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9

Raphael Pinheiro Machado Rehm

Small Scale Variability in Soil Hydraulic Properties in a Headwater Catchment of the Indian Western Ghats

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SMALL SCALE VARIABILITY IN SOIL HYDRAULIC PROPERTIES IN A HEADWATER CATCHMENT OF THE INDIAN WESTERN GHATS

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CONTENTS

ABBREVIATIONS

AL	Arable land
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
AWC	Available water capacity
AWHC	Available water holding capacity
CHNS	Carbon, Hydrogen, Nitrogen, Sulphur
D30	Soil depth 0-30 cm
D60	Soil depth 30-60 cm
D90	Soil depth 60-90 cm
D_b	Bulk density
DEM	Digital elevation model
D_m	Mineral bulk density
D_o	Bulk density of organic matter
D_p	Particle density
DTM	Gigital terrain model
EC_i	Elemental concentration
ES_d	Total elemental stock
f	Infiltration capacity
FAO	Food and Agriculture Organization of the United Nations
FC	Field capacity
FO	Forest
GL	Grassland
HCl	Hydrochloric acid
h_i	Thickness of sampled layer i
ICAR	Indian Council of Agriculture Research
K(h)	Hydraulic conductivity
$K(h)_S$	Saturated hydraulic conductivity
OC	Organic carbon
OM	Organic matter
PTF	Pedotransfer Function
PWP	Permanent wilking point
SA	Shifting area
SC	Scrubland
sc	Stone content
SCA	Specific contribution area
SIC	Soil inorganic carbon
SOC	Soil organic carbon
S_p	Pore space
TWI	Topographical wetness index
WC	Water content
θ_m	Mass soil water content
θ_v	Volumetric water content
θ_{vFC}	Volumetric water content at field capacity
θ_{vWP}	Volumetric water content at permanent wilting percentage

FIGURES

TABLES

1 INTRODUCTION

Soil hydraulic properties are an important component and serve as a key factor for the hydrological interaction between the land surface and the atmosphere (Venkatesh et al. 2011). The movement of water through the soil, the hydraulic conductivity and soil water retention characteristics are affected by basic soil properties such as texture, organic matter content and bulk density (Pirastru et al. 2013). In the humid tropics, extensive changes in land use and land cover have been taken place in the last few decades (Bonell et al. 2010). Changes in land use can impact water resources and consequently soil water conditions (Wagner et al. 2013a). The West Ghats located in the south-western part of India are undergoing enormous changes in land use and deforestation (Jha et al. 2000; Venkatesh et al. 2011). Given that the Western Ghats form the headwater catchments of all major rivers of Peninsular India, there is a growing cause for concern regarding the soil hydrological impacts of such land cover changes. Human activity on soils are generally associated to the reduction of soil quality, efficient macropore networks as well as of animal activity (Pirastru et al. 2013). Lower infiltration rates and storage capacity but higher runoffs and erosion rates were generally observed after the conversion of natural vegetation into cultivated systems. But researches for the specific effects of land use change on the soils of the Western Ghats around Pune are still rare and mostly based on collected data from secondary records (Barakade et al. 2011). The Mula-Mutha river basin in the state of Maharashtra contains with Pune and Pimpri-Chinchwad two major urban centers and experienced an enormous urban and industrial growth during the last two decades (Dhorde et al. 2012). Beside of these cities, Pune district is mainly covered by rural settlements. India is facing a strong demographic and economic growth and both are causing land use change and water shortage, especially during the dry season (Wagner et al. 2015). In areas with seasonally limited water availability local impacts can be important for the entire hydrological system. Some researches on land cover change were taken out for the Mula-Mutha river basin by LANSAT images (Dhorde et al. 2012; Wagner et al. 2015). There could be recognized a growth of settlements and agriculture areas while natural vegetation declined within the last 20 years. But this knowledge does not let draw conclusions about local effects on soils.

Urbanization is causing the loss of forest and nature areas for new settlements and buildings and the increase of agriculture area. While first is leading to rising surface runoff, a growing agriculture system leads to higher water replies (Wagner et al. 2015). Moreover, tourism in India is growing fast and was identified by the World Travel and Tourism Council as one of the foremost growth centers in the world in the coming decades (Husain 2014). Especially the Western Ghats have a great geographical diversity. With their numerous waterfalls, reservoirs, national parks, wilderness and hill stations they attract more and more numbers of nature tourists every year (Husain 2014). The forests of the Western Ghats have been used by native communities for centuries. While these activities can be considered as constant disturbances, todays activities extend substantial pressures on the forest resource. Conversion of forests to agricultural land appears to be the primary cause for deforestation (Jah et al. 2000). Attended by the changes of the natural vegetation, soil properties get affected as well. Several studies were carried out in the Western Ghats monitoring changes in forest management and cover and their effects on soil hydrological parameters (Bonell et al. 2010; Krishnaswamy et al. 2012). In small catchments, a significant decline of saturated hydraulic conductivity and an increased streamflow could be observed after a land use change from natural forest to degraded land forms. Finally, all hydrological effects were concluded to changes in soil properties.

1.1 Motivation

While the hydrological impacts of deforestation are well known, just a few studies have reported the differences in soil moisture regime under different land cover. Indian datasets about the change of soil properties due to land use change and deforestation are not enough reported (Chabara et al. 2003). Small scale studies under different land use types for tropical soils of India are rare (Bhattacharyya et al. 2005). Regional studies observing small scale patterns of the hydrological system should take different land uses and soils depths into account. The knowledge of specific spatial hydrologic soil properties is of major importance for hydrologic models on reginal scale especially in areas effected by land use change (Wagner et al. 2011, 2013). For modelling processes in India, the use of free datasets is required because of the limited data availability (Wagner et al. 2015). Soil properties reported by the Soil Survey Department in India show less data about soil hydraulic characteristics and moisture retention (Adhikary et al. 2008). Instead, spatial distribution of soil data is often derived from large-scaled soil maps like the Digital Soil Map of the World from the FAO (Wagner et al. 2011). The simulation of soil water flow is often carried out by estimating Pedotransfer Functions as empirical relationships between soil hydraulic properties and basic soil data (Kern 1995; Adhikary et al. 2008). The use of soil retention characteristics is necessary for large-scale modeling or pilot studies. But, the application of Pedotransfer Functions is steadily uncertain, because the accuracy of these functions outside of its development dataset is always unknown (Tomasella & Hodnett 1998).

1.2 Objectives

In India, considerable efforts have been made to provide homogenous soil maps and detailed soil classifications, also in and around of the state of Maharashtra (Challa et al. 1995, 1996; Bhattacharyya et al. 2013, 2015; Pal 2012b, 2017a). The present study was taken up to evaluate differences in small scale variability of soil hydraulic properties under different land covers and soil depths in association to slope, elevation and topographical wetness index as terrain attributes. The catchment falls into a homogeneous climatic region and possesses similar soil type and geology but differences in land cover of natural evergreen forest, scrubland, agriculture areas and grassland. This study used limited parameters to predict differences in soil hydraulic properties under different land use types.

Correlations between soil data and terrain attributes associated to different land use types and soil depth were observed to indicate small scale varieties in soil basic parameters and soil hydraulic characteristics. The study is focused on the two specific research questions, (i) if there are significant differences in basic soil properties under different soil depths and terrain attributes and (ii) if there is a recognizable relationship between soil water retention characteristics and different land use categories. Thereby stone content, soil texture, bulk density, soil organic carbon content and water content were measured as basic soil parameters. Additionally, hydrological measurements were taken by a double-ring infiltrometer to indicate infiltration capacity and saturated hydraulic conductivity. Soil water retention characteristics were calculated and validated by Pedotransfer Functions. As terrain attributes slope, elevation and the topographical wetness index (TWI) were observed.

2 TROPICAL SOILS OF INDIA

According to Voeleker (1893) and Leather (1898) and their first scientific attribution of Indian soils, there can be made a simple classification into alluvial, black, red and lateritic soils (Husain 2014). Alluvial soils are found in valleys or flood plains close to river beds or costal lines. The Black soils (often referred to as regur or black cotton soils) could be described as tropical chernozems because of their black color, clayed texture and high productivity. This type of soil covers the most part of Maharashtra developing on the weathered rocks of the Deccan basalt (Pal 2017a). Depending on parent material and climate the black color can also range into red (Husain 2014; Singh & Saroha 2014). The Red Soils of India were classified as red ferruginous soils and are mainly develop on the old rock formation of the Archean and Precambrian land mass (Fig. 4) (Jah et al. 2000). The classification of Red Soil can be understood as a collective term for all tropical soils characterized by reddish color, stable structure, poor base status, acidic in reaction, deeply and highly weathered and not suitable for agriculture systems (Ahmad 1973; Rengasamy et al. 1987; Pal et al. 2000). Red soil formations in India have a wide soil diversity and include the USDA taxonomic soil orders of Entisols, Inceptisols, Alfisols, Mollisols and Ultisols (Pal 2017a). Today there are different scaled maps based on the FAO/UNESCO soil classification as well as based on the working principles of the USDA Soil Taxonomy. The USDA soil taxonomy works with several levels as order, suborder, great group, subgroup, family and series (Soil Survey Staff 1999). Thus, the major tropical Red Soils of India can be classified as Inceptisols (39.4 %), Entisols (23.9 %), Alfisols (12.8 %), Vertisols (8.1 %), Ultisols (2.6 %) and Mollisols (0.5 %) (Bhattacharyya et al. 2009; Pal 2017a). Referred to the soils of Maharashtra they belong mainly to the orders of Entisols (37 %), Inceptisols (31 %) and Vertisols (26 %) as the predominant types, followed by Alfisols (6 %) and Mollisols (< 1 %) (ICAR 2010). In the uplands, they can be thin with no well-developed profiles and are mostly stonier or sandier than the red soils of the lower plains and valleys where they are deep and dark colored fertile loams. The typically reddish color indicates the present of ferric oxides and no hydrated conditions (Husain 2014).

Their pedogenetic process starts with the leaching of soluble salts and carbonate what leads to a pH level less than 7. Up next is the leaching of bases in form of nutrients. In the humid tropics, soils of 2 meters depth without any primary mineral content are common (Thomas 1994; Bremer 1995). Instead the formation of secondary and clay minerals starts. In the strong weathered tropical soils, de-silicification prevents the formation of secondary minerals because of the lack of silicon what is the main component for mineralization. As a consequent, mainly kaolinite is dominating the poor soils of the tropics. The red color is due to an increase in oxidized iron minerals. For dry conditions oxidic circumstances with hematite (ɣ-Fe2O3) prevails as favored product while under wet conditions the process of hydrolyzation products is dominated by the yellow-colored goethite (α-FeOOH) (Weischet 1977). Hence, these soils are commonly described as ferralitic soils and in case of hard crust formation as lateritic soils. Lateritic soils are strong weathered Red Soils which become hard under changing wet and dry conditions and are typical soil formations of the monsoon climate with seasonal rainfall and droughts. They result from impregnation of saprolite with iron oxides and hydroxides. These soils are leached of siliceous, poor in nitrogen and organic matter but rich in iron and aluminum. Laterite is mainly developed on the quartziferous granitic regions of the southern Western Ghats (Fig. 4) (Husain 2014). Some Laterites also cap the summits of the southern Deccan Plateau up to the large and famous duricrusts plateaus of Mahabaleshwar but are normally absent in the basaltic northern part around and above of Pune (Ollier & Sheth 2008).

2.1 Red Soils of the northern Western Ghats

The soil formation on the Deccan Plateau started after the eruption of the basalt flows under tropical humid climate since the Tertiary period (Bhattacharyya et al. 2006 b). The soils developed after the giant basaltic shield was created during the continental drift (Fig. 1). In the end of Cretaceous time scale the Indian land mass passed the Reunion Hotspots in the Indian Ocean where giant lava flows were set free (Bremer 2010; Husain 2014). Subsequent, the continental land mass crossed the equatorial territorial with typical tropical climate during the Paleogene (Fig. 1). After docking on the Laurasia continent, tectonic movements lifted the western part of the Deccan Plateau and let rise the Western Ghats as a giant escarpment. Because of the heavy rains of the annual monsoon, the Ghats stayed tropical until today while the Peninsular India turned into a semi-arid climate environment (Hussain 2014). After millions of years of weathering, the Red Soils of the northern Western Ghats should be expected as general deep and highly weathered soils with low productivity (Bremer 2003; Pal 2017a). Against these considerations, the soils are very well qualified for agriculture use and horticulture (Bhattacharyya et al. 2006a, 2007, 2014; Pal et al. 2012 a, 2015; Pal 2017a). Even the formation of Vertisols is documented wherefore a certain proportion of smectite minerals is assumed (Bhattacharyya et al. 2005).

The formation of Black Soils is common over the widespread semi-arid plateau of the Deccan Basalt while the Red Soils are encountered in the humid tropical mountain areas and over the peninsular India made of acidic rocks as granite, gneiss and schist (Pal et al. 2000). Detailed differences of soil properties on the basaltic and crystalline basements are shown by Laufenberg (2003). Mohr et al. (1972) and Chesworth (1973) named the parent rock as main factor for soil genesis (Fig. 4). By heavy annual rainfalls > 1 500 mm the pattern rock seems to lose its role as pedogenetic factor and the formation of Red Soils dominates even on basaltic rocks by the process of kaolinitization (Bruhn 1990). While in earlier soil maps of India the basaltic Red Soils of the northern Ghats were simply excluded (NBSSLUP 1983), they got the same mapping unit as the granitic Red Soils in more modern soil maps (Husain 2014; Singh & Saroha 2014). Red Soils of western Maharashtra take in a special position. There is a different between the Red Soils of the northern Deccan Basalt and the Red Soils of the Archaean granite of Tamil Nadu in the south (Fig. 4; App., Pic. 3, 4). Both Red Soils develop in areas in which high rainfalls leaches soluble minerals resulting in a loss of basic constituents. The heavy granite red earths hold high amounts of concreting material, contain a typical loamy texture with a distinct amount of sand fraction, contain quartz and are acidic and deficient in humus (Singh & Saroha 2014). The Red Soils developed on basalt do not contain quartz gravels, veins or stone lines like described from the soils on granite rocks and the weathering residues of basalt produces mostly clay (Ollier & Sheth 2008). These soils contain a high humus content and maintain a positive organic carbon balance in general (> 1 %) (Pal et al. 2014). They are described as non-calcareous with a slightly acidic milieu and support a various number of production systems (Bhattacharyya et al. 2005, 2006 b; Venkatesh et al. 2011). And the formation of these organic rich soils is caused by the presence of Ca-rich zeolite minerals mostly common in the sloping regions and uplands of the Deccan Plateau (Bhattacharyya et al. 1993, 1999).

