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# Humusica 2, article 18: Techno humus systems and global change – Greenhouse effect, soil and agriculture*

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ABSTRACT

The article is structured in six sections. A first section is dedicated to the state of the art concerning climatic change and agriculture. Internet-available IPCC maps and cartographic documents made by scientific research centres were used for illustrating forecasted climatic changes. In sections 2 and 3, bibliographic evidences were collected for supporting a vegetation and soil co-evolution theory. Humus, soil and vegetation systems are presented at planetary level in many synthetic maps. In sections 4, 5 and 6 the authors discussed the human influence on soil evolution during the Anthropocene. It appears that humans detected and used Mull humus systems all over planet Earth for crop production and pasture. Human pressure impoverished these humus systems, which tend to evolve toward Amphi or Moder systems, losing their natural biostructure and carbon content.

* Background music while reading: Performance, Alice Phoebe Lou, TEDxBerlin: https://www.youtube.com/watch?v=BepU74BYOtg.

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**1. State of the art about climatic change**

Humanity has to face a global change. The increasing use of fossil organic matter as source of energy for human economic activities delivered in the air a large amount of $CO_2$. This gas having a greenhouse effect, air temperature is alarming increasing since 1960. Since 1988, an Intergovernmental Panel (about 85 experts) on Climate Change (IPCC), set up by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP), is furnishing regular information on climate change, evaluating the risks and supporting a policy of intervention for adaptation and mitigation.

In December 2015, the IPCC was invited to prepare a Special Report by the 21st Session of the Conference of the Parties (COP21) of the United Nations Framework Convention on Climate Change (UNFCCC) in Paris. The Conference reached an agreement to limit the increase in global average temperature to less than 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C. The corresponding report will be available in 2018. Essentially, the global change forecasted with the previous report is confirmed and illustrated in the following figures (Figs. 1–3) extracted from the preceding Fifth Assessment Report (AR5), approved by the 31st Session of the IPCC in Bali (26–29 October 2009). All these and many other graphs are freely available at the IPCC page: http://www.ipcc.ch/report/graphics/.

In a few words, temperature rises by 0.2°C every 10 years (Fig. 1a), a decreasing amount of precipitations has generally been registered in the hottest sites (Fig. 1e), which does not arrange the situation. Because of this increase in air temperature, desert tropical regions will become wider. An exception is presented in Figure 2b: the East Saharian region will receive more precipitation between 2081 and 2100. Many articles of a special issue of the Journal of Experimental Biology and Agricultural Science, entitled "Sustainable Agriculture and Food Security In the Arab World", implement the forecasted new climate for a regional sustainable and more productive agriculture: http://www.jebas.org/?page_id=1752). The water cycle is enhanced (consuming part of the thermal energy of the air), and the North polar cap and surrounding Cryosols/Gelisols are melting. The sea level increases of about 3 cm every 10 years in average, reducing the emerging dry land surface.

As a consequence, food production in terms of change in fishing (maximum catch potential) and agriculture (range of yield change) are influenced, as shown in Figure 3. Focusing on soil and agriculture, it is projected that in the on-going near period 2010–2029 climatic variations will have a relatively diminished effect on yield change, lost hectares being compensated by new ones. In fact, the abandoned arid lands situated on the boundaries of tropical zones may be compensated at high latitude/altitude by the colonisation of formerly unproductive areas which are benefiting from higher temperatures with global change. The process is limited by the available hectares of the emerging areas, and is counteracted by the loss of surface as a consequence of the increasing sea level. Starting from 2030, the global yield change estimate shows a rate of decrease much faster than the rate of increase (Fig. 3b), reducing the quantity of food production while the human population is increasing.

More detailed data and illustrated scenarios in vegetation shift and many other important aspects of climate change consequences are furnished by Gonzales et al. (2010) and Settele et al. (2014).

Focusing on agriculture and food production, Alston et al. (2010) edited a free downloadable volume titled "The Shifting Patterns of Agricultural Production and Productivity Worldwide", illustrating the expected changes continent by continent: http://www.card.iastate.edu/products/books/shifting_patterns/. In chapter 2 of the book "The Changing Landscape of Global Agriculture", Beddow et al. (2010) predict similar changes. An overview is also presented by Max Roser (2016) in the "Land Use in Agriculture" internet page. With an equivalent goal in mind, Van Wart et al. (2013) evaluated the magnitude and variability of differences between crop yield potential or water limited yield potential of operative farm yields, providing a measure of untapped food production capacities.

The described situation is dramatic, especially the severity of the phenomena which will affect all nations and countries of our planet after 2030. If we want to avoid massive migrations of populations, it is necessary to intervene and take measures that could be rapidly operative under worldwide climatic conditions. Human populations would need at least as much water and food as consumed today. Since soil is a crucial factor for water and food production, soil should become a key factor for facing negative effects of global change. A relatively simple soil restoring action should be to increase its content in organic matter. In order to program a coordinated intervention for a generalized soil restoration, in the following pages we will try to:

1) clarify the concept of vegetation-soil coevolution;
2) produce maps of the actual distribution of soils and humipedons all over the planet;
3) identify anthropogenic Agro humipedons sensible to climatic change;
4) describe the functional properties of these Agro humipedons;
5) propose sustainable agricultural techniques compatible with an increase of organic matter content in Agro humipedons;
6) estimate the cost of the operation, comparing it with other actions for climatic change mitigation which are supported by public funds;
7) consider the problem on a global scale recalling the concept of a 4/1000 challenge.

The first four points are analysed here down, solving the others in the final Humusica 2, article 19.

## 2. Vegetation, soil and humus co-evolution

At the end of Humusica 2, article 13, we presented a challenging definition of soil, comprehending solid and relatively fixed parts of it (Humipedon, Copedon and Lithopedon) and more mobile and more changeable "extensions" of soil (Aeropedon in the air, Hydropedon in water, Geopedon in the Earth crust, Symbiopedon in contact with living organisms, and Cosmopedon, made of organic and mineral particles wandering in the space). The soil as an open system connects with the other spheres of our planet, and from this liaison result also these changeable parts of the pedon.

The different humipedons (rich in organic matter and biological parts of the soil) have been aligned along a geological profile, from high altitudes until the bottom of the seas (Humusica 2, article 13, Fig. 30). Here down we extended this vertical distribution to the entire surface of our planet, using existing soil/vegetation maps and finding the relationship between these environmental entities and corresponding spatially distributed humus systems.

Soil and biome maps are available in Internet (soil maps: http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/faounesco-soil-map-of-the-world/en/; https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/use/?cid=nrcs142p2_054013; map of biomes: https://www4.uwsp.edu/geo/faculty/lemke/geog101/lectures/16_global_biome_patterns.html. We disposed of the last version of the WRB Soil Map of the World (ISRIC-World Soil Information, 2015). Field experience allowed us to associate humus systems and corresponding groups of soils and biomes. In Figure 4 we used the WRB soil map as a base for delineating a zonation of humus systems (white lines). These same lines were copied on a USDA soil map base. Colours and soil names used for these two soil maps are different, but the two representations of the world distribution of soils types are very similar. The humus systems were presented in five belts, each one composed of a mosaic of humus systems which are dynamically related [the argument has been treated in: Humusica 1, article 7, section 5 “Where and when humus forms are changing?” and section 6 “Humus forms and scale of investigation”; Humusica 1, article 8, section 7 “Analysis of humus system scales and dynamics (historical, biological, and environmental backgrounds)”]. In each belt, the humus systems are reported along a gradient from the most common in first place on the left to the others, which gravitate around the former in environments which are less favourable for litter biodegradation and organic-mineral soil aggregate formation. In belt number 1, the succession is Moder, Mor, Histic, along a gradient of decreasing air temperature and/or increasing duration of submersion; in belt 2, on base-poor substrates, and in belt 3 on base-rich substrates, we have Mull, Moder, Mor or Mull, Amphi and Tangel, respectively, along gradients of decreasing air temperature and increasing altitude; in belts 4 or 5 we have Mull (earthworm or arthropod Mull), Amphi and Moder, along a gradient of increasing aridity and/or lack of base minerals.

A map of soil pH (used by permission of The Center for Sustainability and the Global Environment, Nelson Institute for Environmental Studies, University of Wisconsin, Madison) shows a useful zonation displaying acidic and basic areas (Fig. 5). Equatorial zones are as acidic as northern areas even if the humus system is completely different, Mull or Mor, respectively. This map shows also that in dry biomes Mull systems tends to be slightly acidic (Andreetta et al., 2016) even under temperate conditions and that, on the other side, Moder systems tend to be less acidic. Even if a very low soil pH (≤ 4.5) is observed in all equatorial zones, temperature and moisture compensate the acidity (Sanchez et al., 2003) and a very active Mull humus system occurs in all these areas (Lavelle et al., 1993), except in white sands or on inselbergs (with very low base and N contents) where Mor and Moder dominate, respectively (Coomes and Grubb, 1996; Kounda-Kiki et al., 2008).

It is well-known that soil scientists use vegetation as a visible indicator for estimating the hidden dimension of soil distribution. On one side this practice biases the drafting of soil maps (which approximate vegetation maps), but on the other side it confirms that in the field, and since a long time, it is possible to observe correspondences between soil and plant distributions (or with geoclimatic maps of the world such as Thorntwait or Köppen-Geiger maps: http://koeppen-geiger.vuwien.ac.at/present.htm. On a biome map proposed by Food and Agriculture Organisation (http://www.fao.org/forestry/fra/80298/en/), by simplifying the preceding maps and reporting only the main delineations, coincidences are shown with dominant Terrestrial, Histic and (new) Para systems (for definitions see Crusto, Bryo and Rhizo systems in Humusica 2, article 13), and thus a clear correspondence appears between biomes and humus systems (Fig. 6). There is a gradual passage from the blue belt of Mor and Histic in tundra and taiga at the North Pole to a large red zone comprehending tropical forests with Mull system on both sides of the equatorial line. Between these circumpolar and equatorial belts, Tangel, Moder and Amphi systems mix their presence and dominate over Mor and Mull in temperate deciduous forests and subtropical woodlands or shrublands. In the south hemisphere, the gradient is inversed and knows a lower development of the area occupied by Mor and Histic systems.

By wanting to associate average measurements of precipitation and air temperature to biomes and humus systems, the map of Figure 6 can be compared with the classical Whittaker Biome Diagram (Whittaker, 1975) on which we also reported names of humus systems (Fig. 7).

Some of the imprecision in the correspondence between biomes and humus systems is due to the fact that in tropical zones mountain reliefs can change locally climatic conditions. Tropical humus systems range from lowland Mull or Amphi to high mountain Moder, Tangel or Mor, up to the formation of an extremely thick Mor in high mountain equatorial forests (Nadkarni and Wheelwright, 2000), and can finish with Para pioneer Bryo or Crusto forms at the top of the mountains, which are not reported in the map. At the same time, soils will range from Planosols, Cambisol, Ferralsols and Luvisols in the lowlands, to Chernozems, Phaeozems, Kastanozems, Regosols in the mountains, to Podzosols, Umbrisols, Leptosols in high mountains, finishing at the very top with Cryosols.

Back to humus systems, we dare to propose a “squared” version of planetary distribution of humus systems using a tree cover map as a base. Less precise than the preceding maps, it has the advantage to be more practical for the purpose of this article, which is to show that the Mull system, the one preferred by humans, is quite universally distributed (Fig. 8).

Before developing this point about the relationship between Mull system and human behaviour, we would like to bring forward some ideas about the concept of ecosystem and soil coevolution.

## 3. Is soil involved in the process of natural evolution?

Plants and animals of a given ecosystem act as “coordinated societies”. These living organisms must possess a common language, a mean to communicate and delineate during the exploitation of available natural resources. They must be able to survive together sharing nutrients or finding a compromise for them, or adopting different strategies allowing co-existence. In fact, individuals of plant species are not casually mixed but form communities, whose specific composition repeats itself under similar ecological frameworks (Darwin, 1859; Clements, 1936; Braun-Blanquet, 1964; Willig et al., 2003). The same occurs also in animal communities and a natural system evolves, and in a given historical moment it reflects past dynamic interactions of biological, physical and chemical factors (Collins et al., 1993; Thompson, 1994; Callaway, 1997; Givnish, 1999). Normally, such communities or ecosystems can be seen as a gradual passage between different ecological juxtaposed systems. However, the variety of ecological gradients is potentially infinite and depends upon the number of systems in contact and upon the steepness of the gradients. It was previously found that "ecogenesis repeats evolution" (see Chertov and Nadporoyhskaya in Humusica 3), which means that there is a correspondence between the evolution of terrestial biota and the primary ecological succession of "biotasoil" systems. For instance, the development of a microbial biofilm towards a Crust humus system, pursuing to Mor and finally to Mull humus systems was observed by Chertov (1990). When passing from a system to another, the rate of change of the more or less interdepending factors of the systems influences the composition of living organisms within the transitional zone. A zone of contact between two systems may be a point of genesis of a new system. For all these reasons, it is really difficult to trace a line between natural ecosystems. However: a) it is possible to locate living organisms of the planet in a few biomes, which in their turn can be subdivided in a reasonable number of large ecosystems enclosed in corresponding dynamic habitats (De Cáceres et al., 2015); b) it is possible to enumerate a reasonable number of sites with similar ecological conditions, which can be inhabited by complementary plants and animals communities; c) for practical surveys or management operations, it is very useful to circumscribe the biological diversity of a vast region, avoiding independent and less functional lists of species; d) the effect of the dominance of single or a few plant and animal species reduces the number of plants and animals gathered in a community to those allowed by the consequent diminished availability of nutrients and energy. Even if these animals or plants are very small, they may appear in the systems in great numbers but their overall biomass is reduced in proportion to the diminished resources.

