected, a critical issue of Asian drylands consists of wind erosion, especially in the continent's major deserts, such as the Arabian desert (states of the Arabian Peninsula and parts of Iraq and Jordan), Syrian desert (Syria, Iraq and Jordan), Karakum (Turkmenistan), Kyzylkum (Kazakhstan, Uzbekistan, Turkmenistan), Taklamakan (China), Gobi (China, Mongolia) and Thar (India, Pakistan). The two most populous countries in the world, China and India (over 2.5 mld people, ~35% of the global population), are of particular interest in this respect, as they include extensive areas affected by wind erosion (especially in northern drylands of China and western drylands of India) (Dregne, 2002), which menaces a population of hundreds of millions. For instance, it is estimated that this land degradation process was strongly affecting over 200 million people in northern China (Gobi Desert and adjacent areas) as far back as half a century ago (Wang et al., 2010). Presently, this type of desertification is affecting extensive areas mainly located in the country's northwestern, northern and northeastern regions (Wang et al., 2008). However, this country, the world's most populated state, is also known for a process called rocky desertification (another form of land degradation consisting of the transformation of karst areas covered by soil and vegetation into rocky lands), which mainly occurs in extensive areas in the southwest (Jiang et al., 2014), as well as in some of the region's small-scale dryland areas.

According to Dregne (2002), water erosion is another main cause of land degradation in the vast drylands of the two countries (in Loess Plateau in China and in the Indian eastern drylands), as well as in those of other densely populated countries on the continent (e.g. Pakistan, in northern drylands); the process is also dominant in highlands/bare mountain areas of Turkey, Iran, Iraq and Afghanistan. The same study states that other important dimensions of land degradation consist of salinization (in extensive dryland parts din China, former Soviet countries, Arabian Peninsula and irrigated areas of the Mesopotamian Plain and the Indus Valley) and vegetation degradation (especially in certain parts of China, Mongolia and central Asia). Land salinization is of interest considering the fact that Asia is seemingly the continent with the most extensive saline soils (D'Odorico et al., 2013), which is due, to a large extent, to several anthropogenic causes (in addition to the natural conditions) that aggravated the process in certain areas of the continent. Such instances are central (the Aral Sea drying in Kazakhstan and Uzbekistan due to the expanding irrigation of the 1960s, which drastically diminished the discharge from the Syr Darya and Amu Darya tributary rivers) (Micklin, 2007) and eastern Asia (land salinization in northeastern China due to the raising of the water table in saline subsoils as a result of the elimination of shrubs and grasses in order to expand croplands) (Dregne, 2002). In the future, the escalation of all these land degradation forms is possible in the Near and Middle East, but also in the eastern Asia, where a considerable expansion of arid and hyper-arid climates is expected (Huang et al., 2016).

Extreme climate events represent another severe problem for the continent, of which the most important are drought and the extreme hazard called dzud (Tachiiri et al., 2008). While drought, the most common natural hazard in almost all drylands, can have various implications, in Asia the indirect pressure on groundwater is particularly alarming. Asian drylands overlap four major global aquifers – North China Plain (China), Northwestern India (India, Pakistan), Arabian (Arabian Peninsula countries, Iraq, Jordan) and Northern Middle East aquifers (Iran, Iraq, Syria, Turkey), and they all recorded drastic decreases over the past decade, mainly due to overexploitation during droughts (Famiglietti, 2014). The most critical situations found with the Northwestern India aquifer (Glazer and Likens, 2012), which recently had the highest depletion rates of all major dryland aquifers of Earth, approximately twice as high as the North China Plain and Northern Middle East (Asia) aquifers, or California Central Valley in North America (Famiglietti, 2014). Although it is possible for these trends to cause food insecurity or water conflicts, a general solution for the Asian water crisis seems to reside in the massive virtual water imports (international cereal commerce) (Barnaby, 2009), that almost tripled on the continent in the past decades (Dalin et al., 2012).