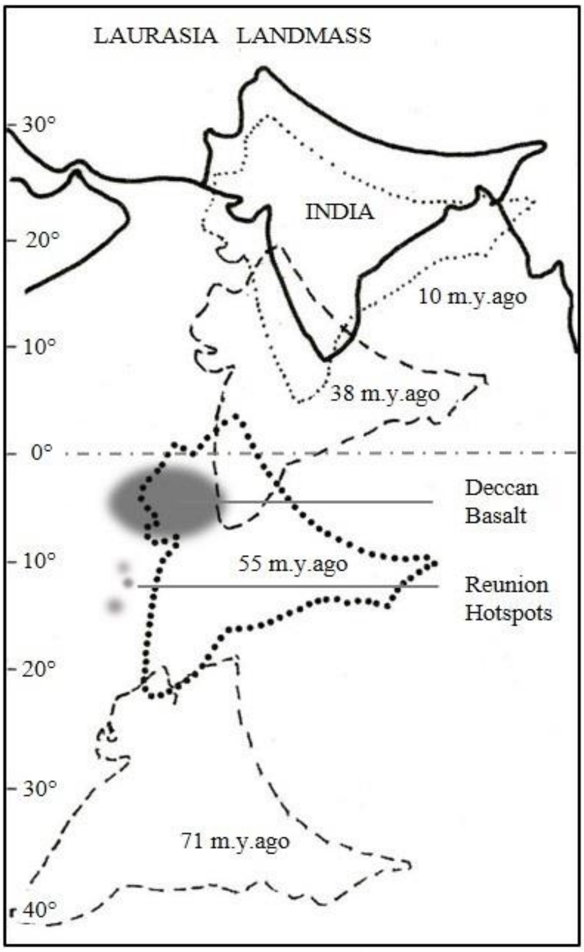


Figure 1: Continental drift of the Indian land mass (modified after Husain 2014).

2.2 Zeolites as soil modifier

Zeolite is a collective term for water based minerals which have the property to take up (hydrate) and to provide (dehydrate) water reversely and to exchange cations of their constituents. But, during this process some of their constituent cations are get exchanged and influence the pedochemical environment in the soil (Bhattacharyya et al. 1999). Their naturally formation is common as secondary minerals in Cenozoic volcanogenic sedimentary rocks (Pal 2017a). Because of the limited occurrence of this mineral it was excluded from many natural processes and researches but was observed in large bulks in the Deccan basalt around Mumbai and Pune (Sukheswala et al. 1974). Today the northern and western formations of the Deccan Basalts of western Maharashtra are known to be rich in zeolites (Bhatta-charyya et al. 1999). In the mountain area heulandite-Ca is the most common of these hydrous minerals (Bhattacharyya et al. 2006 b). The basalt area around Mumbai and Pune was categorized into three zeolite zones described as laumonite zone (predominates with quartz and burial metamorphism), the scolecite zone and the heulandite zone (containing more hydrous types) (Sukhes-wala et al. 1974). The last two decades brought new knowledge about the role of zeolites in soil formation and productivity for the Red Soils on the Deccan Basalt (Pal et al. 2012 b).

The general chemical structure of heulandite is $(X)5[Al9Si27O72]\cdot 24H2O$, were X stands for Ca, Na, K, Sa or Ba elements (Schorn 2017). Positive ions are rather loosely held and can be exchanged for others in a contact solution. These type of mineral affects physical and chemical properties of soil and in further consequences hydraulic properties like drainage, water retention, surface area and degree of hydration (Pal 2017a). Furthermore, the persistent of zeolites improves the process of humification and accumulation of soil organic carbon (Pal et al. 2012b, 2013). Since the Indian Council of Agriculture Research (ICAR) and the National Bureau of Soil Survey (NBSS) reported zeolites in 1990 as the main source for smectite in the soils of the Deccan Trap this kind of minerals are named soil modifier next to gypsum and calcium carbonate (Pal et al. 2012 b, 2013, Pal 2017a). Soil modifier change the pedo-chemical environment of the soil to better soil productivity und agriculture use and management. The present of kaolinitic and oxidic clay minerals show the advanced weathering stages of the soils but they still did not reach the kaolinitic mineralogy in total. It seems like the continuous supply of bases from the zeolites of the weathering basalt gravels helps minerals of smectite to stay in stable formations in that tropical environment (Bhattacharyya et al. 1999). In the light of the fast transformation of smectite minerals to kaolin it is not obviously to find even shrink-swell Vertisols under this climate conditions. But their formation can be explained by the present of zeolite that releases ions resulting in high base status and preventing the transformation of smectite to kaolin (Pal 2017a). With time and loss of the zeolites stock, the Vertisols become more acidic and kaolinitic and form Alfisols, Mollisols or Ultisols (Pal 2017a). The Red soils of the Deccan Trap can be dated back to the Tertiary and the Cretaceous based on their kaolinitic mineralogy combined with Fe and Al content (Bhattacharyya 1999; Pal 2017a). It is assumed that there is a persistence of soils which can exist in a study state over millions of years caused by zeolite soil modifiers (Yaalon 1975; Chesworth 1980; Bhattacharyya et al. 2006 b; Pal et al. 2014).

3 STUDY AREA

The studied headwater catchment is located on the eastern side of the Indian Western Ghats of Maharashtra in the Mulshi region of the Pune district 60 km westerly to the City of Pune (old Poona). Within the area belongs the village Varak (18°27'55. N | 73°27'59. E) as a reference point. The studied drainage basin faces north and drains into the Mulshi-Lake, the biggest reservoir of the Mula-River system (App., Pic. 1). Its primary function is to power Mumbai with electrical energy but also serves for drinking water supplies and irrigation downstream in direction to Pune (Wagner et al. 2013b). The investigation area comprises a total stretch of land of 285 ha with an elevation between 600 to > 1 000 m a.s.l. (Fig. 2). The mountain region is part of the Indian Deccan Basalt Province which can be divided in three morphological units. The Konkan coastal lowland, the Western Ghats as gigantic coast-parallel escarpment end the elevated inland plateau with east-flowing rivers and streams (Pawar & Vishwas 2006). The catchment represents a typical landscape scenery of the Mulshi region.

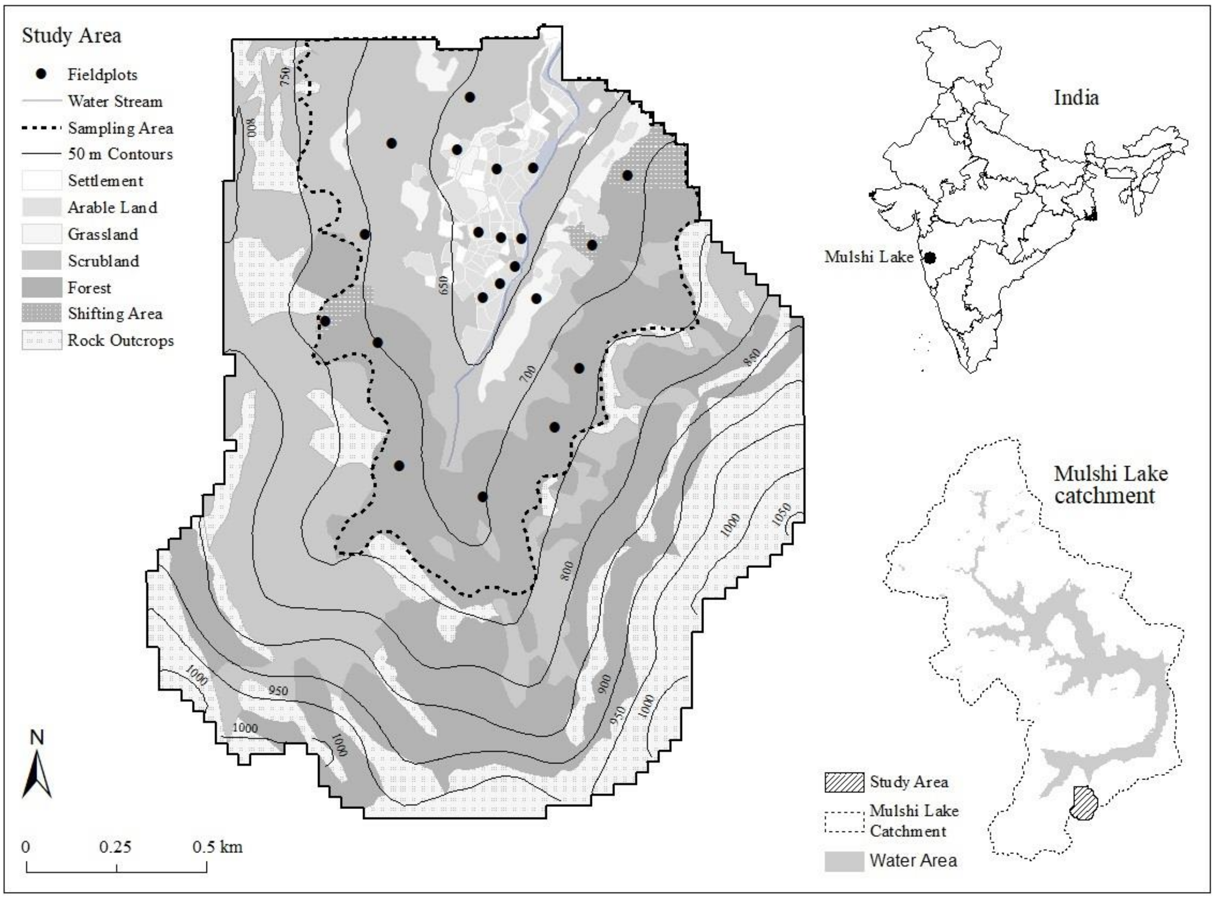


Figure 2: Computed extend of the studied headwater catchment of the Mulshi Lake with sampling area and located field plots. The area outside of the sampling area are dominated by shallow soils and rock outcrops (landscape photograph see App., Pic. 1).

3.1 Climate

The climate of whole India is most affected by the tropical monsoon (ICAR 2010). In this wind system results the characteristic seasonally wet summer and dry winter (Singh & Saroha 2014). Heavy rainfalls during the summer season from June to September due to the southeast winds are coming from the Indian Ocean over the subcontinent carrying a lot of moisture with them (Bonell et al. 2010). On the dry land, the air masses are currently confronted by the West Ghats which rise across 1 600 m causing orographic heavy rainfall (5 000 mm) along the west coast (Bhattacharyya et al. 1999). The mountain relief affects the climate by lee effects on the east side so that the inland is typically rain shadowed and receives less than 1 000 mm rainfall like in Pune City (Fig. 3). There is an annual precipitation decline from west to east of 3 500 mm to 750 mm between Mumbai at the coast and Pune as shown in Fig. 3 (Wagner et al. 2011, 2012, 2013b). The area around the Mulshi-Lake is characterized by a humid tropical climate with a mean annual precipitation of around 3 000 mm with a monthly maximum in July (observed from station data at Mulshi dam, 1988-2008) and a low variation of annual temperature with a mean of 25-27 °C (Bhattacharyya et al. 2006b; Wagner et al. 2015). Regional differences in climate result from several factors including elevation, relief and proximity of water bodies (Husain 2014). This is one reason why soil mapping of the Western Ghats is a complex issue. Small-scale changes in climate from humid tropical at the coastal side to the semi-arid climate in the upland on the west happens within of 100 km and over a high changing relief, causing a confusing mosaic of soil types.

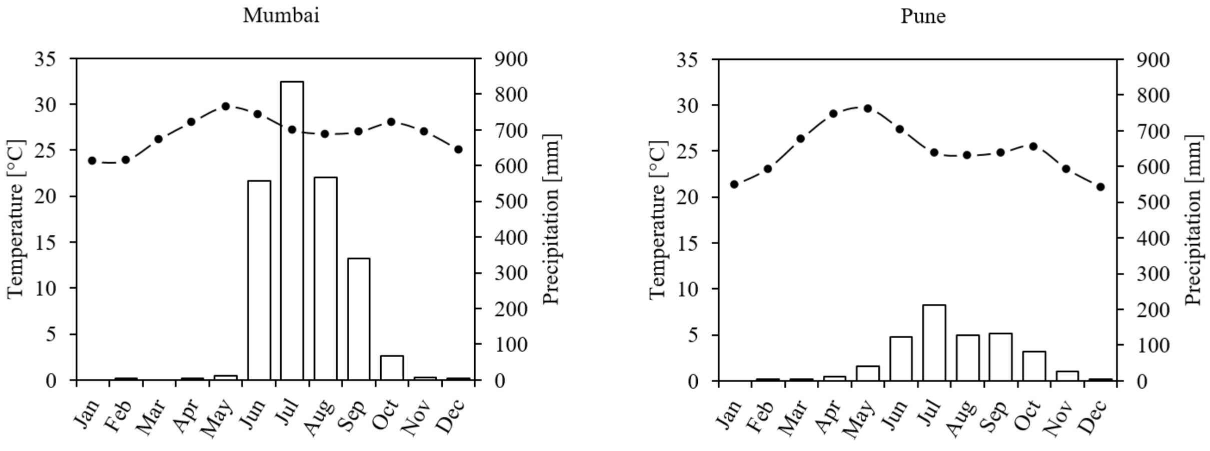


Figure 3: Average weather data between 1982 and 2012 of Mumbai and Pune. Monthly average precipitation and temperature were taken from climate-data.org (Anon. 2017a, 2017b).

3.2 Geology

The geology of the area consists of the Deccan Volcanic Province (Fig. 4), covering an area of more than 500 000 km^2 in the western and central parts of India (Bondre et al. 2004; Sayyed et al. 2016). It was formed during the Cretaceous Period 146 to 65 million years ago by large scale eruption of basaltic lava and intrusions of plutonic rocks (gabbro and granite) with a curved extension of 400 km around Mumbai. This mass was poured out to the surface and reached an assumed thickness of over 3 000 meters (Singh & Saroha 2014; Sayyed et al. 2016). The topography of the step-like appearance of the Maharashtra Plateau is formed by individual horizontal lava flow layers each with an average thickness of 5-30 meters (see App., Scheme). Between the layers sediments can be inter-bedded and the formation can contain small parts of quartz, bauxite, andesite and rhyolite (Husain 2014; Singh & Saroha 2014). After the Ghats were their present aspect has been formed by tectonic movements and river dissection (Bourgeon 1989).

The Western Ghats (Sahyadri) as a great escarpment formation cut across the large Deccan flood basalts in the north and the Precambrian igneous and metamorphic rocks in the south (Bhattacharyya et al. 1993). The study area is in the northern parts of the Western Ghats (Fig. 4) where the basaltic sheet still reaches a thickness over 2 000 m. The Western Ghats are a north-south chain of mountains from the Peninsula in the state of Gujarat to the South up to Kerala and Tamil Nadu (ICAR 2010). As a physical barrier, they rise abruptly from the coastal lowlands of the Arabian Sea and separate them from the inland plateau where they level off with gentle slopes to the east into the drainage basin of the Bhima and Krishna River draining into the Gulf of Bengal (Wirthmann 2000). The mountains form the watershed for the peninsula India where the main rivers like Godavari, Krishna or Kaveri rise from (Ollier & Sheth 2008; Husain 2014). In the northern parts of the Western Ghats the landscape is formed by ridges, hills and rocky plateaus generally over 1 000 m (Bhattacharya et al. 1993; Bondre et al. 2004). The average elevation is around 1 200 m with Mahabaleshwar (1 438 m) as next important peak of the region which mark the relict initial basalt surface (Wirthmann 2000; Singh & Saroha 2014). All the table lands and conical hills of the Western Ghats once formed a single plateau.