Soils are involved in the transmission of genetic information within each natural ecosystem (Cartenì et al., 2016; Mazzoleni et al., 2015a, b; Levy-Booth et al., 2007; Pietramellara et al., 2009; Nielsen et al., 2007, 2015). In given areas of our planet, plants and animals coevolve. Though well-known vertical and more recently proved horizontal gene transfers (Gyles and Boerlin, 2014; Keeling and Palmer, 2008), these communities build more complex and functional ecosystems thanks to perpetual interchanges. The functionality of living organisms is DNA-depending. As a consequence, organisms of a given ecosystem can exchange only if their DNA allows this intercommunication. In other words, living organisms are made of "compatible" DNAs. Things look like if DNA could be transferred among the organisms composing an ecosystem and dynamically circulating in it.

Because living organisms die and their DNA is recycled in the soil, microorganisms (and viruses) must be the tools and vectors that respectively cut DNA and transmit DNA fragments within the system. It is well-known that broken DNA can be "transferred" into bacterial cells and then used in some important chains of bacterial functionalities (Stewart and Carlson, 1986; Lorenz and Wackernagel, 1994; Dreiseikelmann, 1994; Gruenert et al., 2003; Chen et al., 2005). Recent studies show that even plants are able to uptake DNA fragments and that the process could be related to plant biodiversity in planetary biomes (Mazzoleni et al., 2015a, 2015b). A small fragment of DNA generated in a litter is able to enter a host cell, recognize inside its homologous genomic target and activate the machinery involved in DNA repair with consequent integration into the genomic DNA of the host cell (reviewed by Cartenì et al., 2016).

The soil is then not only “an entity” in which plants and animals can store and uptake nutrients but it might be understood as a “melting pot” for the DNA of a given inhabited biome (meaning a confined habitat with relatively homogeneous ecological conditions) of our planet. Dynamically biodegraded and reinvested in the system, soil DNA reorganizes the functional relationships between the organisms living in a given habitat, in a process of co-evolution over time. A Darwinian type of evolution occurs at the same time which can modify the whole ecosystem (dynamically interconnected living organisms and soil), in different areas of our planet.

An estimate of soil and biome co-evolution may be obtained by comparing global maps of main biomes and soil orders. Molecular techniques of (extracellular environmental) DNA “metabarcoding” were recently introduced in Environmental Science as a powerful tool for reliable and efficient monitoring of biodiversity (Taberlet et al., 2012).

Two hundred and fifty million years ago, when the still active and lasting continental drift slowly separated the plates composing the Earth crust, co-evolution begun, that at the present day appears as specific soil-biome ecosystems. During this lapse of time, the biodegradation of litter produced fragments of DNA within each biome, and these fragments contributed, like a common language, to the cohesion of living organisms within each soil-biome unit. As illustrated in Humusica 2, article 13, section 2.6, microorganisms are permanently transported by wind or water or within mineral particle clouds. The fundamental uniformity of the code of life at different scales is related to the time that DNA needs to be biodegraded into fragments and reconstructed. The process and its rate in time, still unknown but under investigation (Cartenì et al., 2016), should be faster on a local scale while it may take more time over large areas. At local and continental scales, humus systems and forms co-evolved with soil and vegetation components of specialised ecosystems (Ponge, 2005, 2013). DNA biodegradation and reconstruction are necessary to maintain the functionality of natural ecosystems. We would like to conserve this functionality even at the level of agronomic systems operating within separated continental plates, at least as a first attempt to preserve soil DNA biodiversity. An attempt to circumscribe seven main plates, in which soil-ecosystem coevolution could have generated differences in soil microbial components, is plotted in Figure 9 (elaborated by The National Centers for Environmental Information, Asheville, NC, with data furnished by Müller et al., 2008). Many works support the hypothesis of a relationship between microbial variability and ecological/geographical distribution (Fulthorpe et al., 1998; Fierer and Jackson, 2006; Leff et al., 2015; Barberán et al., 2015; Fierer et al., 2012; Maestre et al., 2015). We only assume the existence of a stronger relationship between soil microorganisms within a single plate (geographic insulation) than between plates. This fact could be of interest in case of soil management. Plants, litter, soil animals and microorganisms might be more adapted to a continent than to another. We know that humans can meet some intestinal troubles while drinking source water in habitats different enough form those in which they usually live. Is this a reaction of our intestinal microflora to bacteria of another type?

**4. Humus systems and global challenges in the Anthropocene**

Can we use humus systems for monitoring the effects of warming climate on terrestrial ecosystems, as tools against deforestation damages, air and soil pollution, or as indicators for healthy and sustainable food production? To ask these questions, which are often raised by people who want to test the credibility and usefulness of scientists and their research, let us consider some results obtained by observing and classifying humus systems, and applications which may result thereof.

That humus systems can change with changing temperature is now out of doubt. Moder shifts towards Mull have been shown to occur from North to South France, following a gradient of increasing temperature (Ponge et al., 2011). The calculation of the Humus Index (HI) was based on a scaling of humus systems according to an old classification of forest humus forms. The old classification distinguished “main” and “current” humus forms, these adjectives being often implicit and some confusion was inevitable. In the present classification, old main humus forms become humus systems and old current humus forms remain humus forms, corresponding to variations within single humus systems. Ponge et al. (2011) developed an equation relating humus forms (current humus forms of Brêthes et al., 1995) to temperature, HI being the Humus Index (ranging from 1 to 7), and J the average July temperature in °C: **HI = 9 – 0.3 J**.

According to this relationship an increase of 3°C in average temperature for July correlates with a shift of ca. one HI unit, representing for instance a shift from Dysmoder to Eumoder or from Mesomull to Eumull. Other results obtained in northern Italy corroborate this finding (Ponge et al., 2014).

But can we extrapolate these results, obtained on a geographic scale, to a temporal scale: in short, can we expect the same shift in humus systems following the 3°C increase predicted to occur from 2000 to 2050 (Cox et al., 2000)? Several limits may be put to such predictions.

First, we should consider that humus form is not only a question of temperature but also of moisture. The above example of change in Humus index in Italy implies also a certain change of precipitation and moisture along a zonal gradient. Temperature and moisture are cross-correlated. The change of these correlations may not be same on a temporal scale as it is on a zonal scale. Secondarily, we must take into account the dispersal limitation of animals, in particular earthworms, for any predicted decrease of the Humus Index (i.e. shift from Moder to Mull). On the basis of present-day knowledge, it can be suspected that dispersal will be more limiting for latitudinal than for altitudinal changes, since distances to be covered for the same temperature difference are ca. 1000 times less for altitude (Chen et al., 2011). Thus, following this scheme, we expect lowland/southern humus systems (mostly Mull) to climb mountains more rapidly than they will advance northwards.

Third, plant communities are expected to change in response to global warming, with an increase in litter recalcitrance due to a shift in plant functional traits (Díaz and Cabido, 1997). If modelled aridification of the global climate is confirmed in the next decades (Gao and Giorgi, 2008) this would possibly counteract any shift towards Mull, at least in regions where soil moisture is already seasonally very low (Andreetta et al., 2016). In well-buffered and fertile soils, shallowness and poor water storage capacity seem to be driving factors in the genesis of Amphi (Ponge at al., 2014). In a context of aridification of the Mediterranean climate, we expect Amphi to become more frequent than Mull.

Given abovementioned uncertainties in our prediction of future humus systems, there is an urgent need to follow them in a diachronic manner, by including the monitoring of humus systems in existing grids of soil quality assessment (Morvan et al., 2008).

It has been shown that humus systems play a decisive role in the natural regeneration of mountain and northern coniferous forests, and that changes in humus system anticipate vegetation responses to light and hydrological conditions (Ponge et al., 1998). This also applies, although to a lesser extent, to lowland deciduous forests (Ponge and Delhaye, 1995). In that sense humus systems (and their pertaining communities) can be considered as drivers of the sustainability of terrestrial ecosystems. This implies that their survey must be included in the panel of measurements and observations done by foresters before planning management operations. Based on the complex relationships between earthworm communities, humus systems and tree growth phases revealed by Bernier and Ponge (1994), the duration of forest rotations and the size of management units are key factors of forest sustainability. Small management units and long rotations favour the normal cycle of humus systems and soil fertility which is the privilege of unmanaged forests (Page, 1971), avoiding the increase in litter thickness and concomitant soil acidification commonly reported to occur in even-aged conifer plantations (Augusto et al., 2002).

Whether soils are sources or sinks of atmospheric carbon is still a matter of conjecture and depends strongly on climate, land use and, most probably, humus systems (Lal, 2000). The form in which organic matter accumulates (or not) and whether carbon is sequestered (or not) in the profile are key points in this respect (Lal, 2004). At first sight, we can expect increasing earthworm activity (as expected in response to global warming, but see abovementioned objections) to cause carbon destocking, because of the well-known priming effect of earthworms on soil microbial activity (Brown et al., 2000). However, it should present to the mind that carbon stocking/destocking is the net result of two opposite processes: mineralization and humification, the former destroying and the latter building soil organic matter. Since both processes result from the transformation of organic matter by soil organisms, any increase or decrease in soil biological activity will increase or decrease both mineralization and humification, letting unsolved the question of C-stocking or destocking. However, we know that earthworm and associated microbial activities decrease the organic content of the soil in the short-term (priming effect) while they increase it in the long-term, due to the protective effect of carbon sequestration (Martin, 1991). This may have far-reaching consequences on the balance sheet between stocking and destocking of carbon (and other elements) but realistic models based on an extended knowledge of soil biology (thereby opening the soil 'black box') are still lacking, unfortunately, despite recent efforts in agricultural land (Morgan et al., 2010). One of the main challenges is to take into account the diversity of soil conditions, and a reliable identification of humus systems and their functional background may help to achieve this goal.

Do humus systems and, more important, do humus system changes may help to throw light about the problem of carbon stocking or destocking, when soils are faced to climate warming or deforestation? De Nicola et al. (2014) and Andreetta et al. (2011) showed that in Mediterranean climate Mull and Amphi (i.e. humus systems with burrowing earthworm activity) were richer in total organic carbon than Moder, pointing to a carbon balance sheet in favour of long-term (humification) over short-term (mineralization) processes. Thus, under Mediterranean climate, the sequestration of organic carbon within mineral-organic horizons (typical of earthworm ecosystem services) would fix more atmospheric carbon in the soil despite climate conditions favouring mineralization. Similar patterns have been suggested for tropical soils (Martin, 1991) even if we are still waiting for a census taking into account the wide diversity of humus systems known to occur in the tropics (Garay et al., 1995). But what in cool temperate, boreal and mountain conditions, in particular in permafrosts where huge amounts of fossil carbon have begun and are threatened to be increasingly lost to the atmosphere (Zimov et al., 2006)? We can expect that, if microbial communities are activated by heat without burying of organic matter by earthworms (or other Mull-forming organisms) and resulting carbon sequestration, the balance will be in favour of short-term exchanges to the atmosphere, i.e. carbon depletion will result (Shanin et al., 2011). There is an urgent need to survey and map humus systems in a wide range of terrestrial (woodland, heathland, meadows, crops) and semi-terrestrial ecosystems (bogs, fens, wet meadows) and collecting data on humus system/carbon stocks relationships, if we want to improve global predictive models (Jones et al., 2005) and take the good decisions: which kind of agriculture, which kind of forestry, and where we have to change, or not to change, present-day management options.