Dzud, a phenomenon associated to extreme winter cold conditions (snow and ice), can cause problems in some parts of Asia (Mongolia) by creating inaccessibility or unavailability for forage, needed for

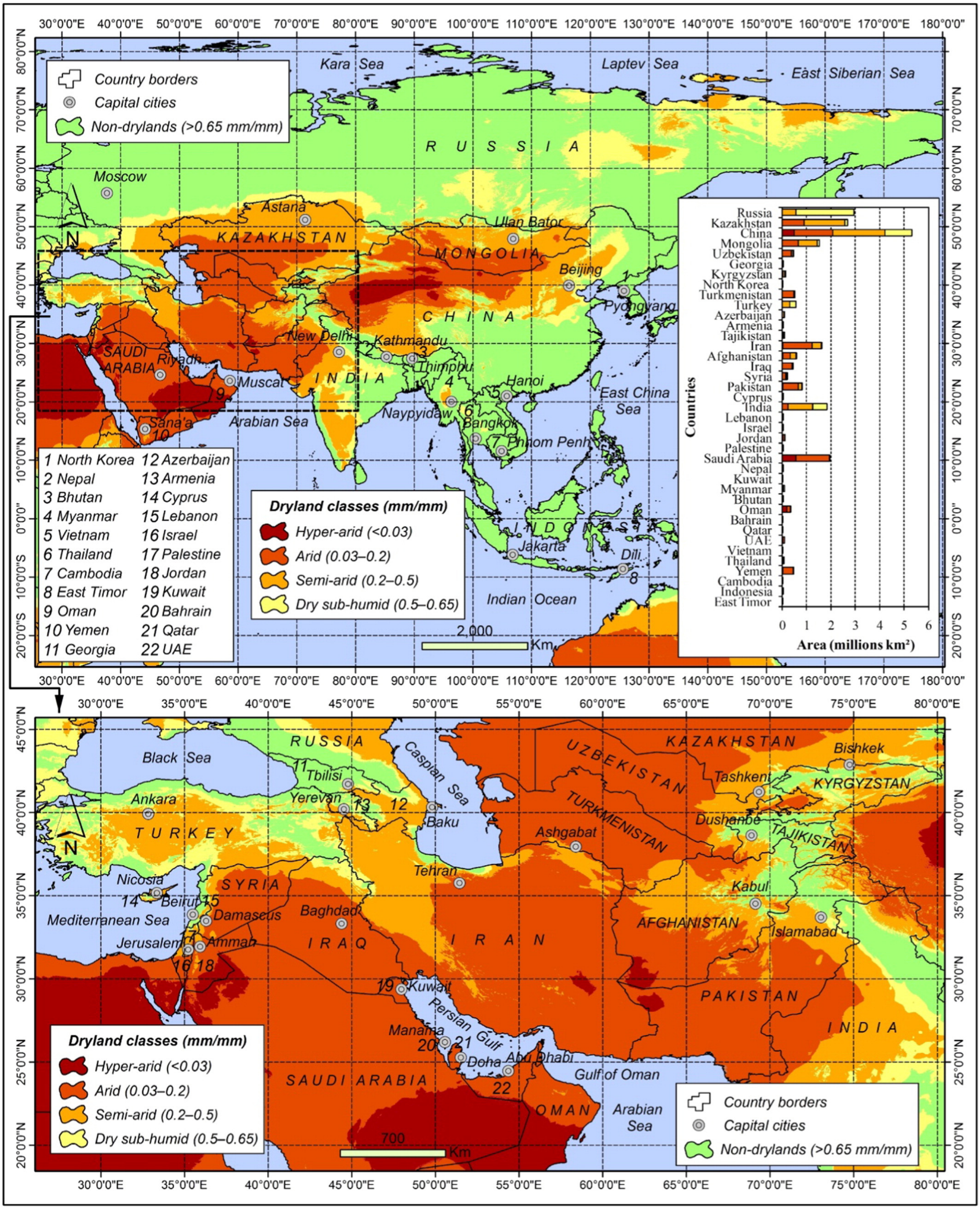

Fig. 7. Spatial representation of dryland systems in Asia. Note: absolute values of drylands area were obtained for country polygons (provided by http://www.gadm.org), using the Mollweide projection (Central Meridian: 0.00).