The most notably features of the Mulshi region are the leveled step slopes formed by the basalt traps (Bremer 2003) (App., Pic. 4). On the steep slopes, the basalt is not highly weathered and the soils are shallow. As pattern rock of the study area black rock basalt, tholeiitic basalt and brecciated formations could be identified (App., Pic. 7, 14). Each basalt trap consists of two types of basalt, the non-vesicular types are hard and compact with irregular fracture (App., Scheme, Pic. 6), the vesicular types contain softer breccia parts (Bondre et al. 2004). The Deccan basalt as volcanic rocks are dominated by dark ferromagnesian minerals and weather faster than granites or gneisses with low charge dioctahedral smectite as weathering products. Compared to the granite formations in the south, the mountain summits of the study area do not contain lateritic crusts. In quarries around Pune zeolites were found and described as silbit and heulandite next to minerals like mica, feldspar and less amounts of quartz. Both could be approved for the study area (App., Pic. 8, 9, 10). Calcite is missing instead (Bhattacharyya et al. 1999). The capacity to hold moisture and nutrients of smectites is even that high, that trees can directly anchor on weathered basalt (App., Pic. 13) and steep slopes and help to preserve the natural forest vegetation (Pal 2017a).

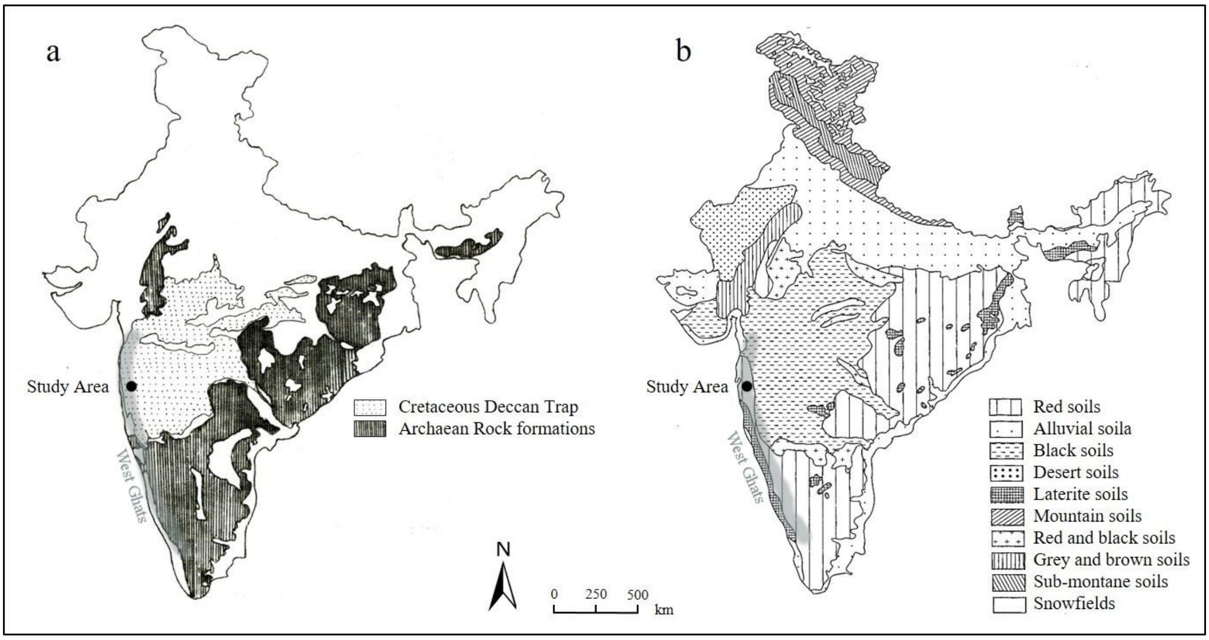


Figure 4: Geographical classification of the two geological main units of the tropical soils of India (a) and distribution of the main soil groups of India (b) (modified after Husain 2014).

3.3 Soils

Following the 1 : 500 000 soil map of Maharashtra (Challa et al. 1996) the soils in the studied headwater catchment can be characterized as very deep, well drained, loamy soils on gently sloping narrow valleys on one hand and very shallow, excessively drained, loamy soils on moderately steeply sloping highly dissected hill ranges of escarpments and narrow valleys on the other hand. For the study area, the in-situ soils are crucial (App., Pic. 2) which get their pedogenetic features from the parent rocks and gets deposited at the valley bottom. Alluvial, black soils and lateritic soils can be excluded. This mountain red soils were mostly classified as acidic Alfisols and belong to the Mollisol-Alfisol-Vertisol catenary described by Bhattacharyya et al. (1993, 2005, 2006b). These sequence holds a special position within tropic soils of India because it has been formed in humid tropical climate since the Tertiary (Bhattacharyya et al. 1999). The climate of the Western Ghats provides weathering conditions which should have left an accumulation of kaolinitic and oxidic minerals like in low base status Ultisols or Oxisols formations (Chesworth 1973, 1980; Bremer 2003). But because of the zeolitic Deccan Basalt there are smectite-rich soils represent including red and yellowish-red soils with gravely-clay texture and shallow to moderately deep with vertic properties in the valleys (Bhattacharyya et al. 2005; Bornell et al. 2010; Pal et al. 2014). Around the study area soils enriched in zeolites and even intact structures of zeolite-minerals could be found on several mountain slopes during the fieldwork (App., Pic. 9, 10). Mollisols are classified as soils with a dark organic-rich surface horizon and high base status and are widespread under thick evergreen forest vegetation (App., Pic. 11) (Soil Survey Staff 1999; Pal et al. 2014). Alfisols are characterized by medium to high base status and subsurface horizons of clay accumulation and are mainly common under sparse forest or scrubland (Soil Survey Staff 1999; Pal et al. 2014). Also, some formations can be found without pedogenetic horizons that have retained original structure of parent material or soils with weakly developed horizons showing alteration of parent materials which could be described as Entisols or Inceptisols (Soil Survey Stuff 1999; Pal 2017a). On the steep slopes, shallow red-yellowish weathered grus profiles or even blank rock outweighs dominates (see App., Pic. 2, 14). Soils of the paddy land can be declared as Vertisols or soils with a vertic subgroup of cracking nature with a clay content more than 30 % in the upper 50 cm and reddish to brown in color (App. Pic. 15, 16) (Laufenberg 2003; Bhattacharyya et al. 2005). The soils of the study area do not contain quartz gravels, are dominated by the clay fraction, rich in soil organic carbon and are non-calcareous (Bhattacharyya et al. 2005, 2006 b; Venkatesh et al. 2011). These soil formations of the Western Ghats are productively cultivated by simple practices (Bhattacharyya et al. 1999).

3.4 Land use

Land use in the catchment follows principally the topography with forest on the slopes, spare forests, scrubland and grassland on the steep slopes due to edaphic conditions (Bremer 2003) and arable land and paddy fields in the valley area close to the headwater stream (Fig. 2). Land use of the whole catchment is dominated by forest (31.7 %) and scrubland (35.1 %) (Tab. 1). Grassland (2.7 %) occupy the shallow soils or rocky areas on outcrops or on top of the mountain ranges. Agriculture areas (3.9 %) are located at valley bottom with small rain-fed rice fields (< 1 ha) (Wagner et al. 2011, 2013b). It is estimated that the soils of the study area could have been under these separation of land uses for centuries (Bhattacharyya et al. 2006 b). That is mainly referred to the natural forest vegetation and the rice fields close to the water stream. According to the local people the upper fields are assumed to be taken under agriculture during the last 20-50 years. Since the Paleolithic (12 000 years BP) humans are affecting the natural ecosystem of the Western Ghats (Ramachandra et al. 2012). They started as hunter gatherers before growing specific food plants. Real farming process began about three millennia ago. Traditional agriculture systems as they are known up to present like paddy fields, shifting cultivation or forest tree plantations started to expanse since the British colonization two centuries ago (Ramachandra et al. 2012). Today more than the half (58 %) of the Maharashtra state is under cultivation while the natural areas are mainly covered with forest or scrub vegetation (ICAR 2010).

Table 1: Land use in the studied headwater catchment of the Mulshi Lake derived from aerial photographs

Land Use	Catchment		Sampled area	
	[ha]	[%]	[ha]	[%]
Arable land	11.1	3.9	11.1	10.0
Forest[a]	90.3	31.7	40.0	35.9
Shifting area	4.5	1.6	4.5	4.0
Scrubland[b]	99.9	35.1	43.7	39.1
Grassland[c]	7.7	2.7	7.7	6.9
Rock outcrop	66.9	23.5	-	-
Settlement & infrastructure	3.1	1.1	3.1	2.8
Stream bed	1.5	0.5	1.5	1.3
Total sum	284.9	100	111.5	100

[a] Include forest types of tropical evergreen forest, semi evergreen forest, deciduous forest.
[b] Includes biotic scrub vegetation, degraded forest forms with short trees, regenerating forest and open forest areas interspersed with scrub- and grass-covered patches.
[c] Grassland also includes areas of shallow soil and rock outcrops.

The state of Maharashtra keeps the second greatest forest cover on the Deccan basalt area (Pal 2017a). For the northern West Ghats, there can be differenced three varies of forest types the tropical evergreen forest, the tropical semi-evergreen forest and the tropical deciduous forest (Bharucha 1983). Evergreen forests are limited to the escarpment on the western side of the Ghats and on areas receiving high amounts of rainfall of more than 2 500 mm and high annual temperature between 25-27 °C. Tall trees and dense low vegetation as well as lianas and epiphytes make this kind of forest practically impassable. The similar semi-evergreen forest surrounds the evergreen forest in areas of slightly less rainfall (around 2 000-2 500 mm) (Bharucha 1983). Because of more seasonally moisture availability these kind of forest is slightly more open and the trees are somewhat lower in high compared to the tropical evergreen forests (Singh & Saroha 2014). Both forest types occur in areas with high relative humanity due to the close distance to the sea. In all evergreen forests hardwood trees dominates and because of deep shade the floors are not covered by grass. In addition to that the tree roots take up much of the moisture and nutrients, so the grass cannot stand this competition and the fallen leaves makes undergrowth impossible (Bharucha 1983). The deciduous forest is the typical monsoon forest type. It grows in regions of again less annual rainfall of around 1 000-2 000 mm but also of high temperatures of around 27 °C. During the dry season, the trees of these forest shed their leaves, generally in March and April. The forest is more open than the evergreen ones but can also occur with dense layers of undergrowth vegetation (Singh & Saroha 2014). The study area mainly holds characteristics of the semi-evergreen forest with some close evergreen parts on the shadow sides but also contains some individual trees shedding their leaves (App., Pic. 17).

In Indian forests burning, fuelwood extraction and grazing are common human activities (Mehta et al. 2016). These interventions can lead to degradation of natural evergreen or deciduous forests to scrub dominated vegetation or grass covered openings (Singh 1994). In the studied headwater catchment, the steep terrain allows two types of farming the shifting cultivation and terrace farming. Shifting agriculture is well known from tropical areas as the slash and burn cultivation. But in the West Ghats the farmers do not prepare fields. Instead the local people clear a forest area by fire and directly seat crops on it. The cleared area gets cultivated for 2-3 years until the natural vegetation starts to take over again and new patches will be chosen (Singh & Saroha 2014). On the burned shifting areas ragi cereals are the most common cultivation. Another kind of annual fire practice is represented by low-intensity fires to promote grazing grasses (Mehta et al. 2016). Therefor dried out patches of grass or scrub land were burned within seconds or minutes by a fast sprawling fire.

Burned patches are often covered by a species of the Strobilanthes (kunthianus) (App., Pic. 23), a common scrub plant located in the mountain forests of the Western Ghats (Anitha et al. 2010). Old degraded forest areas are recognizable by a domination of this plant. The strobilanthes scrub blooms only once every 7 to 12 years and is used by the locales to control the fallow periods for shifted forest areas (Sharma et al. 2008).

The mountain valleys are under paddy agriculture, suited for rain-faded cultivation. Terrace farming enables cultivation even on hill slopes and mountain ranges (App., Pic. 19). By the construction muddy deposits were trapped as fertility material from the surrounding catchment transported by water courses coming from higher regions during the rainy season. Moreover, the terraces get waterlogged or get flooded in the valleys and are planted with water intensive crop. Under the terrace system the fertility of land is maintained. One method is to burn biomass from the natural vegetation around the fields (leaves, tops and branches) to fertilize the soil by the ash deposits. The high soil temperature caused by burning stimulates biological activity and advances organic matter mineralization (Are et al. 2008). The addition of natural fertilizers by farmyard manure, green manure and rice straw is also practiced (App., Pic. 27). During the dry season, the fields lay follow and get ploughed shortly before the next rain period (Srinivasaro et al. 2011; Singh & Saroha 2014). For the study area it is assumed, that tillage does not reach more than 30 cm in depth (App., Pic. 24). Until today the paddy fields of the study area are ploughed by cattle as major energy source in agriculture. The animals have an important role for rural farmers. The cultivation system practiced by the tribal people is a very low level of management (Bhattacharyya et al. 2007).

To promote feeding grass for the cattle, grassland that is left unused for agriculture is set on fire regularly. Young plants are growing right after the first rain. In the Western Ghats, different types of high rainfall grasslands are found above altitudes of 600 m and rainfalls up to 3 000 mm and more. In the studied area, low rainfall grassland with dominant grass species like Apluda (varia) under shrubs and Heteropogon (contortus) on bare rocks are common. Patches of degraded forest and scrubs as well as areas of shallow and dry soil has often changed into grasslands (Bharucha 1983).

4 Materials and Methods

4.1 Sampling framework

Over a time of five weeks a field survey was carried out in the study area close to the Mulshi Lake. The headwater catchment was chosen because of the watershed that was given by the natural rock formation with coexist of similar parent material but differences in land use (Fig. 2; App., Pic. 1). That was crucial to identify the influence of depth, slope and land use on soil variability. All samples and measurements were taken from April to June of 2016 in the end of the dry season when there was no rain. During this period, temporal variability of soil moisture and hydrology are minimized. To represent the different land uses several field plots were located on different slopes and under homogenous land covers of arable land (9x), forest (5x), shifting area (3x), scrubland (3x) and grassland (1x) (Fig. 2). The land use forest (FO) includes all closed and opened forest types of tropical evergreen forest, tropical semi evergreen forest and tropical deciduous forest which occur in and around the catchment (App., Pic. 17). The chosen forest plots were assumed not to be burned for shifting agriculture at least within the last 20 years based on the valuation of historical aerial images and no strobilanthes could be observed as typical plant of burned patches. Current burned forest plots were sampled and classified as shifting areas (SA). Scrubland (SC) includes next to biotic scrub vegetation also degraded forest forms with short trees. That includes also regenerating forest and open forest areas interspersed with scrub- and grass-covered patches (App., Pic. 18). Pure grassland category (GL) includes mostly grazing land with just shallow soils on open rocky phases unable to sample for retention characteristics and differences in soil depth. But there was one wide area that seemed to exhibit deeper soils and because of that there is just one field plot of grassland. Agriculture fields in the studied catchment which are exclusively used for rice cultivation in form of paddy fields were classified as arable land (AL). In the time of sampling the fields were fallow without vegetation (App., Pic. 19). Settlements and riverine tracks were not sampled same as open rock outcrops.