Beside worldwide greenhouse effects, pollution is another threat which concerns directly humus systems, its effects being more local, however. It has been known for a long-time that litter decomposition was impeded, and thus that litter accumulated in soils polluted with heavy metals (Coughtrey et al., 1979). This has been expressed in terms of humus systems by Gillet and Ponge (2002), and was later extended to soils polluted by petroleum deposits (Gillet and Ponge, 2006). Under European conditions with N depositions ranging from 20 to > 100 kg per ha and year, the question of increased N deposition and humus formation should also be addressed. N deposition has the potential to increase soil C storage (Zak et al., 2017). The explanation of organic matter accumulation in polluted soils was first searched in the impact of pollutants on microbial communities (Sterritt and Lester, 1980) but later studies showed that earthworm communities were strongly impacted by soil pollutants (Nahmani and Rossi, 2003), resulting in pronounced changes in soil structure and burying of litter. Enchytraeids seem less sensitive towards heavy metals (Römbke et al., 2002), pointing to a range of humus systems from Mull to Mor with increasing pollution pressure, as this has been shown to occur by Gillet and Ponge (2002). We strongly suggest that the characterization of humus systems could be used as a first cost-effective screening tool for the field assessment of soil pollution, upstream chemical and ecotoxicological analyses.

**5. Humans prefer Mull humus systems**

Together, croplands and pastures have become two of the largest terrestrial biomes on the planet, rivalling forest cover in extent and occupying nearly 40% of the land surface (Asner et al., 2004; Foley et al., 2005). The process begun about 12,000 years ago, when humans understood that Mull humus system was the more adapted to produce their foodstuff. From the humus system point of view, to practice agriculture means to maintain, generate and exploit a Mull system. A Mull system corresponds to a humipedon without organic layers. The fallen litter totally disappears. It is biologically integrated in less than one year in a well-structured A horizon (description of natural humipedons in Humusica 1, articles 4 and 5; Techno and Agro humus systems in Humusica 2, articles 15 and 16). Man intervenes by ploughing (thanks to animal-powered but shallower ploughing in the past, and presently much deeper ploughing with mechanical means), irrigating (in early times by diverting streams until modern times with sophisticated irrigation systems) and fertilizing (with organic and/or mineral manures). All these operations imitate and try to accelerate/accentuate what natural organisms and processes still create in a Mull system (Bertrand et al., 2015; Blouin et al., 2013; Havlicek and Mitchell, 2014; Vergnes et al., 2017) by a) mixing organic and mineral soil particles, b) forming stable soil aggregates, c) aerating the soil and increasing its capacity of oxidation, d) improving its capacity of moisture retention, e) facilitating the exchange between soil, microorganisms and plant roots. It is well known that intensive agriculture, use of pesticides and tillage on the crop side, and extensive cattle ranching on the pasture side, reduce the number of soil engineer organisms (Decaëns et al., 2004; Ernst and Emmerling, 2009; Fragoso et al., 1997; Giller et al., 1997; Scherber et al., 2010).

By considering the most important characters of the topsoils presented by the Soil Survey Staff (2014) and comparing them to morphogenetic characteristics the Agro Mull described in Humusica 2, article 15, it is possible to separate zonal and azonal Agro humipedons. Zonal Agro humipedons develop in temperate, sub-tropical and equatorial areas; azonal ones correspond to Andosols and Vertisols (Figs. 10a, b).

All these Agro humipedons are crucial for human food production. In the following, the original vegetation of these soils as well as their conditions of formation and current biological functioning are described.

### *5.1. Agro humipedons of temperate areas*

Agro humipedons of temperate areas correspond to topsoils of temperate, continental, oceanic and subcontinental forests or grasslands. For evident economic necessity, man replaced forest and grassland ecosystems with croplands and pasture areas. It is possible to distinguish Chernozem and Kastanozem from Cambisol and Luvisol humipedons.

#### *5.1.1. Agro humipedons of Chernozems and Kastanozems*

Climate: Harsh, continental, with succeeding cold/wet (even with snow or ice) and long, dry/warmer periods.

Natural vegetation: Steppe or bush steppe.

Soil organic matter: high annual input of organic matter from aboveground, as leaves and small branches, and below ground as root exudates and dead roots.

Biological functioning: microorganisms (bacteria and fungi) attack the organic matter (above- and belowground) and mineralize part of it during warmer and wet periods; mesofauna feeds on litter and anecic and endogeic earthworms produce organic-mineral black aggregates (Munsell value, humid: ≤ 3.5; chroma ≤ 3), richer in OC (organic carbon) at the top (OC at least 3% in the first 10 cm) and gradually diminishing OC content with depth; macrofauna (moles and mice) building "crotovinas" (tunnels of 3–5 cm of diameter, from the surface until 2 m of depth) and allowing water and nutrient exchange between top and bottom of the soil.

pH of A horizon 6-8.

*5.1.2. Agro humipedons of Cambisols and Luvisols*

Climate: temperate, oceanic or subcontinental.

Natural vegetation: temperate vegetation, all stages, from grasslands to bushes until forests (frequently broadleaf forests).

Soil organic matter: High annual input of organic matter aboveground, as leaves and small branches, and below ground as root exudates and dead roots.

Biological functioning: very rich in microorganisms (bacteria and fungi) which attack the organic matter (above- and belowground), mineralizing the largest part of it; mesofauna feeds on litter and anecic and endogeic earthworms produce organic-mineral aggregates (Munsell value, humid: > 3.5; chroma > 3), richer in OC at the top (OC < 7% in the first 10 cm) with gradually diminishing OC-content with depth; original macrofauna (moles and mice) building tunnels of 3–5 cm of diameter, from the surface until 2 m of depth and allowing water and nutrient exchange between top and bottom of the soil; macrofauna is generally eliminated by man in crop Agro systems.

pH of A horizon 6-8.

In Luvisols all biological characteristics and organic content are lower than in Cambisols.

*5.2. Subtropical-Equatorial Agro humipedons*

Subtropical-Equatorial Agro humipedons are related to the length of the humid season in subtropical and equatorial climates (South edge of Cancer and North edge of Capricorn belts). They may be subdivided along an increasing range of precipitation, from subtropical to equatorial areas:

- Agro humipedons of brown and grey sub-arid or Fersiallitic soils (man transformed, sub-desertic and Mediterranean steppes with chromic Cambisols);
- Agro humipedons of Lixisols and Acrisols (human-transformed, subtropical bushed tree savanne with Ferruginosols)
- Agro humipedons of Ferralsols (human-transformed poor sub-tropical to dense equatorial forest with Ferrallitisols).

Biological functioning: in this subtropical or tropical area, we assist at the confluence of two main humus systems: Mull system made by large earthworms and Moder system generated by arthropods. Under Mediterranean, subtropical and tropical climates, litter often completely disappears from the surface of the soil, being ingested or transformed by arthropods and without formation of an OH horizon. These humipedons are called arthropod Mull. Soil humidity favouring earthworms, drought boosting arthropods, we may then observe the dominance of arthropod Mull in dry tropical areas and a prevailing earthworm Mull in the rainy equatorial zone, with some nuances:

a) very dry ecosystems (soil drought) cannot develop a phanerophytic vegetation. As a consequence, the soil system generally stops its evolution at the stage of the Crusto humus system (Humusica 2, article 13);

b) in less dry ecosystems or in only periodically dry areas, we may observe the development of a vegetation characterized by short cycles of vegetation (grasses, “r” strategy and strong capacity of vegetative reproduction). These plants co-evolved with grazing mammals which induced a genetic capacity to produce secondary roots and to resist grazing pressure. These plants are able to feed microorganisms with root exudates during pedo-climatically favourable periods, generating particular, very functional organic-mineral soil aggregates (Blankinship et al., 2016; Nasto et al., 2014; Spohn and Giani, 2010). As a consequence, soil carbon storage and water capacity increase (Meier et al., 2017; Six et al., 2004). In high altitude cold Tibetan grasslands (showing equivalent plant adaptation?), specific “mattic epipedons” were recently described (Zavišić et al., 2016; Zhi et al., 2017). The energetic and nutritional resources allocated to soil aggregates allow plants to have a short life-cycle even in harsh ecosystems. Classified as Rhizo systems (Humusica 2, article 13), these humipedons may show a divergent evolution. In harsh conditions, they evolve in grassland mattic humipedons. In less difficult temperate conditions, where a forest cover is possible, Rhizo systems may generate from other humus systems. Rhizo can commonly cap a Mull system in secondary eutrophic grasslands. Here, we may observe two superposed humus systems: at the surface, a 3–10 cm thick, mattic humipedon, mostly made of rounded soil aggregates kept in a net of roots; under it, a thicker (10–50 cm) biomacrostructured (with larger and more polyhedric aggregates) A horizon, made by endogeic and anecic earthworms. Both superposed systems lay on a mineral soil horizon. Both systems are well inferred each other. Many roots overpass the bottom limit of the Rhizo system, even if the root density rapidly decreases below it. Earthworms may pass through the roots and come out of the soil. They are looking for litter and may deposit castings at the soil surface.

A Rhizo system may be observed even in steppe and savanna environments, in a soil poorly provided with earthworms or without them. In these dry soils, the precious and fertile soil aggregates of a Mull system are built by termites, ants, insect larvae and many micro-arthropods. In tropical and sub-tropical grasslands, a mosaic of earthworm and arthropod Mull systems is also possible. The relationships between invertebrate ecosystem engineers and soil or climatic parameters at global and local scale are well described in (Brussaard et al., 2012).

c) in a non-acidic soil, when shrub, bush or forest covers prevent the formation of grass patches, the soil is often rich in available water and nutrients. Anecic and endogeic earthworms may be numerous in such humipedons. They form more efficient organic-mineral aggregates than arthropods (Bertrand et al., 2015; Spohn and Giani, 2010). Anecic and endogeic droppings correspond to well-amalgamated organic-mineral aggregates resisting to fast biodegradation, preventing lixiviation and eluviation of minerals, avoiding soil erosion. By integrating new organic matter in old soil aggregates, earthworms may recharge the soil as if it was a battery made of biodegradable/regenerable organic matter (Bouché, 2014).

d) in acidic soil and out of the forest cover, a Rhizo system is found under acidophil lawns (pioneer phase) or under ericaceous allopathic shrubs and bushes. Under tree cover, Rhizo lets its place to Bryo, Moder or Mor systems, on Podzols. Biologically speaking, these humus systems seem to be very functional on acidic soil and in cold climatic conditions (details in Humusica 1, article 2). Instead of biodegrading the organic matter and losing its mineral and organic components through potential lixiviation or eluviation processes, Bryo, Moder and Mor humus systems allow to preserve the largest part of the produced litter. They display thick organic horizons grouped at the top of the soil profile. These horizons undergo a process of biodegradation involving epigeic earthworms, arthropods, bacteria and above all fungi (Berg and McClaugherty, 2014; Datta et al., 2017; Handa et al., 2014). The process of litter biodegradation may know periodic accelerations during short favourable periods. All organic horizons of Moder and Mor are very rich in roots.

d) in equatorial forests, a consistent part of the C cycle takes place in aerial conditions, epiphytes being very common in these ecosystems, biomass developing in many superposed layers of vegetation and biodegradation occurring even “out of ground” (this concept has been developed in Humusica 2, article 17, section 1). This is the reason that makes so damaging the destruction of the aboveground structure of equatorial rainforests.

### *5.3. Azonal Agro Humipedons*

The Agro humipedons of Andosols and Vertisols correspond to the topsoil of transformed forests or grasslands for agricultural purposes.

#### *5.3.1. Agro humipedons of Andosols (topsoils of ex-azonal forests or grasslands on Andosols)*

Their name comes from Japanese “an”= black and “do” =soil, and is used for soils developing on volcanic ashes, with properties related to high levels of iron and aluminium organic and organic-mineral colloids (IUSS Working Group WRB, 2015). These soils may also form in non-pyroclastic silicate-rich materials in cool-temperate and humid climates. In A horizons with andic properties, the presence of organometallic complexes gives a fluffy macrostructure; these A horizons are commonly very dark-coloured (Munsell colour value and chroma > 3, moist), and contain a high amount of organic matter ( > 5%).

There are two major types of andic humipedons: one with acid to neutral pH in which allophane and imogolite are predominant and one with very acid pH in which Al complexed by organic acids prevails. Andosols in intermediate or basic volcanic ash are fertile Agro Mulls, planted to a wide variety of crops. Paddy rice cultivation, a major landuse in lowlands with shallow groundwater, may be classified as Agro Hydro Mull or Agro Anmoor. Very acid humipedons, generally under forest cover, correspond to Moder or Mor Humus systems.

#### *5.3.2. Agro humipedons of Vertisols (topsoils of ex azonal grassland on Vertisols)*

A vertic (from Latin vertere, to turn) humipedon is a very rich in expansive clay, hard to very hard topsoil that, as a result of shrinking and swelling, shows cracks at the surface (dry period) and slickensides and wedge-shaped soil aggregates (IUSS Working Group WRB, 2015).

Climate: subtropical with succession of relatively humid and strong dry periods.

Natural vegetation: herbaceous savanna, unfavourable to trees development.

Functioning: formed from highly basic rocks, latitude between 50°N and 45°S.