ensuring livestock survival (Fernández-Giménez et al., 2012). More specifically, this disaster consists of critical weather conditions during winter (generally deep snow and severe cold) that, coupled with poor forage conditions in the previous summer (especially due to drought), are responsible for mass livestock loss, primarily due to the animals' inability to graze (Tachiiri et al., 2008; Fernández-Giménez et al., 2012). It is estimated that, in Mongolia, dzud events such as the ones in 1999–2001 or 2009–2010 caused catastrophic damages to the country, increasing national herd mortality to 30% and 20%, which translates into ~10 million animals in both cases (Middleton et al., 2011; Middleton and Sternberg, 2013). The phenomenon is not endemic to the Asian continent, and also occurs in high-altitude drylands of the Peruvian Andes (South America), where it accounts for the high mortality of alpaca herds (Middleton et al., 2011).

Similarly to North America, aridity at high latitudes in Asia is a major threat for the cryosphere and, implicitly, to the climate system. Destabilizing the Yedoma permafrost in north-eastern Siberia (Russia), which overlaps the region's dryland systems to a high extent (Fig. 7), is by far the greatest danger to climate warming, given the possible positive feedback generated by releasing CO_2 and CH_4 into the atmosphere (Schuur et al., 2015). In addition to aridity-related pressure (through high average multiannual evapotranspiration), it is possible for black carbon particle deposits on snow and ice to be another major cause of permafrost deterioration (due to an overall climate warming, in connection with albedo changes) in this particular region, as well as in extensive areas in northern Eurasia and North America (Molina et al., 2009). This reasoning is based on the fact that black carbon's impact at high latitudes is generally highly aggressive, and it is estimated that between 0.5 and 1.4 °C of the total temperature increase of 1.9 °C in the Arctic (between 1890 and 2007) could be due to these particles (Molina et al., 2009). The cause for the Yedoma permafrost destabilization could therefore be two-dimensional, i.e. aridity intensification and, to a certain extent, the presence of these aerosols in the region. Although currently there are major concerns related to the fact that the Yedoma region is starting to release carbon from its massive deposits (~500 PgC, stored in a territory that exceeds 1 mil km^2, which encompasses even Central Alaska), which reach an average depth of 25 m (Zimov et al., 2006), its collapse is considered to be irreversible only at ~9 °C regional warming in the 21st century, which is however possible according to pessimistic emission scenarios (Lenton, 2012).

On a smaller spatial scale, permafrost degradation is an important environmental issue presently occurring at lower latitudes as well, i.e. in southwestern semi-arid areas of China, in the Tibetan Plateau. The high altitudes of the Tibetan Plateau, which total ~80% of China's permafrost, or 75% of the Northern Hemisphere's mountains permafrost, are also currently facing the dangers of CH_4 (and CO_2) release, given the context of the rapid retreat and thinning of these frozen areas over the past decades (due to a significant regional climate warming) (Yang et al., 2010). However, it must be noted that methane emissions are at present much lower than in the case of high-latitude permafrost (Yang et al., 2010). At the same time, widespread permafrost deterioration is also responsible for other collateral issues in the region, such as desertification expansion (with an estimated annual rate of ~2%, mainly in the northern, western and eastern regions of the plateau), surface hydrology changes (against the background of snow and ice melt, due to climate warming of ~1 °C in the region, after 1950), or human infrastructure destabilization (e.g. the 1118 km-long Qinghai–Tibetan Railway, of which more than half is built on permafrost terrain, vulnerable to both the current warming, and especially to the one expected for the remainder of the century) (Yang et al., 2010).

3.6. Australia and Oceania

Although drylands are present only in a few small areas of Oceania, in New Zealand (~4300 km^2) and Kiribati (>500 km^2, in Line Islands, most of which in Kiritimati – the country's largest island), Australia is by far the most arid territory – 7 mil km^2 (~90% of the continent), of which 94% with arid and semi-arid climates (Table 7, Fig. 8).