On the area of arable land square field plots of 10 x 10 m were created for sampling. On the other more extensive land uses plots of 25 x 25 m were chosen. The four corner points and the plot center were respectively sampled for texture, field moisture and soil organic carbon. The samples were taken in three subdivided depth increments of each 30 cm up to a depth of 90 cm (0-30 cm, 30-60 cm, 60-90 cm) or until the parent material was reached. During the sampling, soil depths up to 90 cm could be exactly determined using the soil auger as yardstick. The three depth layers are hereinafter referred to as soil depth D30, D60 and D90. Furthermore, each plot was sampled for top soil bulk density (10 cm). Infiltration capacity and saturated conductivity as hydraulic quantity were directly observed in the field by multiple double ring infiltrometer measurements. After laboratory analysis the bulk density was estimated for all depth layers by texture and organic carbon. In addition to that Pedotransfer Functions (PTFs) were calculated by different equation approaches. The sieving and CHNS-analysis were performed from the Environmental and Water Research Engineering Division (Department of Civil Engineering) of the Institute of Technology Madras in Chennai, India.

4.2 Sampling methods and laboratory analyses

A total number of 235 soil samples were collected using a Pürckhauer soil auger (Eijkelkamp, NL; 2 cm inner diameter). On the forest plots, superficial leaf residues and litter (about 10 cm) were removed from the soil surface before measurements were taken (App., Pic. 26). The soils of the catchment are characterized as non-calcareous (Bhattacharyya et al. 2005, 2006b). Anyway, all samples were tested for inorganic carbon by HCl (10 %) in the field. At laboratory soil samples were oven dried (105 °C) until consistently weight and dry weight was measured. The weight of the field moist samples was taken too, to obtain the soil water content (WC) at the time of sampling. All samples were sieved through a 2-mm sieve to remove coarse particles for further analyses. Roots and other apparent organic particles were removed by hand picking. To determine the percentage of coarse soil fraction or stone content (SC), both coarse (> 2 mm) and fine (< 2 mm) soil fraction were weighted. Afterwards the soil samples were homogenized by a hand mortar. Of all 235 homogenized soil samples 15 mg were removed for ongoing soil organic carbon (SOC) analysis.

Soil organic and inorganic carbon content was analyzed by elemental gas-chromatography using a CHNS elemental analyzer (vario MicroCUBE, Elementar, Hanau, Germany). For the analysis, the dried samples were powdered by a 100-micron sieve. 5 mg of each sample was packed air tight in tin boats of 4×4×11 mm in size and loaded in the autosampler. All analyses were carried out as triplicates. The instrument operating conditions were 1 150 °C for combustion tube temperature and 850 °C for reduction tube temperature. As carrier gas was used helium and as combustion gas oxygen (99.9 % purity).

The remaining samples were taken for sieving analysis. Texture was analyzed by sieving method to quantify grain size down to the silt fraction. For sieving process, composite samples of same depth (D30, D60, D90) of each field plot were formed to reduce the sample number. So, each depth layer of each plot was sieved separately until the fine sand fraction (0,15 to 0,075 mm; after the Indian Standard Soil Classification System). The sieving-remain was handled as silt and clay fraction.

To determine soil bulk density (D_b) of the topsoil stainless steel core cutter (length 10 cm; inner diameter 6 cm) were hammered into the soil and afterwards carefully excavated. The volumetric soil sample was dried at 105 °C in laboratory and D_b was calculated from core volume and dry sample weight. Because of the very dry and very clayed soils it was very hard to get undisturbed samples of subsoil bulk density. Anyway, for all 235 samples D_b was calculated from texture and organic carbon content (see chap. 4.4).

4.3 Hydrological measurements

A double-ring-infiltrometer (28 cm in diameter for the inner ring; 45 cm in diameter for the outer ring) was used to determine soil hydraulic properties and estimate field saturated conductivity based on in-situ infiltration measurements at the soil surface. Small, horizontal steps were dug into the surface slope to install the instrument on steep slopes. On every field plot, two double-ring infiltrometer measurements were performed. The rings were always filled up with water to a height of 10 cm to start. The infiltration rates into the soil were measured by manually recording the drop of water level in the inner ring by time. On the arable land, read outs were taken in a time interval of 2 minutes for the first 30 minutes and after that time intervals of 10 minutes for the rest of the total time. The time table was chosen until an apparent steady-state flow was reached for guarantee. In the superior field plots the total time periods ranged between 30 and 60 minutes depended on the infiltration rate and available amount of water. The steady-state infiltration rate reached in field was calculated based on the last three measurements which were assumed to state field saturated hydraulic conductivity. For a uniform application, field measurements were plotted by a curve-fitting regression and the values after 60 min were compared as saturated conductivity $K(h)_S$ (see Fig. 15).

4.4 Data analysis and statistical evaluation

Terrain attributes were calculated with ArcGIS 10.5 (ESRI, USA). A suitable digital elevation model (DEM) based on ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) satellite data with a spatial resolution of 30 m was used for slope and elevation analysis. For slope calculation, a 1 x 1 m interpolated ASTER (based on DTM 30 x 30 m) was used. For a linearly interpolation between the centers of each 30 m x 30 m grid cell of the original ASTER an inverse distance approach was used with a weighting exponent of one. The downscaling was made for precise distinction of the slope and elevation of the studied field plots. Four slope classes were chosen after limit values of FAO (2006) (class 1: < 5° = gently; class 2: 5-10° = sloping; class 3: 10-15° = strongly; class 4: ≥ 15° = steep) and four elevation classes were scaled after the 50 m contours (class 1: < 650 m; class 2: 650-700 m; class 3: 700-750 m; class 4: ≥750 m) for statistical analyses. The mapping of the area is based on aerial photographs. The topographical wetness index (TWI) after (Moore et al. 1991) indicates a secondary parameter for the impact of the topography of the catchment on spatial variability of hydrological landscape properties of the landscape. The TWI was used as a variable for potential soil moisture conditions at the different sampling locations (Wiesmeier et al. 2013).

$$TWI = ln\left(\frac{SCA}{\tan \alpha}\right) \tag{1}$$

where *SCA* is the specific contribution area describing the area as the local upslope area through a certain point of the headwater catchment and α is the local slope in radians.

For all 235 samples bulk density D_b for all depths (D30, D60, D90) was estimated from soil texture and organic matter using the equation developed by Adams (1983).

$$D_b = \frac{100}{\frac{X}{D_o} + \frac{100 - X}{D_m}} \tag{2}$$

where D_b is the soil bulk density (g cm^{-3}), X the percent by weight of organic matter, D_o the average bulk density of organic matter (0.224 g cm^{-3}), and D_m the mineral bulk density (g cm^{-3}). For the organic matter percent, a fraction of 0,5 from the percent of organic carbon content was taken and the mineral bulk density (1.4 g cm^{-3}) was calculated from the texture triangle of Rawls (1983).

Next to the measured SOC content, the amount of total SOC stock was calculated using the method described by Batjes (1996).

$$ES_d = \sum_i^d EC_i * D_b * h_i * \left(1 - \frac{sc_i}{100}\right) \quad (3)$$

where ES_d is the total elemental stock (kg m^{-2}) of the sampled soil profile d, EC_i is the elemental concentration (mg g^{-1}) of sample layer i, D_b is the bulk density (g cm^{-3}) of sample layer i, h_i is the thickness (cm) of sample layer i and sc_i is the percentage volumetric stone content (> 2 mm) of sample depth i. sc_i was calculated by proportion of weight of the coarse and fine soil fraction (mineral bulk density of fine soil was assumed to be 1.4 g cm^{-3}, calculated from the texture triangle of Rawls (1983); density coarse fraction or stone content was assumed to be 2.65 g cm^{-3}).

The percentage pore space in the soils was calculated by classic formula for ongoing calculations.

$$S_p = 100\,\% - \left(\frac{D_b}{D_p} * 100\right) \quad (4)$$

were S_p is the percentage of pore space, D_b the calculated soil bulk density and D_p the particle density (assumed to be 2.65 g cm^{-3} for silicate-dominated mineral soils) (Weil & Brady 2017).

The calculated pore space S_p of each sample, multiplied by the thickness of sampled depth h_i (cm), was to be assumed to represent the maximum of infiltration capacity f (mm) of each sampled profile. To estimate the f of one total profile (f_d) all sampled layers of each drilling position were summed up:

$$f_d = \sum_i^d S_p * h_i \quad (5)$$

An analysis of variance (ANOVA) was performed to test if the mean soil values are significantly different per land use and soil depth. When the homogeneity of variances was violated a Welch F test was run. Based on the chosen land use categories a specific linear regression was performed to identify significant interactions between terrain attributes and the observed soil properties. All Statistical analyses were performed using standard procedures in the Statistical Package for Social Sciences (IBM SPSS Statistics, Version 22.0).

4.5 Tested Pedotransfer Functions

Simulations of soil water flow were estimated by Pedotransfer Functions (PTFs), as empirical relationship between soil hydraulic properties and available measured basic soil properties. As standard procedure PTFs show the volumetric water content. To compare the calculated PTFs with the measured soil water content of the soil samples, the weighted soil water content was converted into volumetric water content (θ_v). Thereto the mass soil water content θ_m (kg kg^{-1}) is needed and commonly expressed in terms of kg water associated with 1 kg dry soil (Weil & Brady 2017).

$$\theta_m = \frac{kg\ water}{kg\ dry\ soil} * 1\ kg \quad (6)$$

To calculate the volume soil water content θ_v (m^3 m^{-3}), the estimated bulk density D_b was assumed.

$$\theta_v = D_b * \theta_m \quad (7)$$

For each soil horizon, the available water holding capacity (AWHC) was estimated as the difference between the water content at field capacity and at permanent wilting percentage.

$$AWC = (\theta_{vFC} - \theta_{vWC}) * h_i \quad (8)$$

where AWC is the available water capacity (mm), θ_{vFC} is the volumetric water content at field capacity and θ_{vWP} is the volumetric water content at permanent wilting percentage. The volume ratio was multiplied by the thickness h_i (cm) of each sampled soil layer and all layers were summarized to give the total centimeters of available water holding capacity (AWHC) of one sampled soil profile.

Four different equations of Pedotransfer Functions were tested. The most qualified model was used to estimate the soil water retention characteristics of the different land uses and soil depths. All estimations were compared with the value of the FAO soil map of the world. In the equations below, the subscripts -330 and -15 000 indicate the pressure head in hPa for field capacity (FC) and permanent wilking point (PWP).

(i) Gupta & Larson (1979) predicted volumetric soil water content at specific capillary pressure related to sand (%), silt (%), clay (%), organic carbon OC (%) and bulk density D_b (g cm^{-3}). They used multiple linear regression equations for given water potentials by regression coefficients a, b, c, d, and e of Tab. 2. The dividend of 1 000 serves to present results related to pressure heads in hPa.

$$\theta_v = \frac{a * sand + b * silt + c * clay + d * OC + e * D_b}{1\,000} \quad (9)$$

(ii) Rawls et al. (1983) developed a similar set of regression equations to relate soil water content to sand (%), clay (%), organic matter OM (%) and bulk density D_b (g cm^{-3}) by different regression coefficients a, b, c, d, and e (Tab. 3).

$$\theta_v = a + b * sand + c * clay + d * OM + e * D_b \quad (10)$$

(iii) Saxton et al. (1986) estimated the PTFs by an analytical retention function from sand (%) and clay (%) content.

$$h_p = A * \theta^B \quad (11)$$

where

$$A = 100 \exp * (-4.396 - 0.0715 * clay - 0.000488 * sand^2 - 0.00004285 * sand^2 * clay)$$

and

$$B = 3.14 - 0.00222 * clay^2 - 0.00003484 * sand^2 * clay$$

(iv) Tomasella & Hodnett (1998) studied Brazilian soils and derived regression parameters for soil water contents by organic carbon OC (%), silt (%) and clay (%) content at different selected pressure heads h_p (Tab. 4).

$$\theta_v = 0.01 * (a * OC + b * silt + c * clay + d) \quad (12)$$

To estimate silt and clay content separately, it was assumed that clay content takes 60 % of the silt and clay content.

$$clay\,\% = (100 - sand\,\%) * 0.6 \quad (13)$$

$$silt\,\% = 100\,\% - sand\,\% - clay\,\% \quad (14)$$

Table 2: Coefficients of the linear regression of Gupta & Larson (1979) in Equation (9).

h (cm)	a	b	c	d	e
40	7,053	10,242	10,070	6,333	-321,200
70	5,678	9,228	9,135	6,103	-269,600
100	5,018	8,548	8,833	4,966	-242,300
200	3,890	7,066	8,408	2,817	-187,800
330	3,075	5,886	8,039	2,208	-143,400
600	2,181	4,557	7,557	2,191	-92,760
100	1,563	3,620	7,154	2,388	-57,590
200	0,932	2,643	6,636	2,717	-22,140
400	0,483	1,943	6,128	2,925	-2,040
700	0,214	1,538	5,908	2,855	15,300
1.000	0,076	1,334	5,802	2,653	21,450
15.000	-0,059	1,142	5,766	2,228	26,710

Table 3: Coefficients of the linear regression of Rawls et al. (1983) in Equation (10).

h (cm)	a	b	c	d	e
200	0,4180	-0,0021	0,0035	0,0232	-0,0859
330	0,3486	-0,0018	0,0039	0,0228	-0,0738
600	0,2819	-0,0014	0,0042	0,0216	-0,0612
1.000	0,2352	-0,0012	0,0043	0,0202	-0,0517
2.000	0,1837	-0,0009	0,0044	0,0181	-0,0407
4.000	0,1426	-0,0007	0,0045	0,0160	-0,0315
7.000	0,1155	-0,0005	0,0045	0,0143	-0,0253
10.000	0,1005	-0,0004	0,0045	0,0133	-0,0218
15.000	0,0854	-0,0004	0,0044	0,0122	-0,0182

Table 4: Coefficients of multiple linear regressions of Tomasella & Hodnett (1998) in Equation (12).

h, cm	a	b	c	d
0	2,24	0,298	0,159	37,937
10	0	0,530	0,255	23,839
30	0	0,552	0,262	18,495
60	0	0,576	0,300	12,333
100	0	0,543	0,321	9,806
330	0	0,426	0,404	4,046
1000	0	0,369	0,351	3,198
5000	0	0,258	0,361	1,567
15000	0	0,150	0,396	0,910

5 RESULTS AND DISCUSSION

The deepest soils were expected to be found under arable land. But, these fields could have lost their thickness by terracing process. An average total soil depth of 50 cm (by soil auger borings) could be observed under arable land. Grassland areas were widespread on steep slopes with shallow soils. Anyway, the sampled grass plot contained a mean total soil depth of 45 cm. The burned forest plots (shifting area) were located on steep slopes and had a mean soil depth of 53 cm. The forest plots were located on steeper slopes as scrubland and contained a mean soil depth of 55 cm. Finally, the deepest soils were found under scrubland with a total mean soil depth of 74 cm. Similar conditions are described by Bhattacharyya et al. (1993, 1999) with soil depths between 16 and 150 cm and always highly weathered conditions in the C horizon. In general, between soil depth and terrain attributes there could be observed a significant correlation between soil depth and the elevation classes ($R = 0.249$; $p < 0.01$).