Generally used for grazing of cattle or sheep. The shrink-swell activity allows rapid recovery from compaction. They are almost impermeable and suitable for rice when saturated. Very hard when dry and sticky when wet, they can hardly be worked.

*5.4. Agro humipedon maps*

The planetary distribution of pastures, meadows and croplands is reported on a map published by the Center for Sustainability and the Global Environment (SAGE) at the University of Wisconsin, Madison. We added red lines for delimiting the Earth geological plates (Fig. 11a). We also assigned Rhizo Mull humus systems (built by dominant earthworms or macroarthropods) to pastures and meadows and Agro or Agro Hydro Mull humus systems to croplands. Statistical data and more precise geographical distribution of crop yields are available in FAO (http://www.fao.org/faostat/en/#data) and World Bank (https://data.worldbank.org/data-catalog/world-development-indicators) documents. In "Our World in Data" (https://ourworldindata.org/), Roser and Ritchie (2017) illustrate and briefly present many FAO and World Bank graphs/maps/data in a net source entitled "Yields and Land Use in Agriculture" (https://ourworldindata.org/yields-and-land-usein-agriculture/).

In Figure 11b, we refer to Beddow et al. (2010) and group four maps of main crops. These maps can be easily compared to the preceding one, allowing geographically localising the main crops within each continental cropland area. Carbon storage in terrestrial ecosystems (source of background map: Ruesch and Gibbs, 2008), tree cover (Source: FAO world's forest map 2010) and main humus systems are shown on Figure 11c. All these bulk maps allow to see a kind of "state of the art" and to associate humus systems to agricultural soils, carbon storage and tree cover at planetary level. Comparing these maps with preceding figures, it is also possible to add information about soil, climate and potential vegetation (biomes). Knowledge about seaside and river-sea-ocean beds is so poor that corresponding humus systems and soils are not reported on the maps. At larger scale, humus systems and soil types are interconnected through hydro-, aero- and symbiopedons, as drafted in Humusica 2, article 13. Martin and Margy Meyerson in collaboration with Claire Hoch and Chieh Huang published an "Atlas for the End of the World", i.e. an Atlas for the Beginning of the Anthropocene. We suggest to reach this page (http://atlas-for-the-end-of-the-world.com/world_maps_main.html) and look at presented specific maps.

## 6. Conclusions

The aim of the present article is to help estimating the extent of soil resources available for agriculture in forthcoming years. Humans should be able to produce food for an increasing human population faced to a still-on-the-road global change. In the OECD-FAO Agricultural Outlook 2017–2026 (http://www.agri-outlook.org/) the following key messages are reported:

- "Over the ten-year outlook period, agricultural markets are projected to remain weak.
- Future growth in crop production will be attained mostly by increasing yields, and growth in meat and dairy production.
- Agricultural trade is expected to grow more slowly, but remain less sensitive to weak economic conditions than other sectors.
- Real prices are expected to remain flat or decline for most commodities."

Roser and Ritchie (2017) concluded their analysis of FAO/World Bank data and Ausubel et al. (2013) historical paper as follows:

- Crop yield increases are correlated to irrigation, improved varieties of cereals, application of fertilizer and tractor inputs.
- The 'peak farmland' predicted for 2009 (Ausubel et al., 2013) is still not reached.
- The majority of our arable land is used for cereal production (700 million ha); the most dramatic increase in land allocation is in the production of oil crops (300 million ha; increasing by 4 million ha/yr).
- Poultry and pig farming have a land footprint 8–10 times lower than cattle breeding. This means humans can make notable reductions in the environmental impact of their food diets simply by substituting lower-impact meat products for beef or mutton.

A complementary article (Humusica 2, article 19: Technohumus systems and Global Change – Conservation agriculture and 4/1000 proposal) gives practical principles of sustainable agriculture. In a few words, the authors of this article suggest to prefer conservative (preserving soil biodiversity and soil organic carbon storage) to intensive (use of mineral fertilizers, pesticides and mechanical inputs) agriculture, applying organic compost as manure and using biological instead of mechanical machineries for restoring soil structure and promoting its natural production potential.

## Authors' contributions

A. Zanella: Article redaction and composition of figures, coordination; H. Hager, J. Galbraith, O. Chertov, J.F. Ponge, A. Andreetta, M. De Nobili: collaboration for preparing and arranging figures 4, 5, 6, 7, 8, 10, revision of the text; J.F. Ponge: redaction of section 4: Humus systems and global challenges in the Anthropocene; S. Pignatti: discussion with A. Zanella (Castelporziano, Rome, Italy, June 2013) about the role of DNA as possible generalized language between soil and plants.

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**Figure captions**

**Fig. 1.** Look at the past time (1900–2010). Since 1960, the annual average temperature (a) and the mean sea level (d) are increasing and the Artic sea ice extent is diminishing (c). Surface temperature and quantity of annual precipitations over land knew a variation illustrated in (b) and (e). From Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change; Fig. 1 = Figure 1.1., page SYR-83 [Core Writing Team, Pachauri, R.K. and Meyer, L. (eds.)]. IPCC, Geneva. Reproduced with permission.

**Fig. 2.** Comparing past (1986–2005) and future (2081–2100) times. The increasing trends in average surface temperature (a) and sea level (c) are very clear; the distribution of average precipitation shows an impoverishment of rain water in subtropical areas and an increase of it in equatorial and pole regions. The SE-Sahara region may benefit from higher precipitation, which seems in counter trend with the range observed between 1951 and 2010 (Fig. 1e). From Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change; Fig. 2 = Figure 2.2., page SYR-98 [Core Writing Team, Pachauri, R.K. and Meyer, L. (eds.)]. IPCC, Geneva. Reproduced with permission.

**Fig. 3.** Risk estimation for food production, in fishing (a) and agriculture (b) activities. From Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Fig. 3a = Figure 2.6 (a), page SYR 102; Fig. 3b = Figure 2.7, page SYR-103 [Core Writing Team, Pachauri, R.K. and Meyer, L. (eds.)]. IPCC, Geneva. Reproduced with permission.

**Fig. 4.** Zonation of humus systems over a) Soil Orders (Soil Survey Division, USDA, 2005: http://www.nrcs.usda.gov/Internet/FSE_MEDIA/nrcs142p2_050722.jpg), and b) Soil Groups References, WRB 2015 Global soil map, from ISRIC-Soil Data Hub, ISRIC World Reference Base for Soil Resources (WRB): http://www.isric.org/explore/wrb, reproduced with permission. On both maps, even if colours are different, the correspondence between Soil Orders or Soil Groups References and humus systems is evident even with maps having a different shape. The same range from Mor to Mull systems, from North or South poles until Equator, appears on both maps and follows the vegetation change shown in Figure 6.

Legend: 1) Moder, Mor and Histic = from Moder to Mor Terrestrial systems and all Histic systems: 2) Mull, Moder, Mor = very common Mull, to Moder and less common Mor: 3) Mull, Amphi, Tangel = from very common Mull, to Amphi and less common Tangel; 4) Mull, Amphi, Moder = from very common Mull to Amphi and less common Moder; 5) EaMull = Earthworm Mull; ArMull = Arthropod Mull; 6, 7 and 8) Dynamically associated Para humus systems: common humus systems developing aside (in mosaic) or partially integrated in the main humus systems.

**Fig. 5.** Soil pH and humus systems. Source: The Nelson Institute Center for Sustainability and the Global Environment, University of Wisconsin-Madison, Map of Soil pH, slightly modified (addition of pH values to the legend), the black arrows over the pH standard colours indicate

the theoretical range of pH variation within each different terrestrial humus system. Humus systems are taken from Figure 4a.

Legend: 1) Moder, Mor and Histic = from Moder to Mor Terrestrial systems and all Histic systems: 2) Mull, Moder, Mor = very common Mull, to Moder and less common Mor: 3) Mull, Amphi, Tangel = from very common Mull, to Amphi and less common Tangel; 4) Mull, Amphi, Moder = from very common Mull to Amphi and less common Moder; 5) EaMull =Earthworm Mull; ArMull =Arthropod Mull; 6, 7 and 8) Dynamically associated para humus systems: common humus systems developing aside (in mosaic) or partially integrated in main humus systems.

**Fig. 6.** Global ecological zones of the world (http://www.fao.org/forestry/fra/80298/en/) and humus systems as distributed in Figures 4a and b. Main correlations between humus systems and Soil Orders (USDA) or Groups (WRB) are respected. Sources of global ecological zones of the world: Food and Agriculture Organization of the United Nations (2010), Hansen et al. (2001), Carroll et al. (2009), GAUL (2008), and Iremonger and Gerrand (2012). FAO map of global ecological zones: http://www.fao.org/forestry/fra/80298/en/. Reproduced with permission.

Legend: 1) Moder, Mor and Histic = from Moder to Mor Terrestrial systems and all Histic systems; 2) Mull, Moder, Mor = very common Mull, to Moder and less common Mor; 3) Mull, Amphi, Tangel = from very common Mull, to Amphi and less common Tangel; 4) Mull, Amphi, Moder = from very common Mull to Amphi and less common Moder; 5) EaMull =Earthworm Mull; ArMull = Arthropod Mull; 6, 7 and 8) dynamically associated para humus systems: common humus systems developing aside (in mosaic) or partially integrated in main humus systems.

**Fig. 7.** Relationship between main biomes and humus systems (modified from Whittaker, 1975). Names of main humus systems have been simply written over the graph (Graphical source in http://www.ck12.org/book/CK-12-Biology-Concepts/section/6.9/).

**Fig. 8.** A simplified version of the planetary distribution of humus systems. Humus systems are reported as belts on a FAO world's forest 2010 map. At the bottom of the map a triangle representing the profile of a schematic mountain with calcareous or siliceous sides, and main humus systems disposed in approximated altitudinal ranges. Sources of FAO world's forest 2010 map: Food and Agriculture Organization of the United Nations (2010), Hansen et al. (2001), Carroll et al. (2009), GAUL (2008), Iremonger and Gerrand (2012). FAO world's forest map 2010: http://www.fao.org/forestry/fra/80298/en/. Reproduced with permission.

**Fig. 9.** Distribution of humus systems on seven main geological plates. The figure was obtained by superposing the lines distribution of humus systems (Figure 5) on a freely downloadable image of plant Earth plates, slightly modified for adjusting the scale (maps used as sources of plates: http://www.ngdc.noaa.gov/mgg/ocean_age/data/2008/ngdc-generated_images/whole_world/2008_age_of_oceans_plates.jpg, public domain, https://commons.wikimedia.org/w/index.php?curid=6972903). Data in Müller et al. (2008), reproduced with permission. The main seven plate-soil domains have been circumscribed with regular circles for better visualizing them.

**Fig. 10.** Distribution of humus systems (natural and Agro) on: a) a map of Soil Orders (Soil Survey Division, USDA, 2005: http://www.nrcs.usda.gov/Internet/FSE_MEDIA/nrcs142p2_050722.jpg, and b) Reference Soil Groups, WRB 2015 Global soil map, from ISRIC-Soil Data Hub, ISRIC World Reference Base for Soil Resources (WRB): http://www.isric.org/explore/wrb, reproduced with permission.

Legend: 1) Moder, Mor and Histic = from Moder to Mor Terrestrial systems and all Histic systems: 2) Mull, Moder, Mor = very common Mull, to Moder and less common Mor: 3) Mull, Amphi, Tangel = from very common Mull, to Amphi and less common Tangel; 4) Mull, Amphi, Moder = from very common Mull to Amphi and less common Moder; 5) EaMull =Earthworm Mull; ArMull =Arthropod Mull; 6, 7 and 8) Dynamically associated Para humus systems: common humus systems developing aside (in mosaic) or partially integrated in main humus systems.

**Fig. 11.** Land use in agriculture. Croplands and pastures. We added geological plates and humus systems to a map published by the Center for Sustainability and the Globe Environment (SAGE) at UW Madison (https://news.wisc.edu/new-maps-reveal-the-human-footprint-on-earth/#continue). Reproduced with permission; b) Distribution of major crops across the world (from Beddow et al. 2010, grouped); c) top: Carbon storage in terrestrial ecosystems (map source: Ruesch and Gibbs, 2008, http://cdiac.ess-dive.lbl.gov, reproduced with permission) and main humus systems; c) bottom: FAO world's forest 2010 map and main humus systems. By comparing (a) and (b) it is possible to put a glance on the planetary reserve of agricultural soils (human food) and on the part of the Earth still occupied by forest deserts, tundras and ice caps. In (c) we can associate carbon storage, tree cover and humus systems. Source of Global agro-climatic zones and crop geographies for the year 2000: Beddow et al. (2010), chapter 2, Figure 2.2, Panels a, b, c and d. Crop allocation data are documented by You and Wood (2005), Global agro-ecological zones were modified from Sebastian (2006). Sources of FAO world's forest 2010 map: Food and Agriculture Organization of the United Nations (2010), Hansen et al. (2001), Carroll et al. (2009), GAUL (2008), Iremonger and Gerrand (2012). FAO world's forest 2010 map: http://www.fao.org/forestry/fra/80298/en/. Reproduced with permission.