As the world's driest continent, considering the ratio of drylands to the continent's total area, Australia is currently facing several important

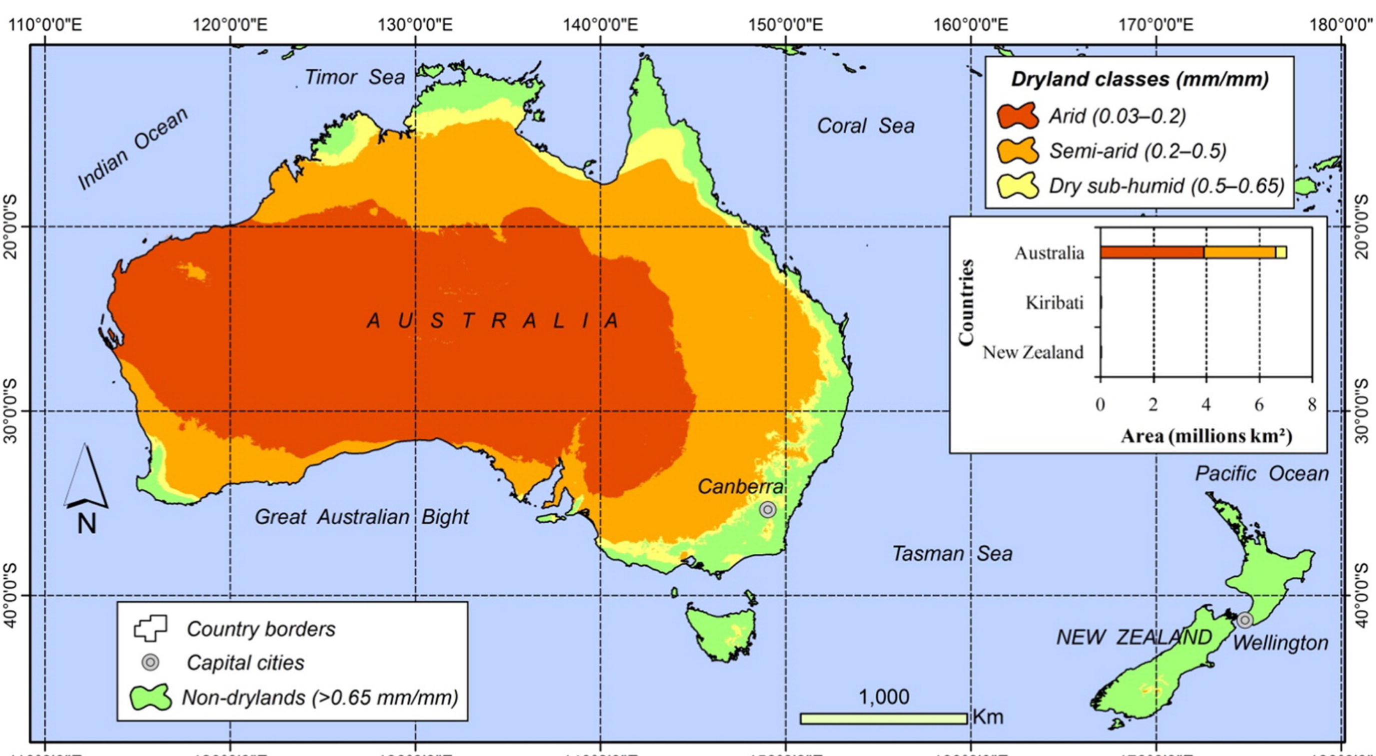

Fig. 8. Spatial representation of dryland systems of Australia and Oceania. Note: absolute values of drylands area were obtained for country polygons (provided by http://www.gadm.org), using the Mollweide projection (Central Meridian: 0.00).

environmental issues. They mainly related to land degradation, a process that has escalated as a result of the European colonization of the past two centuries, which has determined a series of swift transformations in the natural environments by increasing agricultural activity. The expansion of agricultural lands up to 60% of the continent's area, of which 90% is attributed to livestock grazing (Dregne, 2002), is therefore the main cause of the land systems' transformation, in the context of the prolonged pressure of overgrazing in the rangelands.