The terraced paddy fields of arable land located on the flat valley bottom between 611 to 641 m a.s.l. in elevation (mean height: 630 m) were treated as flat leveled fields without slope. Because of their small size they could not be calculated by the DEM. Scrubland mainly covered areas of 7.2 to 15° in slope (mean slope: 11.6°) and 655-707 m a.s.l. (mean 677 m). Forest and shifting areas showed similar terrain conditions with an average slope of 14.3° (10.3-19.4°) and a mean elevation of 710 m a.s.l. (688-727 m) for forest and 15.9° (6.7-22.4°) and 691 m (658-735 m) for burned forest. Grassland covered mainly the steep slopes (18.6° in mean) with mean elevation of 658 m a.s.l. A significant correlation between the different land uses and the terrain attributes was given ($p < 0.001$).

Based on a valuation of images it was noticeable that the different types vegetation seems to be bond on the distribution of the vesicular and non-vesicular flood basalts (App. Scheme and Pic. 1, 5).

5.1 Land use and soil depth specific soil properties

5.1.1 Stone content and texture

For stone content (> 2 mm) a significant different caused by land use could be identified for the first soil depth increment D30 ($p < 0,001$). Shifting area had the highest stone content with 22.9 %. A similar amount of stones was observed for forest (13.4 %) and grassland (13.5 %). Distinct less stones could be observed under arable land (9.1 %) and scrubland (3.4 %).

In the second soil depth D60 the highest stone contents were again found on grassland (16.4 %) and shifting area (15.3 %). The lowest stone content was measured under scrubland (4.7 %). Forest and arable land showed a similar amount of gravel around 10 %.

In the last soil depth D90 the mean stone contents of the different land use types ranged between 1.7 % and 5.4 % with a total mean value of 3.6 %. For the second and third soil depth increment D60 and D90 the ANOVA null hypothesis of equal stone contents on different land uses could not be rejected ($p = 0.067$, $p = 0.520$).

There could be observed a decrease of mean stone content with increasing soil depth from 11.28 % for D30 to 3.56 % for D90 in general (Fig. 5). The stone content was measured from soil samples taken with a Pürckhauer soil auger with an inner diameter of 2 cm. By that bigger stones could not be sampled but Bhattacharyya et al. (1999) mentioned an increase of gravel (≥ 2.5 cm in size) of 20 % with depth and a total stone content of 40 % in the C-horizon. It is assumed, that especially the stone content of the subsoil was underestimated due to the sampling method and indeed a higher stone content could dominate in the subsoil. Big stones in deeper layers could be mistakenly interpreted as parent material. Hence, the decline of sample number with depth might result from a higher stone content in the subsoil preventing a deeper penetration with the soil auger. The general small stone content in the of scrubland (3.5 %) could be explained by deep and well-developed soil formations.

Regarding texture, the sand content in the studied headwater catchment ranged between 3.3 % and 33.8 % in total with a mean sand content of 15.3 %. The highest mean sand content was under arable land (20 %) and the lowest sand content was observed under scrubland (10.5 %). For the clay fraction, it can be assumed an average content of more than 50 % in general (Bhattacharyya et al. 1993; 1999; 2005). The depth wise variation of the sand content under different land use is presented in Fig. 6. Differences in grain-size distribution were more obvious on flat areas as on slopes recognizable by the high range between maximum and minimum on the plain fields of arable land.

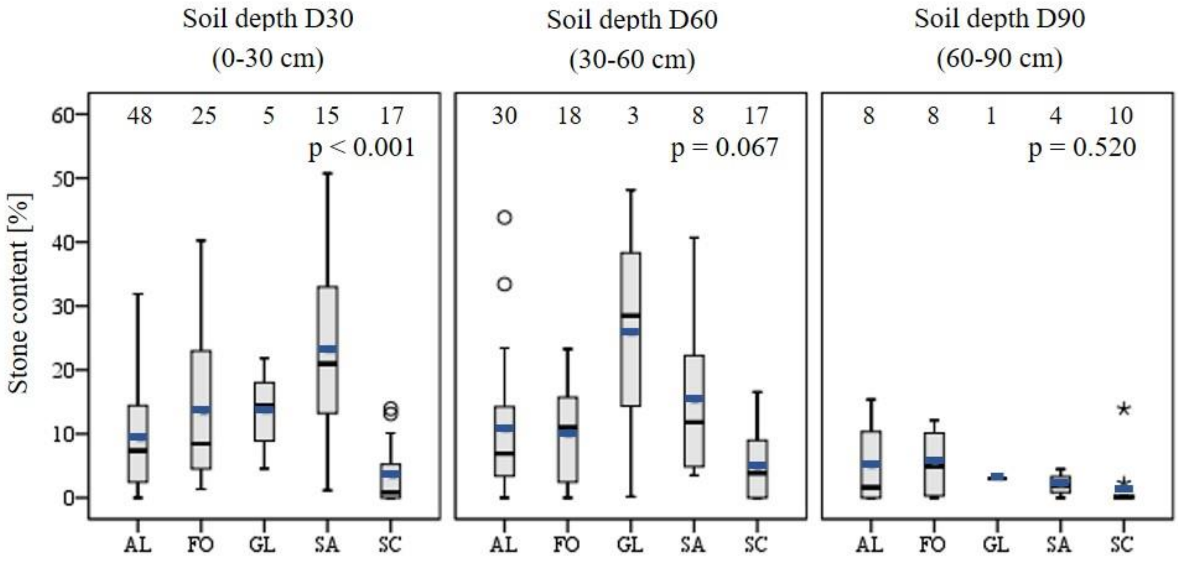


Figure 5: Box-plots of weighted stone content in the different soil depths and under different land use (AL = Arable land, FO = Forest, GL = Grassland, SA = Shifting Area, SC = Scrubland); boxes show the median and the 1. and 3. quartile, whiskers give the minimum and maximum; circles represent outliers (≤ 95th percentiles) and stars represents extreme outliers (> 95th percentiles); blue crossbars show mean values; values above boxes give number of samples; p gives significance value of the ANOVA.

In the first increment of sampling depth D30 (0-30 cm) the sand contents ranged between 3.3 % and 33.5 %, with a mean of 17.3 % (Fig. 6). Under arable land the sand contents were slightly higher with a mean of 20.4 % while scrubland showed the smallest sand contents with an average amount of 8.7 %. The ANOVA null hypothesis of equal mean sand contents in soil depth D30 under different land uses could be rejected ($p < 0.001$). Grassland had to be excluded from the ANOVA analysis because just one composite sample was available and no variance could be calculated. Nevertheless, the sand content under grassland was added to Fig. 6.

In the second soil depth D60 (30-60 cm) the mean sand content (14.7 %) declined significantly compared to D30 ($p = 0.007$) with a minimum and maximum of 6.2 % and 33.8 %. Noticeable is an average higher sand content under arable land (18.9 %) and again the ANOVA null hypothesis of no land use specific differences in the mean sand content could be rejected ($p = 0.005$).

In the last sampling depth D90 (60-90 cm) the sand content ranged between 6.8 and 32.7 % with an average value of 13.6 %. The decrease in mean sand content between D60 and D90 was not significant ($p = 0.082$). Again, arable land showed the highest mean sand content (19.9 %). The null hypothesis of the ANOVA could not be rejected ($p = 0.130$) for the last soil increment. In D90 land use could not be indicated for spatial variability in sand content.

Certainly, the distribution of the silt and clay fraction acted reverse to the sand fraction and the ANOVA gave the same statistical dependences. Significant differences caused by land use could be observed for the first and second soil depth. In both layers, the lowest silt and clay content could be observed on arable land (79.6 % in D30, 81.1 % in D60) and the shifted areas (80.5 % in D30, 85.6 % in D60), while forest and scrubland showed high contents (Fig. 6). On the burned fields, a lower amount of silt and clay could be recognized. Under shifting area, the strongest increase of mean silt and clay content with increasing soil depth from 80.5 % in topsoil (D30) to 91.2 % in subsoil (D90) could be observed (not significant). Fire seems to influence soil grain size distribution. It is assumed that fire in the upper layer forms some stable soil aggregates by oxidation based on iron compounds.

Differences in texture were observed at the sand content by sieving process. The silt and clay content were not analyzed separately which does of course limit the validity of small scale variations. The measured sand content ranged between 3.3 % and 33.8 % in total with a mean content of 15.6 %. The clay content was assumed to be 50 % and fits to the soil properties of Red Soils described by Bhattacharyya et al. (2007) with 6-10 % for sand, 37-40 % for silt and 40 to 55 % for clay. Bhattacharyya et al. (1993) observed mean values of 13 % for sand, 29.3 % for silt and 57.7 % for clay on mountain slopes of Bhimashankar 60 km north of Pune. In total, the literature values range between 3 to 25 % for sand and between 50 to 60 % for clay referred to the Red soils of the Western Ghats (Pal 2017).

Based on the theory of Bremer (1971) the high sand content on the paddy land could be explained by the erosion of clay due to suspension. Under waterlogged conditions of the rainfed cultivation management the soil aggregations can get in solution. Hence, on arable land the small particles can get removed by water erosion during the monsoon months, while they stay as stable fractions on the slopes covered by forest and scrubland. The same soil fraction was expected for forest and burned forest. But the shifting areas had a significant lower silt and clay content in the upper soil layers D30 and D60, and showed a higher silt and clay content in the subsoil D90. This could be explained by the loss of organic matter during the burning process which leads to the decomposition of soil aggregations formed by OM. In further consequences, the unfixed clay minerals were relocated into the subsoil. But the fields were burned in March during the dry season and there was no rain which could cause a dislocation of the soil particles to the subsoil. So, this hypothesis requires a repeating burning process on the same area for centuries.

Are et al. (2008) studied the effect of slash and burn cultivation on soil physical properties of Alfisols in Nigeria and observed a reduction of 27 to 29 % in the clay content of the soil after burning the forest patch. Like Hubbert et al. (2006) they explained this effect by the disruption of soil aggregations by the loss of organic matter during the burning process. Coincident, fire can promote soil aggregate stability by the irreversible cementation of clay minerals to silt- or sand-size particles due to pedogenetic oxides (Giovanni et al. 1988; Are et al. 2008). Iron Oxides can bind clay particles like Rao et al. (1988) demonstrated in Karnataka State. Kaolinitic soil properties were observed before and after the removal of iron oxides. The removal of iron oxides leads to an increase in clay percentage. Depending on fire intensity and heating temperature, either the loss of organic soil aggregations or the cementation process predominates. This fact

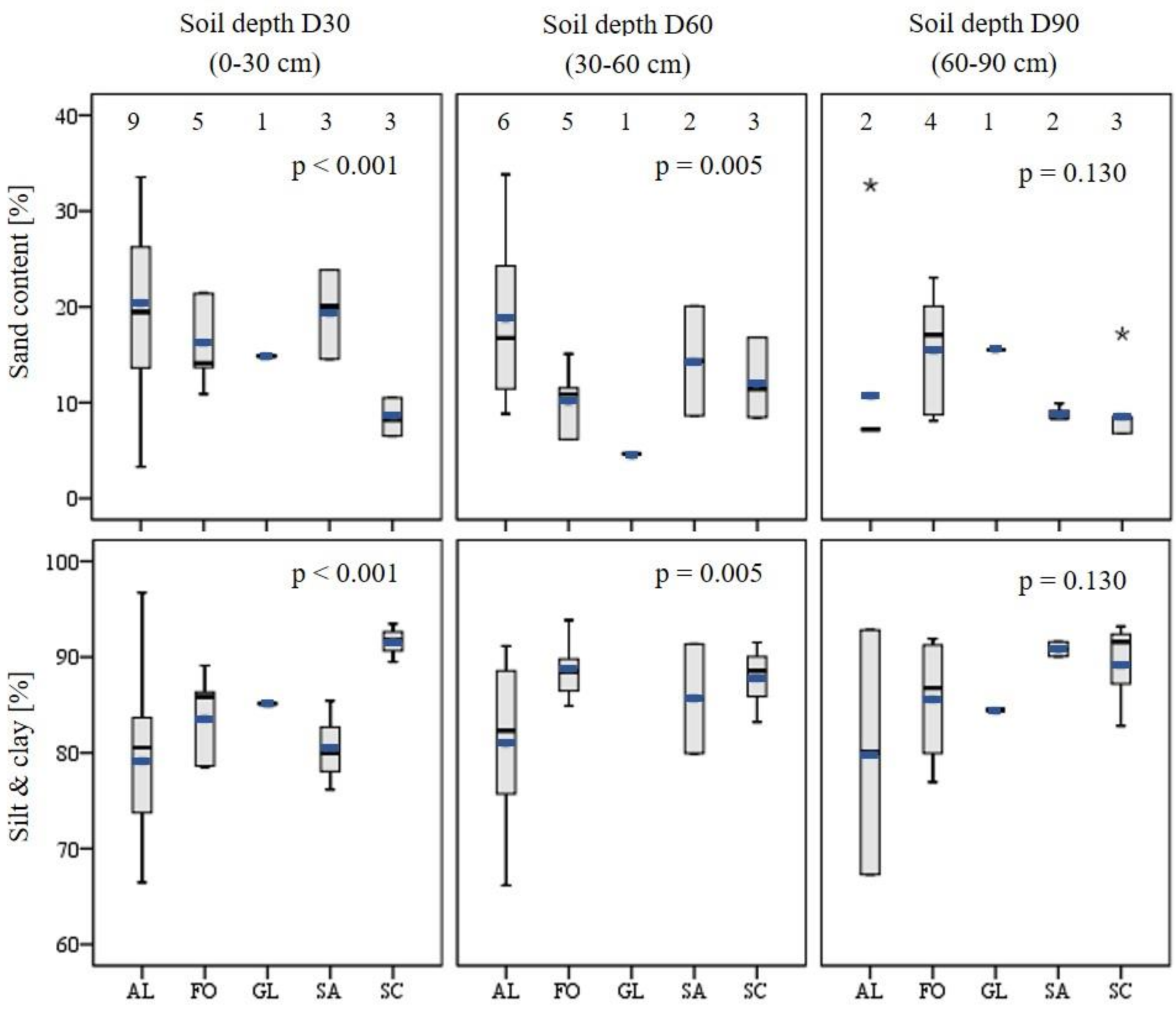


Figure 6: Box-plots of soil texture in the different soil depths and under different land use (AL = Arable land, FO = Forest, GL = Grassland, SA = Shifting Area, SC = Scrubland); boxes show the median and the 1. and 3. quartile, whiskers give the minimum and maximum; stars represent extreme outliers (> 95th percentiles); blue crossbars show mean values; values above boxes give number of composite samples; p gives significance value of the ANOVA.

could explain the differences in texture between forest and shifting area. Compared to the forest plots, soils under shifting area showed a 20 % higher sand content in the first soil depth D30 and a 27 % higher sand content at the second soil layer D60. In the topsoil and second soil depth the process of cementation due to high heating temperatures seems to dominate. During the field work, a more intense red coloring of the top soil could be observed on the shifting areas (App., Pic. 25). That speaks for rise of sand content in the upper soil layer by oxidation. On the top soil were also observed worm casts as very stable structure which are assumed to have enough stability to withstand even heavy rainfall (App., Pic. 21) (Shipitalo & Protz 1989). By mechanical tillage this effect is lost on paddy land, while the dams between the fields can hold their position (App., Pic. 20). In contrast, in the last soil depth D90 there was a decrease of 36 % of sand content between forest and shifting area. Regarding to the isolation of the soil, the heating temperature seems not to reach a high level in soil depth D90 and the decay process due to the distortion of organic components dominates. This theory could also explain the similar levels of sand content of arable land where applied biomass gets burned regularly.