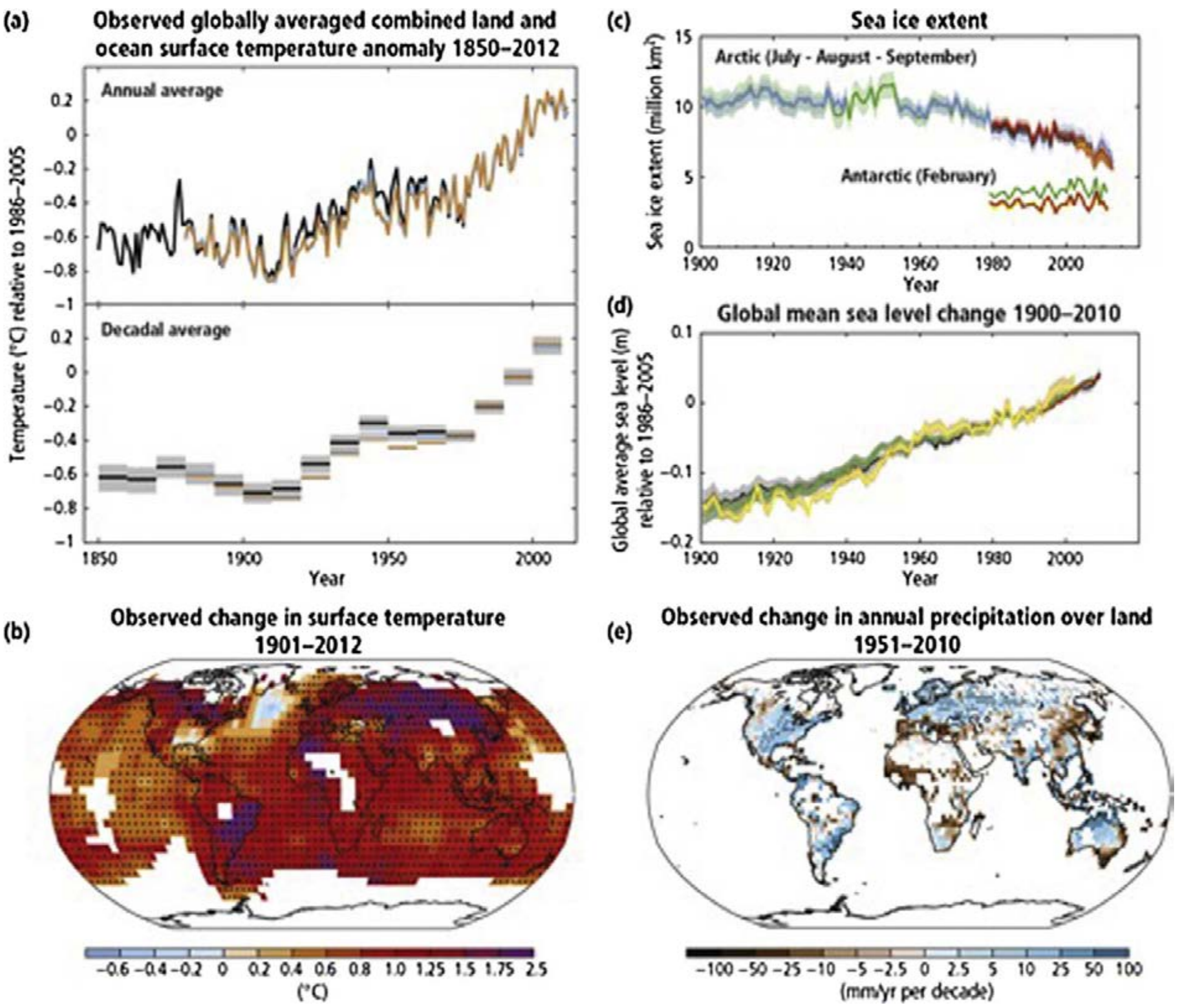

(a)
Observed globally averaged combined land and ocean surface temperature anomaly 1850–2012
Annual average
Decadal average
Temperature (°C) relative to 1986–2005
Year
(b)
Observed change in surface temperature 1901–2012
−0.6 −0.4 −0.2 0 0.2 0.4 0.6 0.8 1.0 1.25 1.5 1.75 2.5
(°C)
(c)
Sea ice extent
Arctic (July - August - September)
Antarctic (February)
Sea ice extent (million km²)
Year
(d)
Global mean sea level change 1900–2010
Global average sea level (m) relative to 1986–2005
Year
(e)
Observed change in annual precipitation over land 1951–2010
−100 −50 −25 −10 −5 −2.5 0 2.5 5 10 25 50 100
(mm/yr per decade)

Fig. 1

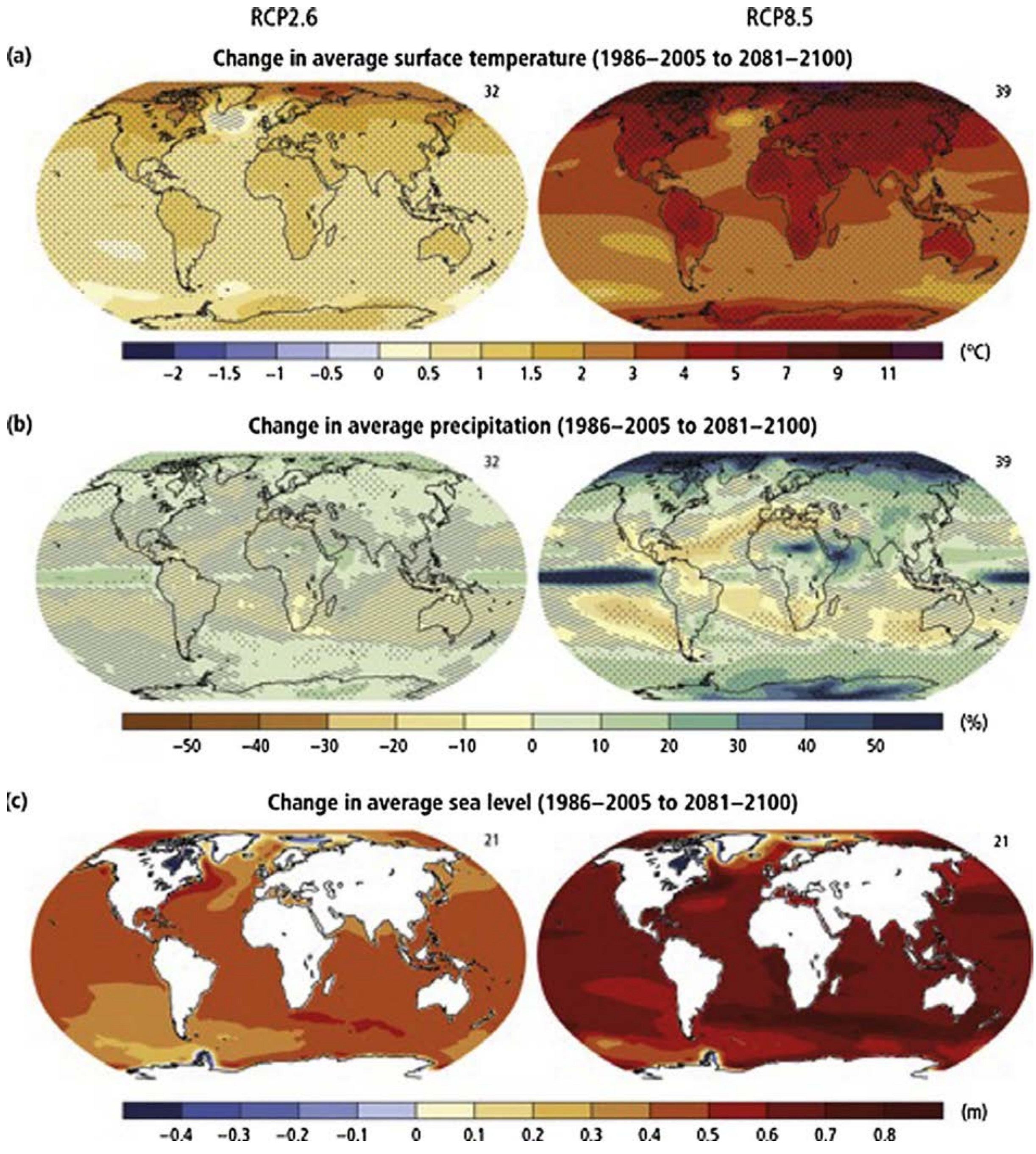

RCP2.6
RCP8.5
(a)
Change in average surface temperature (1986–2005 to 2081–2100)
32
39
−2 −1.5 −1 −0.5 0 0.5 1 1.5 2 3 4 5 7 9 11
(°C)
(b)
Change in average precipitation (1986–2005 to 2081–2100)
32
39
−50 −40 −30 −20 −10 0 10 20 30 40 50
(%)
(c)
Change in average sea level (1986–2005 to 2081–2100)
21
21
−0.4 −0.3 −0.2 −0.1 0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8
(m)

Fig. 2

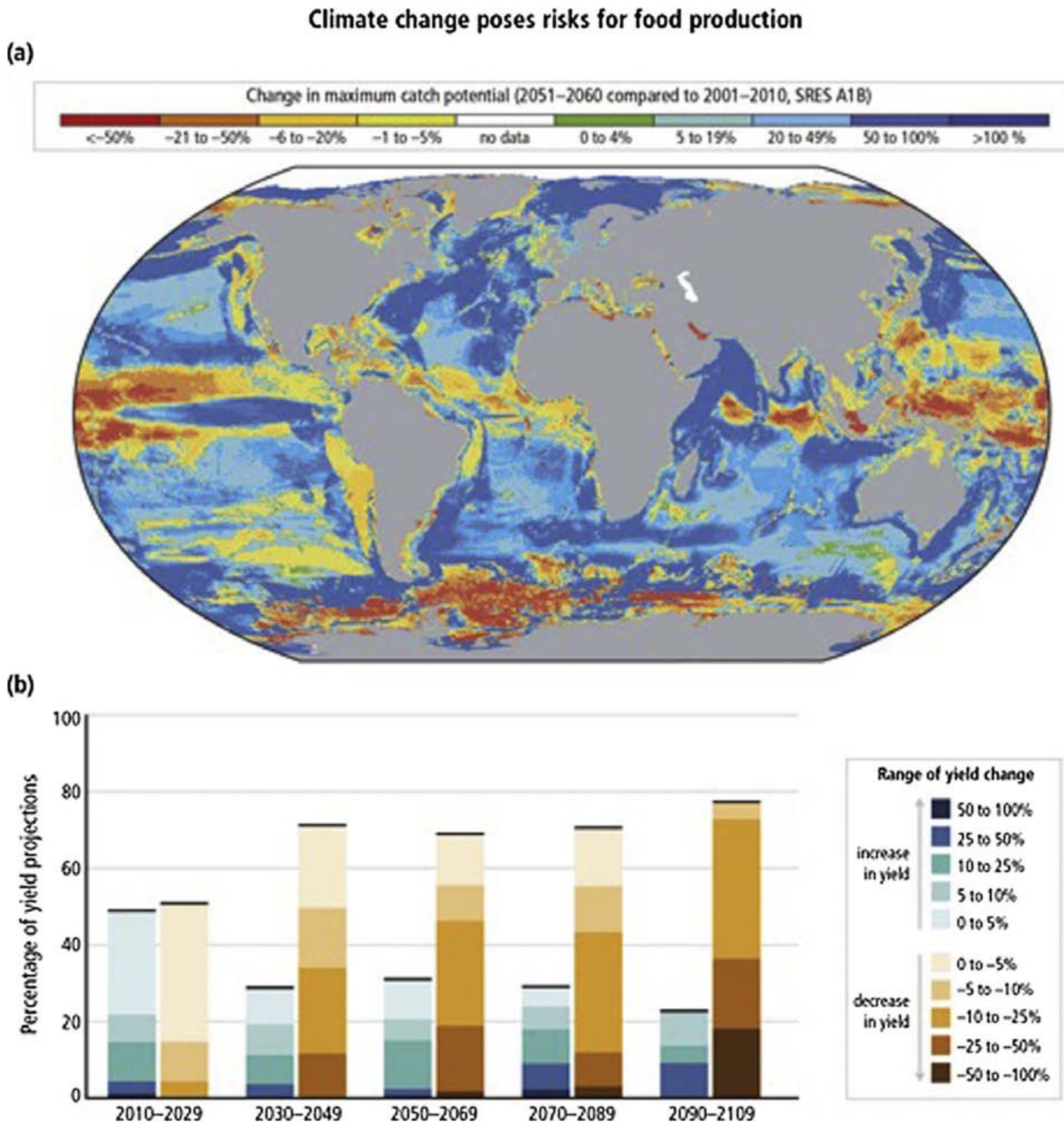

Climate change poses risks for food production
(a)
Change in maximum catch potential (2051–2060 compared to 2001–2010, SRES A1B)
<-50%
−21 to −50%
−6 to −20%
−1 to −5%
no data
0 to 4%
5 to 19%
20 to 49%
50 to 100%
>100 %
(b)
Percentage of yield projections
100
80
60
40
20
0
2010–2029
2030–2049
2050–2069
2070–2089
2090–2109
Range of yield change
increase in yield
50 to 100%
25 to 50%
10 to 25%
5 to 10%
0 to 5%
decrease in yield
0 to −5%
−5 to −10%
−10 to −25%
−25 to −50%
−50 to −100%