Presently, land salinization, soil erosion and natural vegetation loss are the main forms of land degradation (Dregne, 2002). Salinization is an extremely severe problem that affects ~30% of the Australian land area (Rengasamy, 2006), which could potentially make it the continent that is most severely affected by this environmental problem, given the extensive areas (in the west) of high salinity soils (D'Odorico et al., 2013). It is considered that, in addition to the natural topographic conditions that favored surface salt accumulation, land salinization in western Australia was caused by the elimination of deep-rooted native vegetation in order to ensure the anthropogenic expansion of pastures, which favored the rising of the saline groundwater table (Rengasamy, 2006). At the same time, excessive irrigation in the Murray-Darling Basin (south-east) is another anthropogenic cause for the continent's land salinization issue.

Natural causes, such as prolonged droughts, account for the intensification of certain dryland disturbances such as wind erosion and dust mobility (D'Odorico et al., 2013) in the Lake Eyre Basin – the primary dust source of the Australian region (Mitchell et al., 2010), or in the continent's main deserts (Great Victoria, Great Sandy, Tanami, Simpson and Gibson deserts). Dry periods also account for the frequent occurrence of large-scale fires (in certain years, e.g. 2000 and 2001, fires affected over 9% of all arid and semi-arid lands), which has disastrous implications for infrastructure, homesteads, public health, soil erosion or greenhouse gas emissions (Turner et al., 2011). At the same time, in the context of climate warming, droughts have also become a major factor in the diminishment of the continent's main water resources, surface – the Murray-Darling Basin (Cai and Cowan, 2008), or groundwater – Canning Basin aquifer (Famiglietti, 2014) resources. As arid and semi-arid climates are expected to expand towards east, certain problems identified in this region of the continent may grow more severe by the end of this century. However, this could be counterbalanced by a large-scale improvement in environmental conditions in the central and western regions of the continent, where an amelioration of the arid climate is expected (Huang et al., 2016).

4. Major international efforts for combatting dryland issues

Given the multidimensional problems raised by dryland systems, international initiatives on mitigating/stopping land degradation have intensified over the past decades, as this is the greatest threat of dry environments. Globally, the United Nations (UN) played an essential role first and foremost by creating the United Nations Convention to Combat Desertification (UNCCD) in 1994, in Paris (UNCCD, 1994), although the first actions started being implemented as early as two decades ago, at the United Nations Conference on Desertification (UNCOD) in 1977, which took place in Nairobi (UNCOD, 1977). Presently, UNCCD's reach is global (having been ratified by all member states of the UN), and action programs have been monitored at the twelve Conferences of the Parties planned between 1997 and 2015.

At the same time, other various initiatives have been carried out by the UN, through the United Nations Environment Programme (UNEP) or by certain UN specialized agencies. One of the largest contributions of UNEP to arid environments was sponsoring the first attempt to globally map (including humid regions) the human-induced soil degradation, through the Global Assessment of Soil Degradation – GLASOD project (Oldeman et al., 1990), on which the first (UNEP, 1992) and second (UNEP, 1997) editions of the World Atlas of Desertification were based. Although a major shortcoming of the study was omitting the vegetation degradation process, GLASOD was considered to be widely superior to similar studies conducted before 1990 (Dregne, 2002).

The analysis of vegetation degradation became available almost two decades later, through an ecological approach developed by the Food and Agriculture Organization (FAO) in the Land Degradation Assessment in Drylands – LADA project (Bai et al., 2008). With its two components – Global Land Degradation Assessment (GLADA) and Global Land Degradation Information System (GLADIS), the project can be considered one of the most important contributions of this UN specialized agency in understanding the genesis, expansion and severity of land degradation in global drylands (as well as in non-drylands), thus indirectly supporting the subsequent development of sustainable land management solutions (FAO, 2013).

Notable actions in fighting land degradation were also conducted by other UN specialized agencies, such as the United Nations Educational, Scientific and Cultural Organization (UNESCO), World Meteorological Organization (WMO) or World Bank Group (WBG). UNESCO is known to be the first UN agency to show interest in scientifically understanding arid environments, as it has been conducting related projects since the second half of the 20th century. A series of important projects were carried out after 1970 by UNESCO's Programme Man and the Biosphere, such as the remarkable Sustainable Management of Marginal Drylands – SUMAMAD (UNESCO, 2008).