Significant higher amounts of silt and clay under scrubland could be explained by plain slopes. Erosion processes are less effective than on steeper slopes. Noticeable grain size distribution due to animal action could not be identified. One ton of fine soil per hectare and year can be moved by soil fauna, causing a decomposition of soil texture (Bremer 2010). The tropical soils of India are described as highly porous with a lot of biological activity by termites and earthworms (Büdel 1986; Bourgeon 1989). Termites are widespread in subtropical climate (Bremer 1995). But it is known that termites do not colonize in cracked clayed soils due to shrink and swell processes (Bremer 2010). In the study area termite hills were found under scrub and forest vegetation in limited number. By that it is assumed that pedogenetic processes predominates the distribution of soil texture.

5.1.2 Soil organic carbon

In the first layer D30 the soil organic carbon content ranged between 0.3 % and 14.6 % as minimum and maximum with a mean concentration of 4.21 %. The highest SOC contents were found under natural forest and shifted area with mean SOC values of 5.69 % and 6.15 % (Fig. 7). Under arable land (3.47 %) the mean soil organic carbon contents were slightly higher compared with grassland and scrubland.

For D30, there could be observed a strong variability on high significant level caused by land use ($p < 0.001$). The ANOVA null hypothesis that mean land use specific SOC contents show no differences in soil depth D30 could be rejected.

In the sample increment between 30-60 cm (D60) the ANOVA null hypothesis could also be rejected ($p = 0.001$). The mean content of SOC contained 3 % with a range between 0.3 % and 9.3 %. Again, the highest SOC content was observed in the forest soils with an average rate of 4.7 %. On the shifting areas, after the clearing process by fire the mean SOC content decreased to 2.9 % and was on the same level as arable land (2.9 %).

The SOC content in the third soil depth D90 decreased again with total values from 0.8 % to 5.4 %. The mean content of organic carbon in 60-90 cm depth was 2.5 % but no significant different could be observed between the specific SOC content of the land use categories in the subsoil. The ANOVA of mean equal SOC contents under different soil management in the soil depth D90 could not be rejected ($p = 0.597$).

The organic carbon sequestration of the studied soils under different land uses and terrain positions with a mean SOC content of 3.5 % and maximum values more than 10 % seems very high. But comparison measurements with a muffle furnace showed similar values between 2.9 % and 10.2 % in total. In general, the mean SOC at soil depth D30 was significantly higher than in D60 ($p = 0.001$) and D90 ($p < 0.001$). This vertical gradient of SOC was most obvious in the forest soils were the topsoil is covered by superficial leaf residues and litter (Fig. 7). Arable land (3.1 %) contained more SOC than grassland (2.4 %) and scrubland (2.3 %). It was surprising to see some agriculture areas which showed even similar SOC contents like the forest system with SOC rates up to 10.4 %.

The mountain area of the Deccan Plateau and the coastal plains are known for high accumulation of SOC due to higher altitude coupled with an acidic soil environment and high rainfall (Venkanna et al. 2014; Sreenivas et al. 2016). For the Red Soils in humid tropical climate organic carbon contents > 1 % have been described several times. Sarika et al. (2014) observed amounts of SOC between 0.2 to 1.2 % in the top soil (30 cm) of vertic soils in eastern Maharashtra. Venkanna et al. (2014) indicated with CHNS-analyzer SOC amounts up to 1.1 % in Alfisols, Vertisols and Inceptisols.

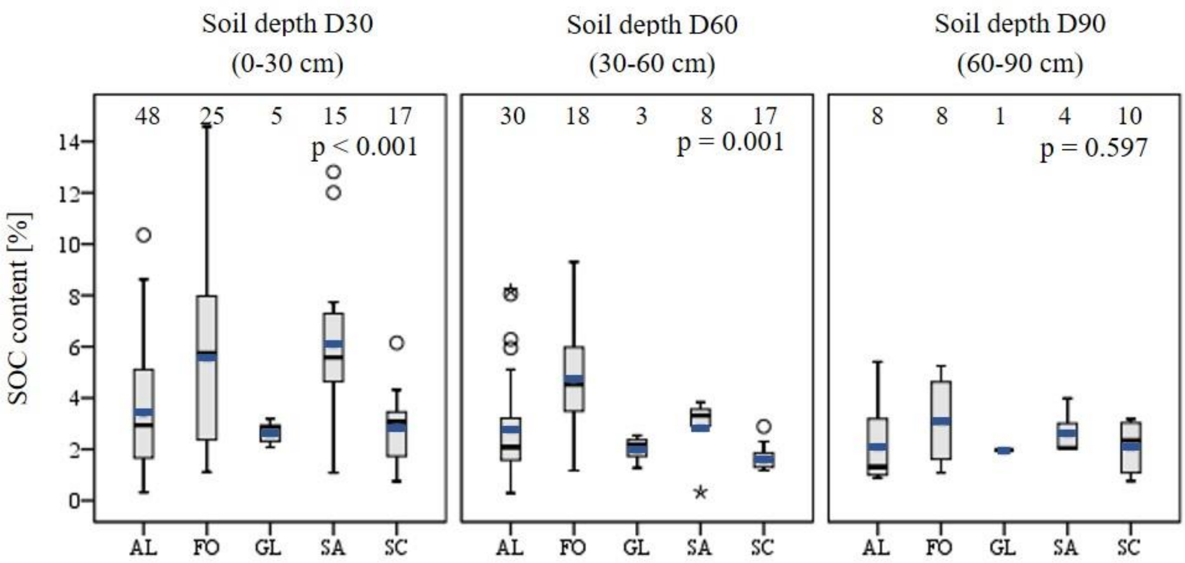


Figure 7: Box-plots of soil organic carbon (SOC) content under different land use and in the different soil depths (AL = Arable land, FO = Forest, GL = Grassland, SA = Shifting Area, SC = Scrubland); boxes show the median and the 1. and 3. quartile, whiskers give the minimum and maximum; circles represent outliers (≤ 95th percentiles) and stars represents extreme outliers (> 95th percentiles); blue crossbars show mean values; values above boxes give the number of samples; p gives significance value of the ANOVA.

Bhattacharyya et al. (1993, 1999) observed that Alfisols and Mollisols of the northern Western Ghats contain a moderate amount of zeolitic smectite which are responsible for the storage of such high amounts of SOC in the mountain soils (1.2 to 2.6 % in the top layer of 30 cm). Smectite offers a high surface charge density and by that an important property for SOC sequestration and these soils contain more SOC than the Vertisols of the plateau (Bhattacharyya et al. 2005). To some extent the sand structure is build up by zeolites particles and can store organic carbon too (Bhattacharyya et al. 1999). Bhattacharyya et al. (2000) calculated SOC contents for representative soils in various physiographic regions of India (to 30 cm depth), with values of 0.2 to 4.2 % for the zeolitic plains and areas near the west coast. Pal et al. (2014) gives a range between 1 and 5 % for some mountain soils of western India. During a scouting expedition some kilometers western of the study area a topsoil of Mollisols under evergreen forest was sampled where a SOC content of 4.4 % was resulted.

In general, the red forest soils developed on basalt in moist climate show very high SOC values of more than 2 % (Bhattacharyya et al 2007). This can be confirmed by measurements of 3.1 to 5.7 % on the forest plots. Comparing the amount of SOC under forest and arable land, there could be recognized a loss of 37 %. Anyway, with a mean SOC content of 3.1 % the arable land contains a high amount of SOC even after decades or more of cultivation. On the one hand, Chabara et al. (2003) describes similar losses of SOC up to 40 % after a land use change from forest to agriculture. On the other hand, it was observed that some agriculture lands can show similar SOC contents as forest systems due to organic fertilization by farmyard manure and added biomass (Bhattacharyya et al. 2014).

In the time of the field study on a sampled field added dry grass was burned within minutes. The plot was sampled again and there could be observed a rise in SOC content of 3 % (from 3.2 to 6.1 %) in the topsoil (30 cm). No change in SOC content could be detected in the second soil depth D60.

Singh (1994) observed high amounts of SOC (around 2 %) under rainfed conditions with absence of any chemical fertilizers in the north-eastern hill region if India. The highest SOC values were reached due to the litterfall on fields where trees were growing around. It is assumed, that SOC levels can be maintained at high level even after deforestation for more than 15 years due to the low-level management of cultivation (Bhattacharyya et al. 2006 a, 2007). Sahrawat et al. (2005) indicated a study-state status of soil organic carbon in some soils which have been under a rice system for at least of 20 years. Under rainfed paddy land, the Red Soils can accumulate a good amount of OC and wetland rice systems have even the potential to sequester atmospheric carbon as SOC (Sahrawat et al. 2005; Bhatta-charyya et al. 2014). Moreover, Bhattacharyya & Pal (2003) and Singh et al. (2011) have shown a positive SOC balance for some rice based cropping systems in India. Also, Mandal et al. (2007) mentioned a positive SOC balance under rice systems in subtropical regions of north eastern India (annual grow of 0.3 kg m^{-2}). That could explain the high SOC rates on the rainfed paddy fields of the study area.

Comparing SOC-stocks (kg m^{-2}) instead of SOC contents (%) a similar variation was reflected. Again, forest could be indicated as biggest SOC storages with mean stocks of organic carbon of 12 kg m^{-2} in D30, 9.9 kg m^{-2} in D60 and 7.8 kg m^{-2} in D90 (Fig. 8). It seems like that natural forest offers the best conditions for SOC production and accumulation. Under shifting area similar SOC stocks could be observed but with obvious less SOC in D60 (6.8 kg m^{-2}). Arable land and scrubland almost store the same amount of SOC with 9 kg m^{-2} for D30, 6.5 kg m^{-2} for D60 and D90. This was very interesting, because arable land contained a less soil thickness of more than 20 cm in average. Consequently, arable land seemed to store more SOC than scrubland in sum. Least SOC was stored under grassland with a decrease of carbon storage from 8 kg m^{-2} in the first and 3.4 kg m^{-2} in the last soil depth. In general, there could be observed statistical differences between the various land use categories for the first and second soil depth D30 ($p = 0.011$) and D60 ($p = 0.002$). Thus, for SOC values represented in stocks the ANOVA null hypotheses could be rejected for D30 and D60, but not for the last soil depth D90 ($p = 0.818$).

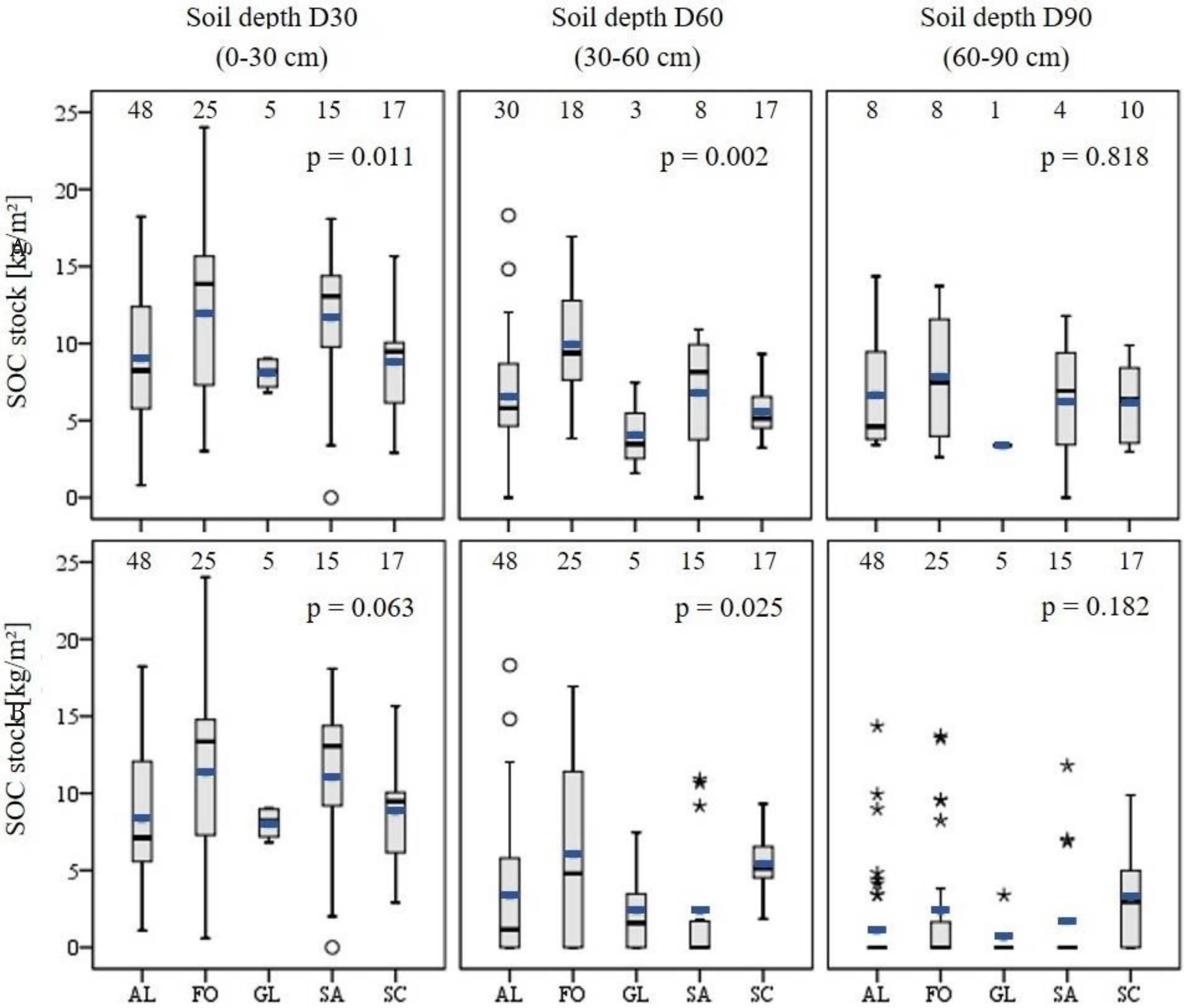


Figure 8: Box-plots of soil organic carbon (SOC) stock in the different soil depths and under different land use (AL = Arable land, FO = Forest, GL = Grassland, SA = Shifting Area, SC = Scrubland); boxes of plot A excluded blank values and show a decreasing number of samples with increasing soil depth; in B missing samples are rated as 0 kg m^{-2} with constant sample number in all soil depths; boxes show the median and the 1. and 3. quartile, whiskers give the minimum and maximum; circles represent outliers (≤ 95th percentiles) and stars represents extreme outliers (> 95th percentiles); blue crossbars show mean values; values above boxes give number of composite samples; p gives significance value of the ANOVA.