Fig. 3

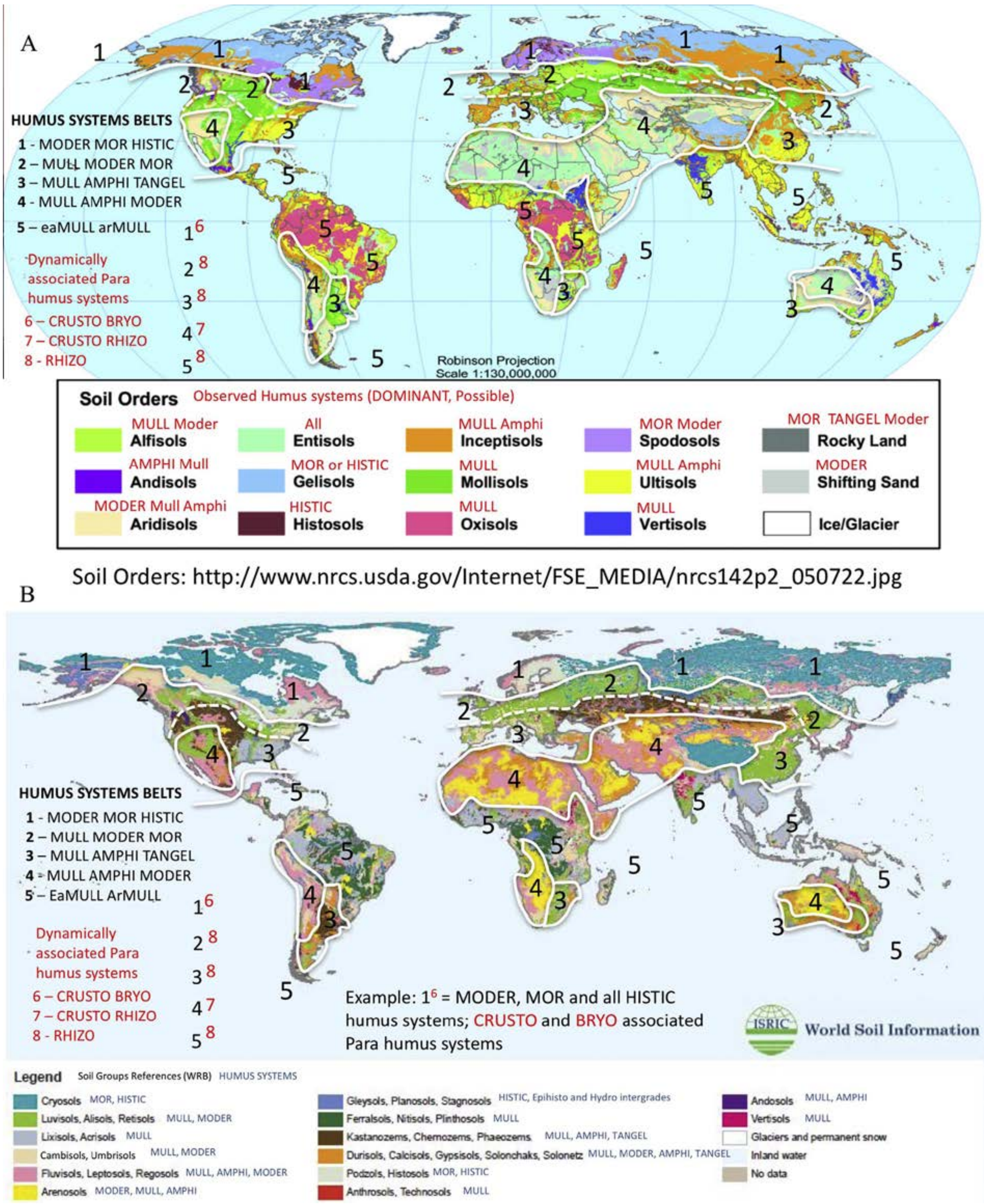

A
HUMUS SYSTEMS BELTS
1 - MODER MOR HISTIC
2 – MULL MODER MOR
3 – MULL AMPHI TANGEL
4 - MULL AMPHI MODER
5 – eaMULL arMULL
Dynamically associated Para humus systems
6 – CRUSTO BRYO
7 – CRUSTO RHIZO
8 - RHIZO
1 6
2 8
3 8
4 7
5 8
Robinson Projection
Scale 1:130,000,000
Soil Orders
Observed Humus systems (DOMINANT, Possible)
MULL Moder
Alfisols
All
Entisols
MULL Amphi
Inceptisols
MOR Moder
Spodosols
MOR TANGEL Moder
Rocky Land
AMPHI Mull
Andisols
MOR or HISTIC
Gelisols
MULL
Mollisols
MULL Amphi
Ultisols
MODER
Shifting Sand
MODER Mull Amphi
Aridisols
HISTIC
Histosols
MULL
Oxisols
MULL
Vertisols
Ice/Glacier
Soil Orders: http://www.nrcs.usda.gov/Internet/FSE_MEDIA/nrcs142p2_050722.jpg
B
HUMUS SYSTEMS BELTS
1 - MODER MOR HISTIC
2 – MULL MODER MOR
3 – MULL AMPHI TANGEL
4 - MULL AMPHI MODER
5 – EaMULL ArMULL
Dynamically associated Para humus systems
6 – CRUSTO BRYO
7 – CRUSTO RHIZO
8 - RHIZO
1 6
2 8
3 8
4 7
5 8
Example: 1 6 = MODER, MOR and all HISTIC humus systems; CRUSTO and BRYO associated Para humus systems
ISRIC World Soil Information
Legend Soil Groups References (WRB) HUMUS SYSTEMS
Cryosols MOR, HISTIC
Luvisols, Alisols, Retisols MULL, MODER
Lixisols, Acrisols MULL
Cambisols, Umbrisols MULL, MODER
Fluvisols, Leptosols, Regosols MULL, AMPHI, MODER
Arenosols MODER, MULL, AMPHI
Gleysols, Planosols, Stagnosols HISTIC, Epihisto and Hydro intergrades
Ferralsols, Nitisols, Plinthosols MULL
Kastanozems, Chernozems, Phaeozems MULL, AMPHI, TANGEL
Durisols, Calcisols, Gypsisols, Solonchaks, Solonetz MULL, MODER, AMPHI, TANGEL
Podzols, Histosols MOR, HISTIC
Anthrosols, Technosols MULL
Andosols MULL, AMPHI
Vertisols MULL
Glaciers and permanent snow
Inland water
No data

Fig. 4

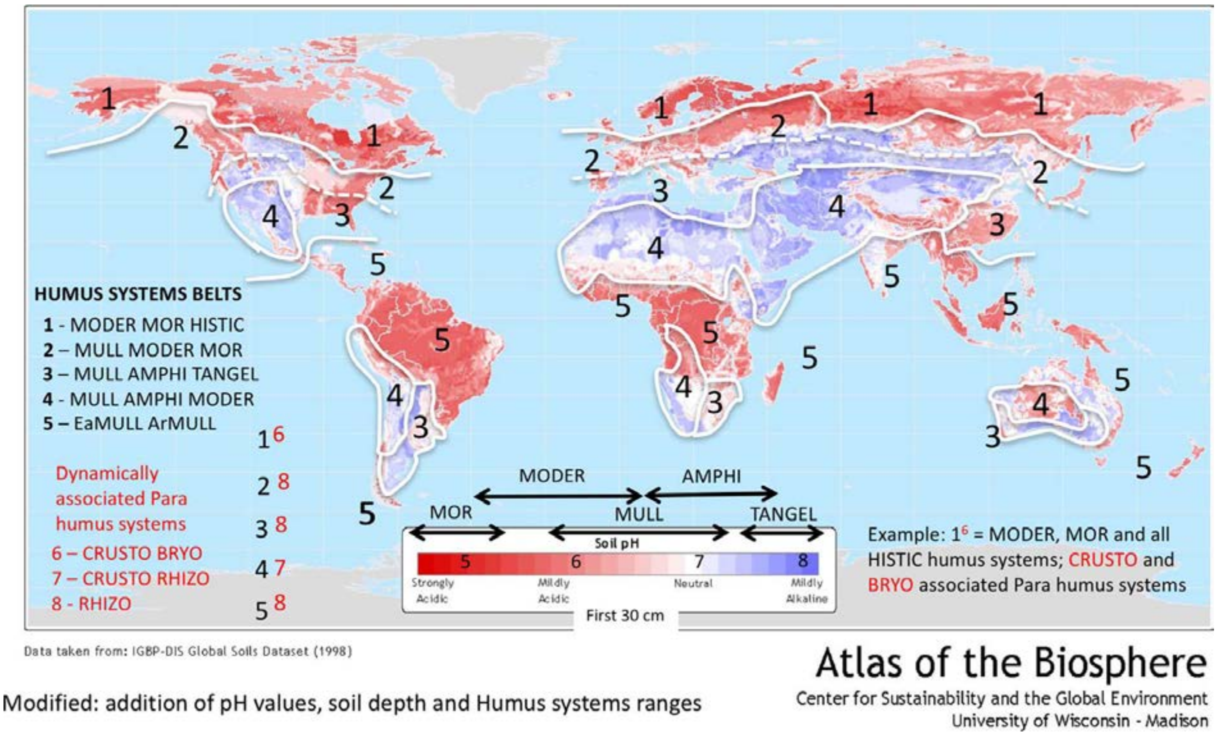

HUMUS SYSTEMS BELTS
1 - MODER MOR HISTIC
2 – MULL MODER MOR
3 – MULL AMPHI TANGEL
4 - MULL AMPHI MODER
5 – EaMULL ArMULL
Dynamically associated Para humus systems
6 – CRUSTO BRYO
7 – CRUSTO RHIZO
8 - RHIZO
1 6
2 8
3 8
4 7
5 8
MODER
AMPHI
MOR
MULL
TANGEL
Soil pH
5
6
7
8
Strongly Acidic
Mildly Acidic
Neutral
Mildly Alkaline
First 30 cm
Example: 1⁶ = MODER, MOR and all HISTIC humus systems; CRUSTO and BRYO associated Para humus systems
Data taken from: IGBP-DIS Global Soils Dataset (1998)
Modified: addition of pH values, soil depth and Humus systems ranges
Atlas of the Biosphere
Center for Sustainability and the Global Environment
University of Wisconsin - Madison