Also, WMO, with its Agricultural Meteorology Programme, Hydrology and Water Resources Programme, or World Climate Programme, supported and encouraged international cooperation in order to improve the meteorological/hydrological/climatic conditions of desertification. Another example is WBG, which, through its Global Environment Facility Programme, supported the fight against desertification by offering international grants, as it is also one of UNCCD's financial instruments.

In addition to UN initiatives, the Consultative Group for International Agricultural Research (CGIAR), the spatial data source of the Global Aridity Index values used in this paper, is another international organization that plays a major role in identifying solutions for dryland issues, primarily through its International Center for Agricultural Research in the Dry Areas (ICARDA). With the help of the CGIAR Research Program on Dryland Systems, which it oversees, ICARDA is known to provide science-based systems solutions for African and Asian environmental issues, such as water scarcity, food insecurity, land degradation and climate change (ICARDA, 2015).

All these international initiatives, complemented by certain national projects, were essential for combating various global dryland issues in the past decades. However, given the speed and intensity of the climate changes expected to occur this century, which have a high potential of aggravating all dryland issues, it is necessary that global and regional efforts become faster, bigger and better. One of the most viable solutions would be the large-scale afforestation of degraded lands, as indicated by several ongoing projects such as the great green walls of China (Wang et al., 2010) and Sub-Saharan Africa (O'Connor and Ford, 2014), or the large-scale afforestation of fast-growing tree species in South America (Argentina, Paraguay, Uruguay) and Australia (Maestre et al., 2012a). In a wider context, a global solution would be climate change mitigation by means of geoengineering (carbon dioxide removal and solar radiation management techniques), considered to be promising techniques for limiting global warming by manipulating the climatic system on a large scale (Vaughan and Lenton, 2011).

5. Conclusions

Although drylands are restrictive environments due to water scarcity, they have a global importance in terms of spatial dimension, ecosystem diversity and anthropic complexity, considering in the last case that more than a third of the world population is condensed in these critical areas. The analysis of the drylands extent, using the Global Aridity Index (a high-resolution spatial climate database developed by the CGIAR

Consortium for Spatial Information), highlighted extensive global regions affected by aridity that total ~45% of the global land area, 4% more than the initial estimations found in most scientific sources. This difference is plausible, given the improved methodology for obtaining the Global Aridity Index (higher accuracy in estimating the PET) and especially the longer time periods of the data series, which included the climate warming recorded at the end of the 20th century, responsible for the spatial expansion of global aridity. Therefore, given the new findings regarding the current extent of arid environments, the study calls on the United Nations to reconsider the spatial distribution of the Globe's dryland systems, primarily in order to intensify global initiatives to fight desertification via UNCCD, UNEP or certain specialized UN agencies.

Considering the imminent climate warming of the next decades, it is possible that climatic aridity will reach a new critical spatial dimension by the end of the 21st century, which will correspond to roughly half of the global land area, or even more. This state of affairs is highly problematic, considering that the estimations presented in this paper suggest a far more aggressive expansion of systems that become drier in comparison with those that become wetter, which means the unanimously acknowledged statement "dry gets drier, wet gets wetter" could be reinterpreted as "dry gets drier, but more than wet gets wetter". In this context, the intensification of land degradation (the main environmental perturbation currently found in dryland systems) is to be expected, as is the anthropic crisis associated to the increase of poverty, food insecurity, human migration and regional political instability. Moreover, against the background of a possible rise in aridity at high latitudes, where dry sub-humid and semi-arid systems are already present, a major threat is the danger of destabilizing the cryosphere by the end of the century, which can speed up climate warming by releasing significant amounts of permafrost carbon, or by decreasing the albedo on a large scale.

However, all these imbalances can be mitigated by humanity by reaching a closer cooperation between nations, that will result in the implementation of concrete measures aimed at drastically limiting global warming. In this general respect, perhaps the most promising strategy, if not the only one, is to implement large-scale geoengineering solutions, especially the ones based on carbon sequestration that involve less risks for the Earth's systems.

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