The mean SOC stock of the study area reached 8.5 kg m^{-2} in total with 10 kg m^{-2} for D30, 7.1 kg m^{-2} for D60 and 6.7 kg m^{-2} for D90. But these values can vary depending on the handling of missing soil samples due to low soil depths (Fig. 8). The mentioned SOC stocks were calculated by excluding missing samples. So, the number of samples decrease with increasing soil depth. Like that the trend of SOC stock within soil depth can be represented. But to present the SOC stock of an area, may be missing soil samples should be valued with a stock of 0 kg SOC m^{-2} instead. In this way, the number of samples will not change with depth and a less mean stock of 5.2 kg SOC m^{-2} with 9.5 kg m^{-2} for D30, 4.2 kg m^{-2} for D60 and 1.8 kg m^{-2} for D90 would be calculated. That is causing a different of 3.3 kg m^{-2} over all three depths. Most clearly this occurrence can be illustrated between arable land and scrubland. While arable land seemed to store the same SOC than scrubland over all depths by excluded missing samples, rated blank values change this observation totally as shown in Fig. 8. Especially in the subsoil D90 the SOC stock shows high differences with 1.1 kg m^{-2} for arable land and 3.2 kg m^{-2} for scrubland. That different is caused because under scrubland more than 50 % of the sampling locations reached the last sampling depth D90 (10 from 17). Under arable land the number reached not more than 17 % (8 from 48). Hence, in soil depth D90 can be stored more SOC under scrubland due to soil thickness. Finally, the handling of not reached subsoils can cause a huge range of uncertainty. The real amount of total stored SOC in the headwater catchment is assumed between the two boundary scenarios of 5.2 kg m^{-2} and 8.5 kg m^{-2}.

For comparison, in Gujarat, the neighbor province of Maharashtra, Dinakaran & Krishnayya (2008) observed SOC values between 1 and 9 kg m^{-2} under different land uses and a sampling depth of 150 cm. The amount of organic carbon of paddy land was about 3 kg m^{-2} and 1.5 kg m^{-2} at a duration of cultivation of 10 and 50 years. For the Indo-Gangetic area it is estimated an annual addition of about 0.1 kg m^{-2} of biomass by harvest left over and added manure and biomass (Mandal et al. 2007). Chabara et al. (2003) calculated mean SOC densities for 1 m soil depth in the range of 7 kg m^{-2} under tropical dry deciduous forest, 11.1 kg m^{-2} for tropical moist deciduous forest and 13.9 kg m^{-2} for tropical evergreen forest. Rodenkirchen & Richter (1994) observed a soil organic carbon stock of 2.3-7.5 kg m^{-2} on similar basaltic flood lavas in Hawaii.

5.1.3 Soil inorganic carbon

Soil inorganic carbon (SIC) was only observed on the recent burned forest areas (shifting area, SA) with the highest mean rates in the first sampled soil depth D30 (1.1 %) (Fig. 9). While the occurrence of soil inorganic carbon seems to be bound on the land use of shifting area a significant variation in soil depth could not be indicated ($p = 0.331$). Mean SIC contents of 0.7 % for D60 and 0.8 % in D90 were measured (Fig. 9). It was not expected to find any calcium carbonate in the study area due to geology and because in areas of high annual rainfalls (> 1 000 mm) $CaCO_3$ usually can be ruled out (Laufenberg 2003). While the low leveled flood basalts on the base can contain parts of sediment limestone and carbonate on the southern and northern offsets of the Deccan Plateau, the basaltic mountain range of Mulshi are described as non-calcareous (Büdel 1986; Bremer 1995; Bhattacharyya et al. 2005; Venkatesh et al 2011). As the parent material does not indicate inorganic carbon, only snails and other shell-bearing mollusks which died by the fire could be identified as a source for carbonate in the field. A conspicuous number of shells have been found on the filed plots of the shifting areas (App., Pic. 22).

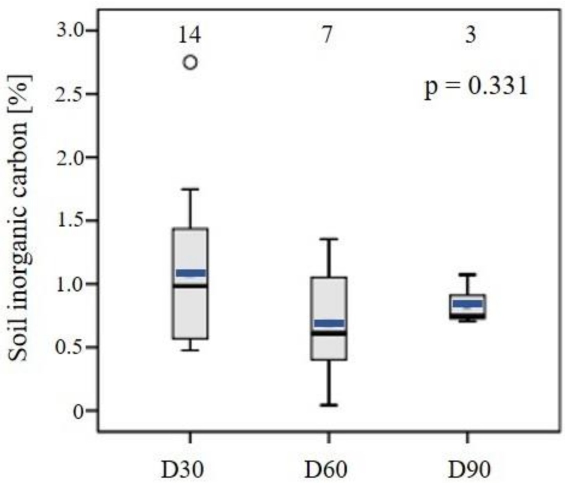


Figure 9: Box-plots of soil inorganic carbon content in the different soil depths; .boxes show the median and the 1. and 3. quartile, whiskers give the minimum and maximum; circles represent outliers (≤ 95th percentiles); blue crossbars show mean values; values above boxes give the number of samples; p shows significance of the ANOVA.

The shells were found in a regular spread, but not under comprehensive appearance. Even if the plots have been burned for several times, a comprehensive presence of soil inorganic carbon in all sampling depths would be still unexpected. In addition to that on other land uses, where snails also die naturally, no single amount of inorganic carbon could be detected by CNHS analyzer. That fact gave some suspicion to the SIC-snail theory. Bhattacharyya et al. (2007) estimate a dislocation of SIC into lower layers caused by irrigation effects. But there could no source of carbon be detected. The soils of the study area are non-calcareous and acidic. Instead a chemical reaction in the soil caused by the forest fire was assumed for the presence of SIC. The Ca-rich zeolite minerals in the basalt were observed as a source of Ca^{2+} ions causing a very high concentration up to 20 cmol kg^{-1} of Ca in the soil (Bhattacharyya et al. 2007). After Scheffer & Schachtschabel (2010) an essential part of the total soil-Ca is always available in exchangeable conditions. Under alkaline soil water pH levels or high temperatures Ca^{2+} ions can react with HCO_3 in soil water to $CaCO_3$ (Guo et al. 2016; Sreenivas et al. 2016). Alkaline pH levels can be excluded but a reaction under high temperature is assumed to be responsible for the presence of SIC under shifting areas. Arable land and grassland also gets burned but do not contain SIC. That can be explained first by the low intensity of the fire and second with missing soil water content. Soils of arable land contained 40 % and grassland 50 % less soil water than forest soils (Fig. 12). In the upper layer of arable land and grassland the water content indicates a hydrological pressure head less than -15 000 hPa (PWP) (Fig. 17) and by that may be excluded it from chemical reaction. Soils under dry semi-arid climate for example show lower SIC contents than soils in sub-humid climates (Pavar & Kale 2006; Bhattacharyya et al. 2007). Sreenivas et al. (2016) describes a varying content of SIC density in soil of the northern alluvial plains. In these plains, generally high saline-sodic salt affects soils with high amounts of SIC. It is estimated, that the formation of $CaCO_3$ in these soils gets produced by the reaction of Ca^{2+} ions with HCO_3 in alkaline soil types (Sreenivas et al. 2016). The soils of Andhra Pradesh and on the southern part of Deccan plateau (Karnataka) developed from granite-gneissic complexes. An accumulation of SIC could be observed which is also attributed to high rates of Ca^{2+} depletion and the reaction of these minerals with HCO_3 of the soil water (Sreenivas et al. 2016). The same reaction of soil inorganic carbon is described in croplands of the upper Yellow River Delta in China (Guo et al. 2016)

A significant negative linear correlation between soil water content and SIC could be observed ($p < 0.05$). This can lead to the misunderstanding, that SIC mainly appears in dry soils with low soil moisture. But the opposite is the truth. Originally the burned forest plots contained higher amounts of soil water but lost it during the fire process.

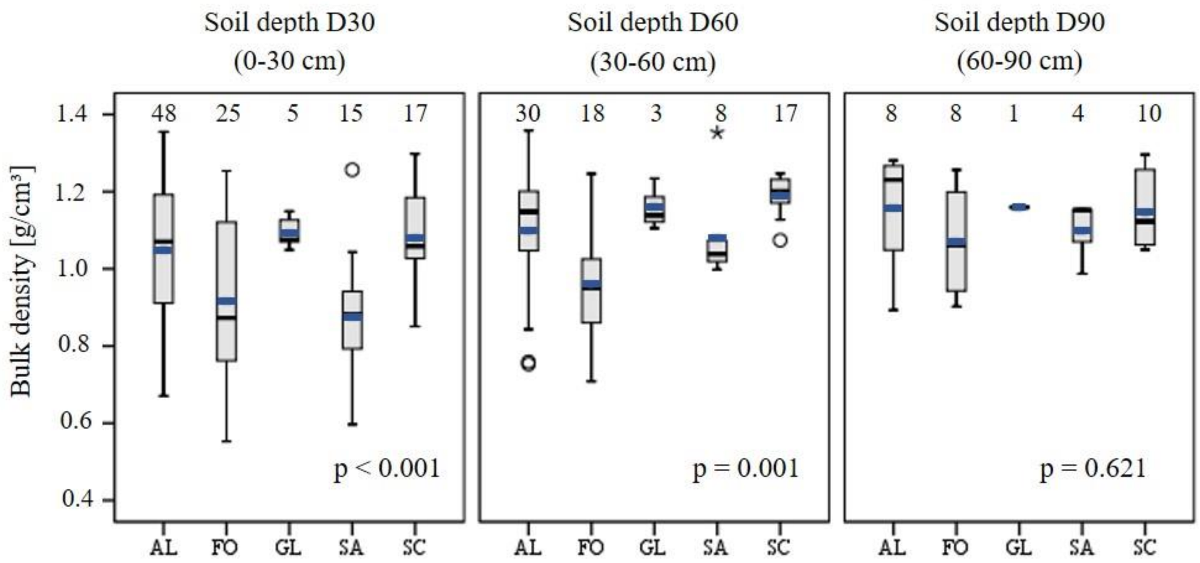


Figure 10: Box-plots soil bulk density of the different soil depths and under different land use (AL = Arable land, FO = Forest, GL = Grassland, SA = Shifting Area, SC = Scrubland); boxes show the median and the 1. and 3. quartile, whiskers give the minimum and maximum; circles represent outliers (≤ 95th percentiles) and stars represents extreme outliers (> 95th percentiles); blue crossbars show mean values; values above boxes give number of samples; p gives significance value of the ANOVA.

5.1.4 Bulk density

For bulk density (D_b), the null hypothesis from the ANOVA of equal mean D_b under all land uses could be rejected for the soil depths D30 ($p < 0.001$) and D60 ($p = 0.001$). For the subsoil, it seems like land use does not cause a significant different in D_b. For the last depth increment D90 the ANOVA null hypothesis could not be rejected ($p = 0.067$) (Fig. 10). A higher average soil bulk density was found on cultivated soils (1.08 g cm^{-3}) compared to natural forest (0.96 g cm^{-3}). The variation of D_b reached total ranges up from 0.55 to 1.26 g cm^{-3} under forest and 0.67 to 1.35 g cm^{-3} under arable land. Under the more slopy soils of the forest aggregation is assumed to cause such high varieties in D_b. Anyway, land use as well as soil depth are affecting soil bulk density, especially of the topsoil. As only used variable in Equation 2, high rates of organic carbon caused a conspicuous low D_b but fit into the range calculated by Adams (1983).

In the first soil depth D30 forest and shifted area were the only types of land use with a mean D_b less than the total average D_b of all land uses of 1 g cm^{-3}. Minimal D_b was found under forest with 0.55 g cm^{-3} and a maximal D_b on the paddy fields with 1.35 g cm^{-3} (Fig. 10). The conversion of forest to paddy land leads to a significant increase of soil bulk density ($p = 0.007$). Deforested areas (SA) used for field crops showed an increase of almost 15 % in D_b in the topsoil (30 cm).

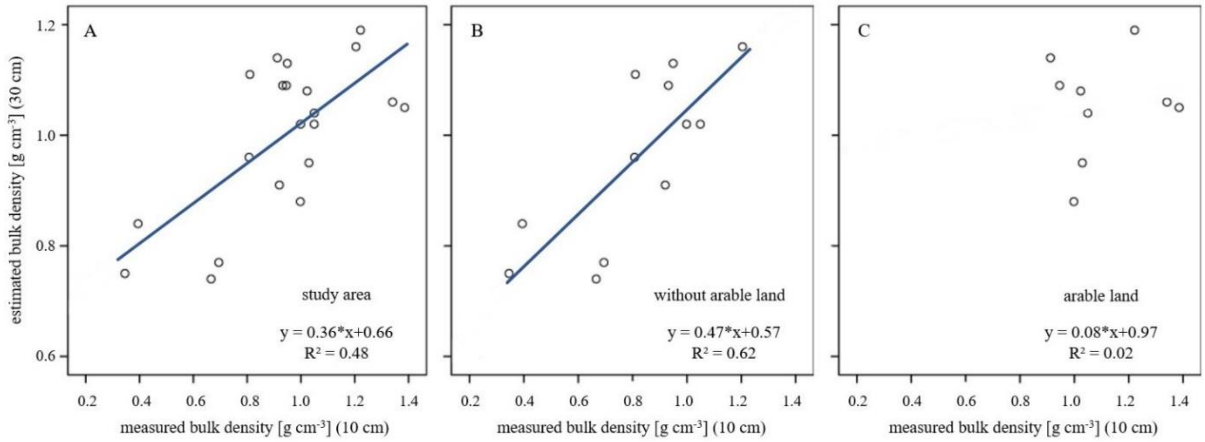


Figure 11: Correlation between measured soil bulk density (for 10 cm topsoil) and estimated mean soil bulk density (for 30 cm topsoil); A shows the correlation of all taken soil samples of all land uses; B shows the correlation of all samples but without arable land; C shows the correlation for arable land only.

For the two layers of the subsoil (D60 and D90) most obviously there can be observed an increase (no significant) of D_b between forest and shifted area. That could be explained by the disintegrated soil aggregates formed by organic matter leading to fulfillment of pores. Dislocation of clay particles into the subsoil causes a strong significant increase of D_b with increasing soil depth from D30 to D90 ($p < 0.001$). Good developed Bt-horizons could be found on all different land use types (App., Pic. 31). The highest mean D_b were found under scrubland (1.13 g cm^{-3}) and grassland (1.12 g cm^{-3}) in the deepest sampling increment D90 and can be explained by the high amounts of silt and clay (Fig. 10).