Fig. 5

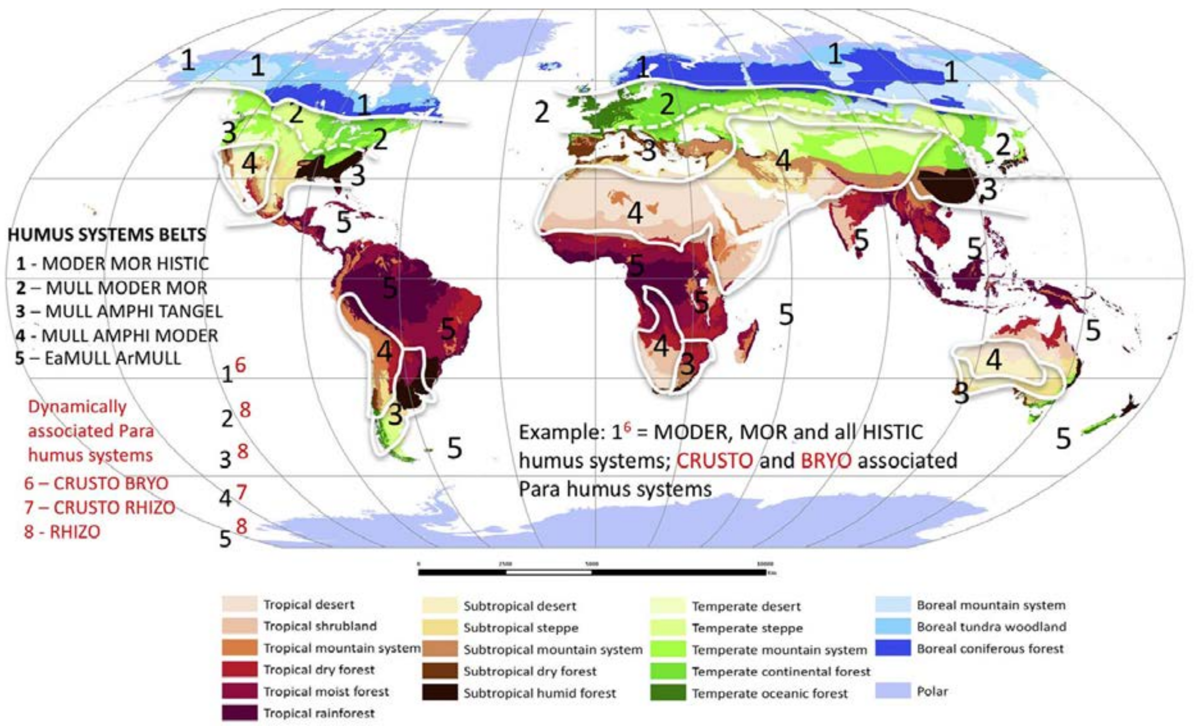
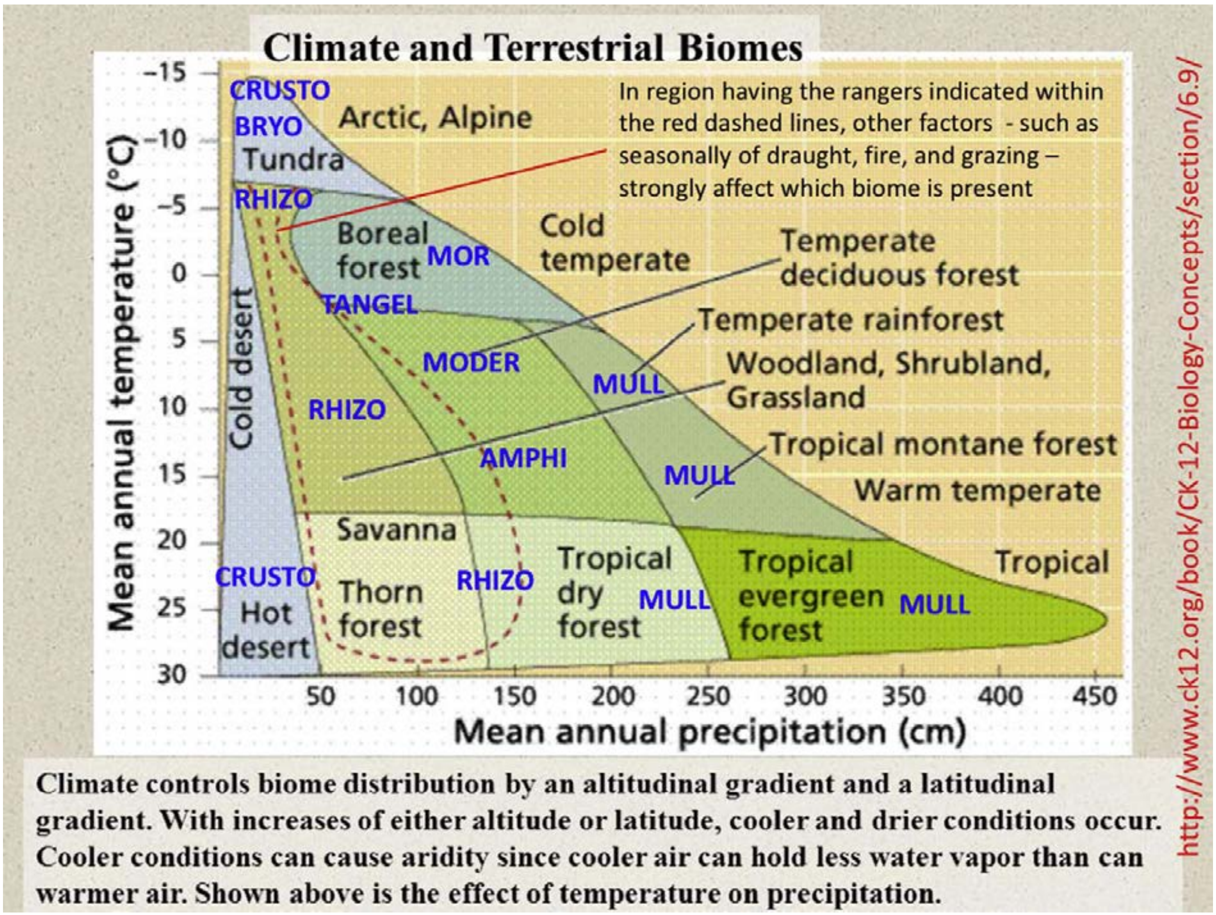

HUMUS SYSTEMS BELTS
1 - MODER MOR HISTIC
2 – MULL MODER MOR
3 – MULL AMPHI TANGEL
4 - MULL AMPHI MODER
5 – EaMULL ArMULL
Dynamically associated Para humus systems
6 – CRUSTO BRYO
7 – CRUSTO RHIZO
8 - RHIZO
1 6
2 8
3 8
4 7
5 8
Example: 1 6 = MODER, MOR and all HISTIC humus systems; CRUSTO and BRYO associated Para humus systems
Tropical desert
Tropical shrubland
Tropical mountain system
Tropical dry forest
Tropical moist forest
Tropical rainforest
Subtropical desert
Subtropical steppe
Subtropical mountain system
Subtropical dry forest
Subtropical humid forest
Temperate desert
Temperate steppe
Temperate mountain system
Temperate continental forest
Temperate oceanic forest
Boreal mountain system
Boreal tundra woodland
Boreal coniferous forest
Polar

Fig. 6



Climate and Terrestrial Biomes
In region having the rangers indicated within the red dashed lines, other factors - such as seasonally of draught, fire, and grazing – strongly affect which biome is present
Arctic, Alpine
CRUSTO
BRYO
Tundra
RHIZO
Boreal forest
MOR
Cold temperate
Temperate deciduous forest
TANGEL
Temperate rainforest
Woodland, Shrubland, Grassland
MODER
MULL
Cold desert
RHIZO
Tropical montane forest
AMPHI
MULL
Warm temperate
Savanna
CRUSTO
Hot desert
Thorn forest
RHIZO
Tropical dry forest
MULL
Tropical evergreen forest
MULL
Tropical
Mean annual temperature (°C)
−15
−10
−5
0
5
10
15
20
25
30
50
100
150
200
250
300
350
400
450
Mean annual precipitation (cm)
Climate controls biome distribution by an altitudinal gradient and a latitudinal gradient. With increases of either altitude or latitude, cooler and drier conditions occur. Cooler conditions can cause aridity since cooler air can hold less water vapor than can warmer air. Shown above is the effect of temperature on precipitation.
http://www.ck12.org/book/CK-12-Biology-Concepts/section/6.9/


Fig. 7

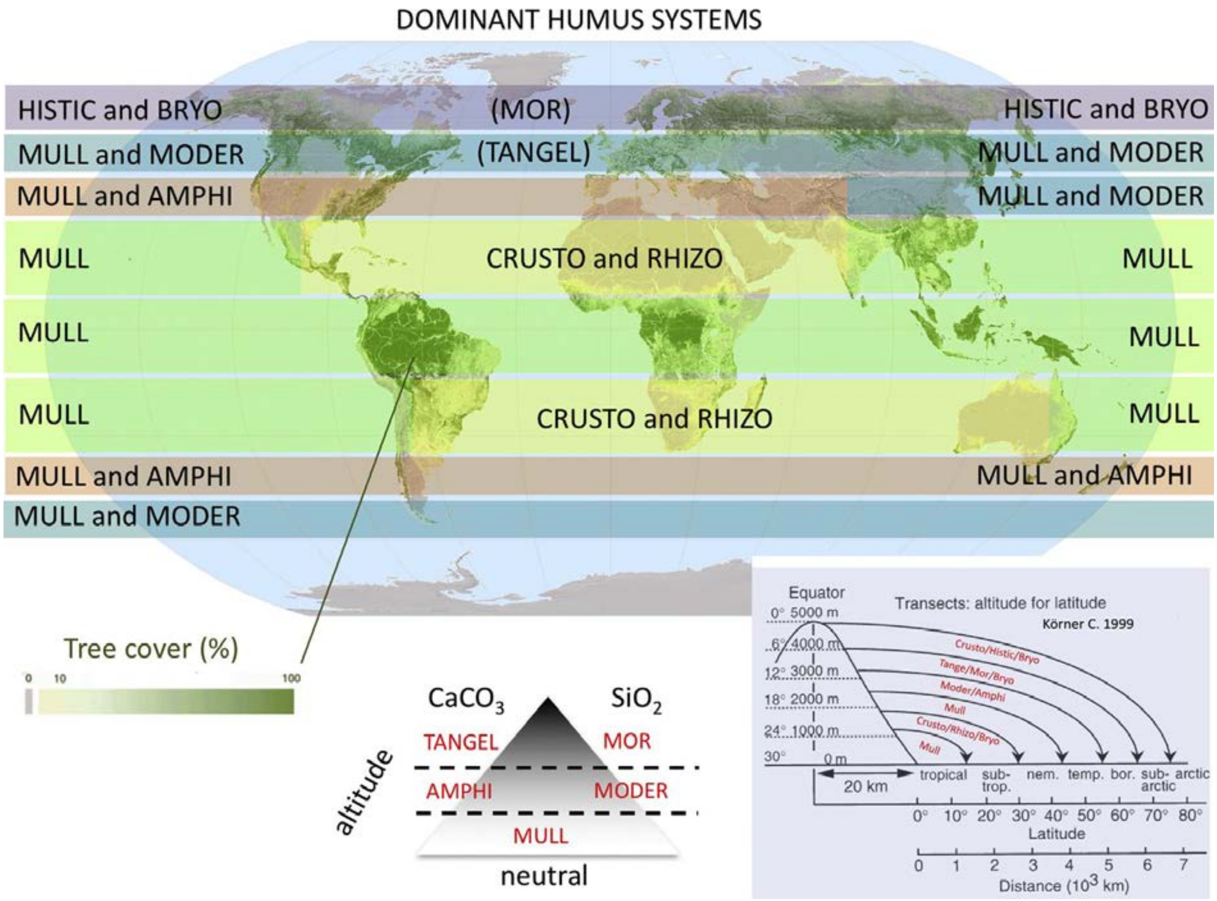

DOMINANT HUMUS SYSTEMS
HISTIC and BRYO
(MOR)
HISTIC and BRYO
MULL and MODER
(TANGEL)
MULL and MODER
MULL and AMPHI
MULL and MODER
MULL
CRUSTO and RHIZO
MULL
MULL
MULL
MULL
CRUSTO and RHIZO
MULL
MULL and AMPHI
MULL and AMPHI
MULL and MODER
Tree cover (%)
0 10 100
$CaCO_3$
$SiO_2$
TANGEL
MOR
AMPHI
MODER
MULL
altitude
neutral
Equator
Transects: altitude for latitude
Körner C. 1999
0° 5000 m
6° 4000 m
12° 3000 m
18° 2000 m
24° 1000 m
30°
0 m
20 km
Crusto/Histic/Bryo
Tange/Mor/Bryo
Moder/Amphi
Mull
Crusto/Rhizo/Bryo
Mull
tropical
sub-trop.
nem.
temp.
bor.
sub-arctic
arctic
0° 10° 20° 30° 40° 50° 60° 70° 80°
Latitude
0 1 2 3 4 5 6 7
Distance ($10^3$ km)

Fig. 8

Par NOAA — http://www.ngdc.noaa.gov/mgg/ocean_age/data/2008/ngdc-generated_images/whole_world/2008_age_of_oceans_plates.jpg, Domaine public, https://commons.wikimedia.org/w/index.php?curid=6972903

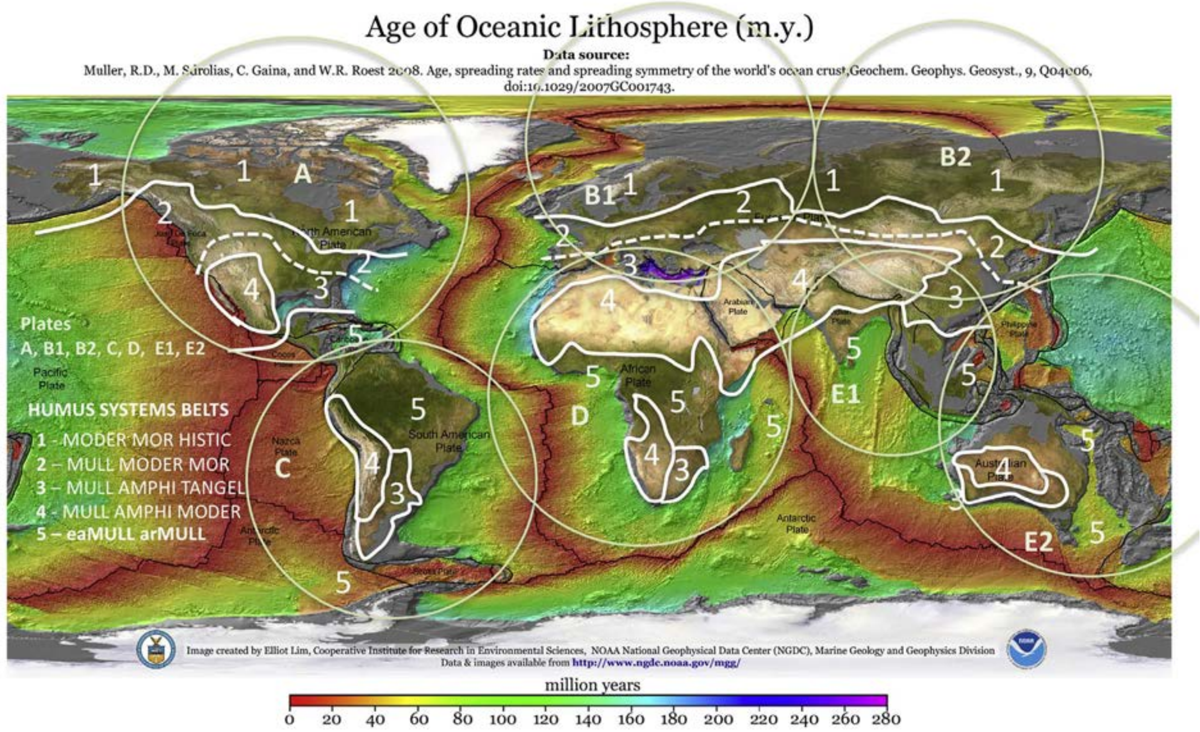
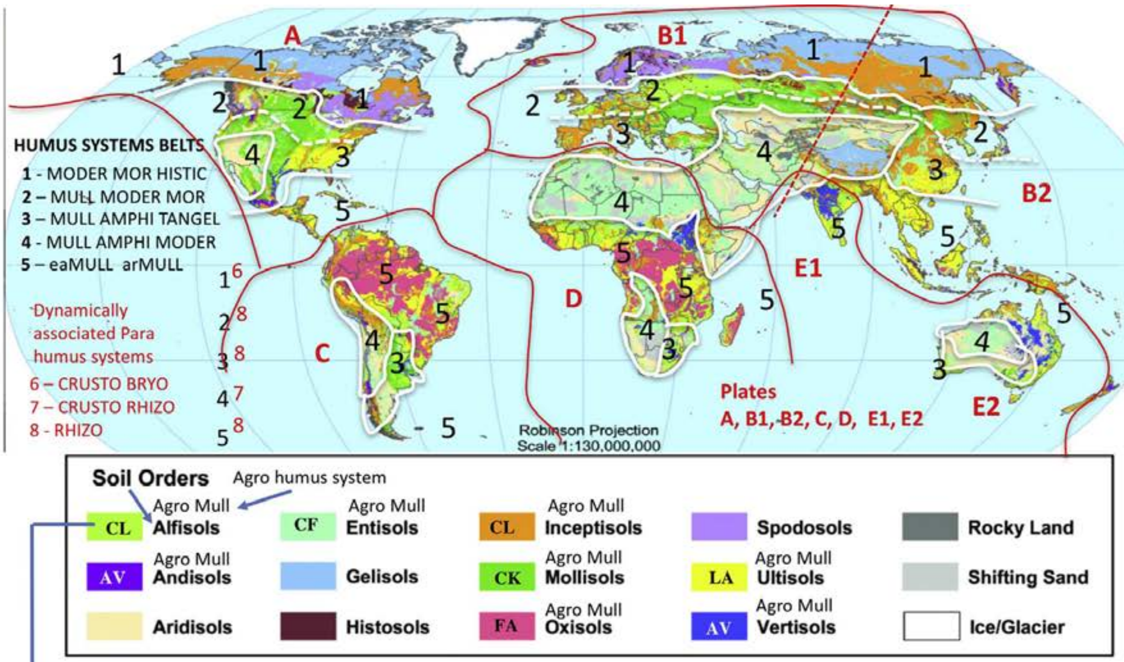


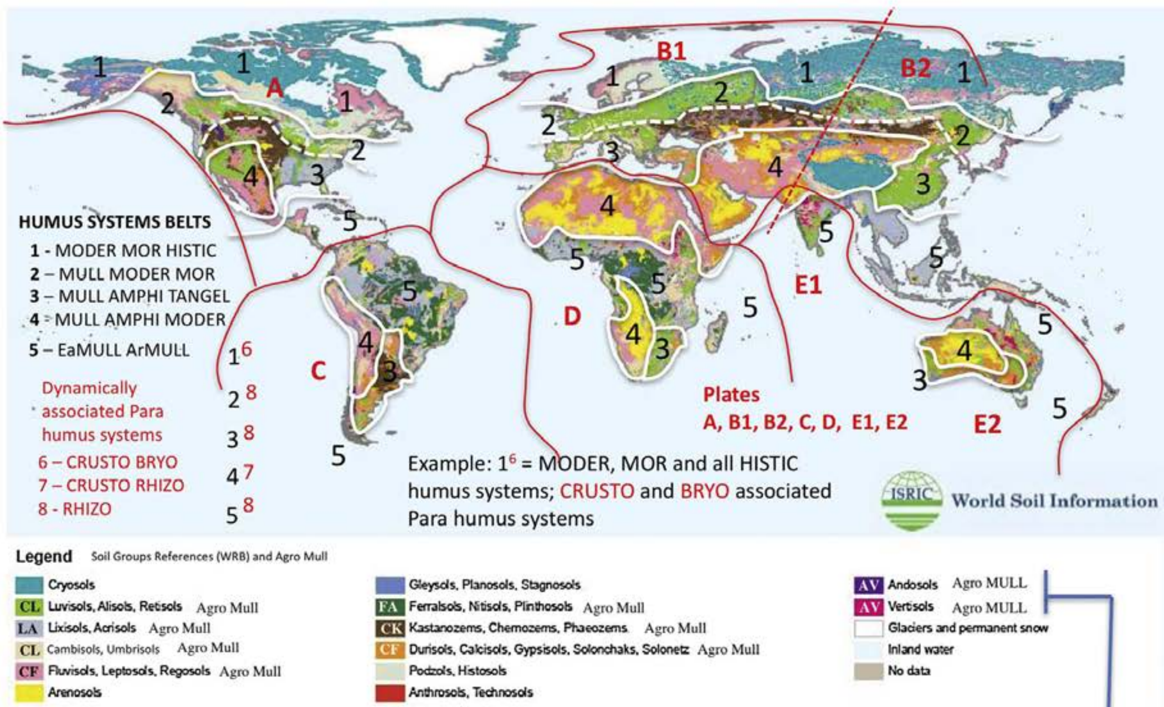

Fig. 9

A




**Temperate Agro Mull:**
**CL** = Agro humipedons of Cambisols and Luvisols = anthropically transformed forests or grasslands
**CK** = Agro humipedons of Chernozems and Kastanozems = anthropically transformed forest or pasture lands
**Subtropical-Equatorial Agro Agro Mull:**
**CF** = Agro humipedons of brown and grey subarid or fersiallitic soils = antrhopically transformed subdesertic and Mediterranean steppes on chromic Cambisols
**LA** = Agro humipedons of Lixisols and Acrisols = anthropically transformed subtropical bushed tree savanne on ferruginosols
**FA** = Agro humipedons of Ferralsols = anthropically transformed poor subtropical to dense equatorial forest on ferrallitisols
**AV** = Agro humipedons of Andosols and Vertisols = anthropically transformed forests or grasslands

B




**Temperate Agro Mull:**
**CL** = Agro humipedons of Cambisols and Luvisols = anthropically transformed forests or grasslands
**CK** = Agro humipedons of Chernozems and Kastanozems = anthropically transformed forest or pasture lands
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**AV** = Agro humipedons of Andosols and Vertisols = anthropically transformed forests or grasslands

Fig. 10

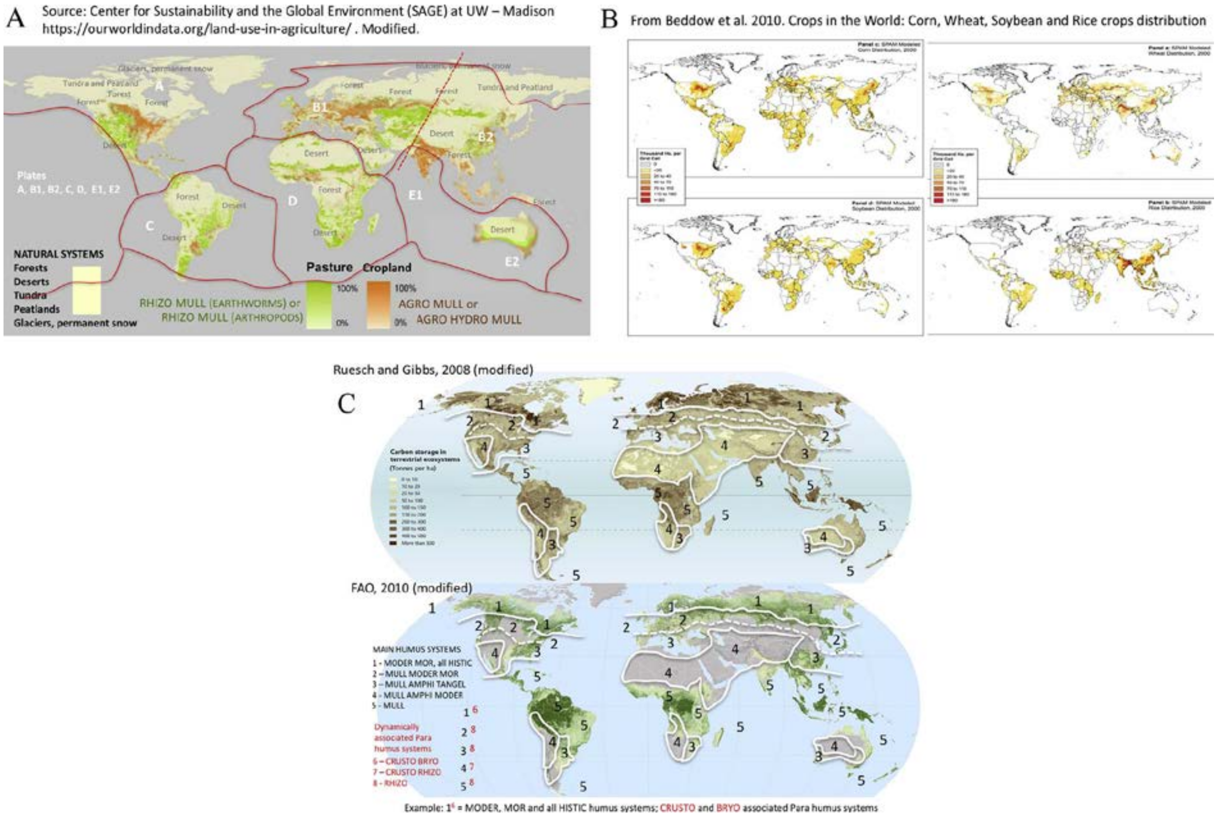
A
Source: Center for Sustainability and the Global Environment (SAGE) at UW – Madison
https://ourworldindata.org/land-use-in-agriculture/ . Modified.
Plates
A, B1, B2, C, D, E1, E2
NATURAL SYSTEMS
Forests
Deserts
Tundra
Peatlands
Glaciers, permanent snow
Pasture
Cropland
RHIZO MULL (EARTHWORMS) or
RHIZO MULL (ARTHROPODS)
AGRO MULL or
AGRO HYDRO MULL
B
From Beddow et al. 2010. Crops in the World: Corn, Wheat, Soybean and Rice crops distribution
Ruesch and Gibbs, 2008 (modified)
C
FAO, 2010 (modified)
MAIN HUMUS SYSTEMS
1 - MODER MOR, all HISTIC
2 – MULL MODER MOR
3 – MULL AMPHI TANGEL
4 – MULL AMPHI MODER
5 - MULL
Dynamically
associated Para
humus systems
6 – CRUSTO BRYO
7 – CRUSTO RHIZO
8 - RHIZO
Example: 1⁶ = MODER, MOR and all HISTIC humus systems; CRUSTO and BRYO associated Para humus systems

Fig. 11