Murty et al. (2002) observed by the review of 20 works a higher bulk density with an average of 13 % in agriculture soils compared with natural forest. For the study area, the difference of mean D_b between forest (0.96 g cm^{-3}) and arable land corresponds a similar difference of 12.5 %. D_b for the rainfed rice fields varies because of the vertic properties of the soils. It is known, that D_b of Vertisols varies greatly because of their shrinking and swelling nature (Håkansson & Lipiec 2000; Bhattacharyya et al. 2007). Sarika et al. (2014) observed bulk densities between 1.2 to 1.9 g cm^{-3} in the top soils of vertic soils in the eastern of Maharashtra. Again, the conversion of forest to paddy land led to a significant increase of soil bulk density (Sarika et al. 2014). Compared to forest the shifted areas showed a higher bulk density (0.97 g cm^{-3}). Similar trends were measured by Giovanni et al. (1988), Hubbert et al. (2006), Are et al. (2008) and can be explained by the loss of OM during the burning process. This leads to the disruption of soil aggregations formed by OM.

Bulk density was calculated for all sampling depths D30, D60 and D90 and measured by a soil core for the first 10 cm. A comparison of the measured D_b by the soil core (10 cm) and the calculated D_b for topsoil (30 cm) by excluded stone content showed a linear correlation of $R^2 = 0.48$ (Fig. 11 A). Differences between the estimated and measured soil bulk density were assumed to be caused by the different soil depths. By that, a stronger correlation was expected under arable land because of a uniform topsoil up to 30 cm due to tillage. Surprisingly, the smallest correlation of measured and estimated soil bulk density was observed instead (Fig. 11 C). When arable land was excluded from the analyses the correlation reached a determination of $R^2 = 0.62$ (Fig. 11 B). It seems like the unnatural compression of the agriculture fields cannot be calculated by Equation 2. It has to be assumed that the estimated soil bulk density for arable land was slightly underestimated for the topsoil (30 cm).

Under arable land and forest a mean bulk density of 1.08 g cm^{-3} and 0.96 g cm^{-3} could be calculated (0-30 cm) while bulk density measured by core cutter ranged from 1 to 1.5 g cm^{-3} (arable land) and 0.92 to 1.09 g cm^{-3} (forest) for the topsoil (0-10 cm). Islam & Weil (2000) observed in Bangladesh similar bulk density with soil cores under cultivated soils with 1.4 g cm^{-3} and 1.2 g cm^{-3} under natural forest (0-15 cm).

5.1.5 Soil water content

The spatial variability of soil water behaves like soil bulk density in all layers. For the first and second sampled depth increments D30 and D60 the ANOVA null hypothesis of no land use specific differences in mean values of WC could be rejected with a significance level of $p < 0.001$. For the subsoil from 60 until

90 cm (D90) the ANOVA null hypothesis could not be rejected ($p = 0.570$). The average volumetric amount of soil water increases with increasing soil depth. In the lowest layer (D90) is almost stored the double amount of water (31 %) compared with the first layer D30 (16.6 %) (Fig. 12). So, there is an impact on small scaled variation of soil water availability caused by different land uses and soil depths.

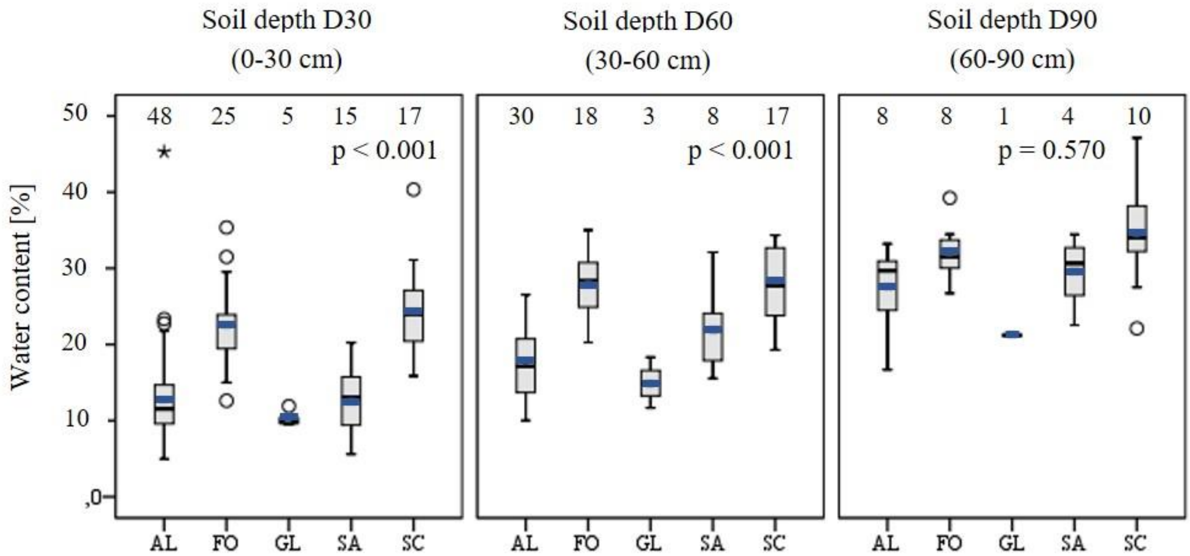


Figure 12: Box-plots of soil water content in the different soil depths and under different land use (AL = Arable land, FO = Forest, GL = Grassland, SA = Shifting Area, SC = Scrubland); boxes show the median and the 1. and 3. quartile, whiskers give the minimum and maximum; circles represent outliers (≤ 95th percentiles) and stars represents extreme outliers (> 95th percentiles); blue crossbars show mean values; values above boxes give number of samples; p gives significance value of the ANOVA.

In the topsoil increment D30 (0-30 cm) the mean soil water contents ranged between 10.2 % (grassland) and 24.1 % (scrubland) in total with values of 12.8 % and 12.6 % for arable land and shifting are as well as 22.6 % under forest. These differences can be explained by cover of vegetation (Venkatesh et al 2011) and it is assumed that higher amounts of organic matter help to contain more moisture in the soil (Wahl et al. 2003). Arable land plots were tilled and fallow and grassland totally dried out. The shifted areas lost in average more than 40 % of their topsoil water content after the forest fire (Fig. 12). The outlier under arable land cannot be explained but seems not to have natural causes. It almost reaches the maximum value of soil water and could not be recognized in lower soil depths.

For the second soil depth D60 the mean water content ranged between 14.9 % and 28.2 % with a mean value of 22.9 %. And in the third soil depth increment D90 the water contents had again a higher range from 21.2 % to 34.4 % with a higher total mean value of 31 %. The soil moisture content on the paddy lands increases with depth more steeply like on forest or grassland soils because of surface ploughing and total missing plant cover during the dry season (Fig. 12). Forest fire has a great effect on the topsoil while the subsoil still contains similar water contents as forest soils (29.6 %)

A significant relation ($p < 0.01$) between silt and clay content and soil moisture could be indicated. Instead no correlation could be observed between soil moisture and soil organic carbon. Adhikary et al (2008) also detect no significant correlation between the SOM of Indian soils and water content values. It is assumed that the water content in the studied soils can reach higher levels due to the water storage by smectites (Bhattacharyya et al. 2006 b). In general, forest and scrubland soils contained the most soil moisture in all soil depths at the end of the dry season. That could be explained by the higher amount of silt and clay. As observed by Venkatesh et al. (2011) for soils of tropical southern India, forest land use had to require higher amounts of rainfall to reach the maximum soil moisture level. The top layer (50 cm) of forest never reached the field capacity during the four-year study period because of fast water movement in the upper layer.

5.1.6 Infiltration capacity

The calculated pore space S_p of each sample, multiplied by the thickness of the sampled depth, was assumed to represent the maximum of possible infiltration capacity. Spatial variability of infiltration rate was supposed mainly to be controlled by soil depth. The ANOVA null hypothesis of no land use specific mean infiltration capacity could be rejected for the first soil depth increment D30 ($p = 0.015$) (Fig. 14). For the soil depths D60 and D90 the ANOVA null hypothesis could not be rejected ($p = 0.358$; $p = 0.314$). A significant different in depth could just be calculated between the first D30 and second D60 layer ($p < 0.001$). Between the depth D60 and D90 no significance variability of the infiltration capacity could be observed ($p = 0.914$).

In the first soil depth (D30), arable land showed the smallest mean infiltration capacity of 173.6 mm (Fig. 14). Compared with forest (185.4 mm) and scrubland (177.6 mm) infiltrability seems to decrease as land use intensity increases like summarized by Zimmermann et al. (2006).

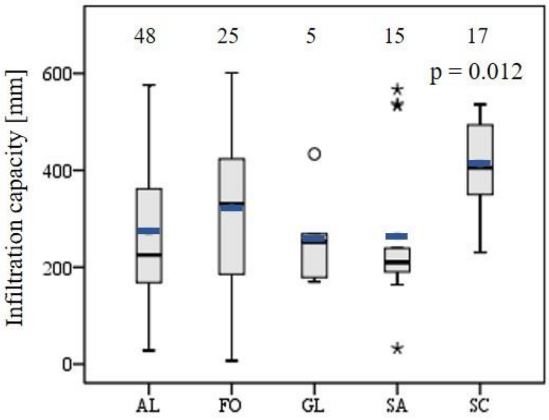


Figure 13: Box-plots of infiltration capacity under different land use (AL = Arable land, FO = Forest, GL = Grassland, SA = Shifting Area, SC = Scrubland); boxes show the median and the 1. and 3. quartile, whiskers give the minimum and maximum; circles represent outliers (≤ 95th percentiles) and stars represents extreme outliers (> 95th percentiles); blue crossbars show mean values; values above boxes give the number of samples; p shows significance of the ANOVA.

In the second soil depth increment between 30-60 cm the infiltration capacity of grassland decreases with a mean of more than 36 % (to 112.9 mm). This strong decrease is caused by dominated shallow soils under grassland. The mean decrease of possible infiltration under arable land just holds 13 % (Fig. 14). It is assumed pore volume decreases in deeper soil layers due to fine soil and organic particles which logs the macro pores (Are et al. 2008). Expect of scrubland under D60 there are high variations of infiltration capacities within the different land uses. The low outliers were caused by less reached sampling depth. For the third soil depth D90 there is no significant change compared to D60.

To calculate and compare the infiltration capacity of one total soil profile (f_d, Eq. 5), the infiltration capacity of all sampled layers (D30, D60, D90) had to be summarized. Thus, the highest mean infiltration capacity was observed under scrubland with a total average water absorption of 410.8 mm followed by forest, arable land, shifting area and grassland with respectively 324.4 mm, 268.3 mm, 263.1 mm and 262.8 mm (Fig. 13). Under grassland the value can even expected to be less, because special deep soil formations were sampled

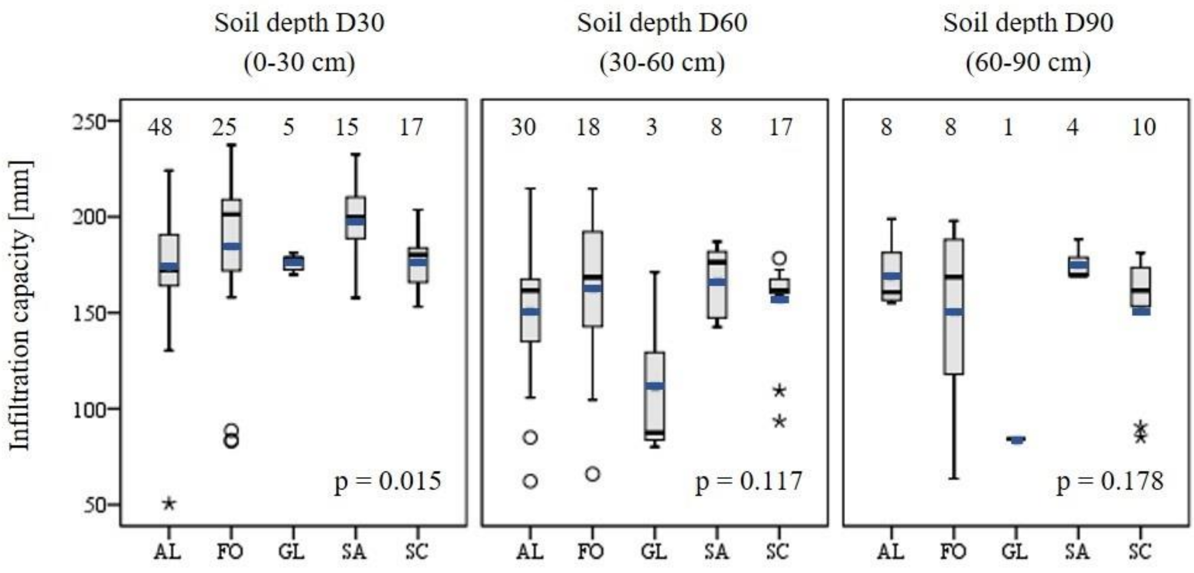


Figure 14: Box-plots of infiltration capacity in the different soil depths and under different land use (AL = Arable land, FO = Forest, GL = Grassland, SA = Shifting Area, SC = Scrubland); boxes show the median and the 1. and 3. quartile, whiskers give the minimum and maximum; circles represent outliers (≤ 95th percentiles) and stars represents extreme outliers (> 95th percentiles); blue crossbars show mean values; values above boxes give number of composite samples; p gives significance value of the ANOVA.

among the usually shallow soils under grassland. Significant differences were declared between the single land use categories ($p = 0.012$).

By that, the soils of the study area can theoretically absorb an average amount of 302 mm after the first monsoon rainfalls. Regarding the studied soils contained water at the time of sampling, this amount of soil water had to be deducted from the total infiltration capacity to get an impression of the real amount of water the soils can absorb after the dry season. This calculation made a different, but did not change the ranking of scrubland (305.4 mm), forest (260.8 mm), arable land and shifting area (246.3 mm) plus grassland (228.5 mm). That means the soils of the headwater catchment can absorb a mean amount of 258 mm of the first rain. The sampling area of the headwater catchment can absorb more than 265 million liters of water in total and contained more than 48 million liters of water at the time of sampling. That implies around 15 % of the possible infiltration capacity is still stored as soil water in the catchment even at the end of the dry season.

5.1.7 Saturated soil hydraulic conductivity

Red soils are described as soils with the most steadily saturated hydraulic conductivity referred to black and laterite soils (Bonell et al. 2010). Nevertheless, soil hydraulic conductivity represents a no steady soil property and variates with time, soil moisture and heterogeneity in macropore flow. For example, on arable land ploughing can change the infiltration conditions. Due to high infiltration rates, the main flow is assumed to happen in the soil and surface runoff just appears under saturated conditions like Bremer (2010) describes for the tropics in general.

In the field, a steady-state flow was achieved within 30 to 60 min. Thereby maximal flowrates up to 54 cm h^{-1} could be observed under forest and 48 cm h^{-1} on shifting area. Mean hydraulic conductivity K(h) under both land use categories reached 13.1 cm h^{-1} after a mean time of 31 to 39 min (Tab. 5). Rohdenburg (1983) named infiltration rates up to 40 cm h^{-1} under natural forest in the tropics. Are et al. (2008) also mentioned extremely high flow rates for double-ring infiltrometer measurements on Alfisols in Nigeria. They observed effects of forest fire on the hydraulic conductivity and could measure 58 to 67 cm h^{-1} under forest and reduced rates of 24 to 30 cm h^{-1} on burned forest patches within the first hour. Like Hubbert et al. (2006) they observed a decrease in pore volume after burning up to 10 % caused by destroyed aggregations and ash deposit which clogged pores and consequently reduced saturated hydraulic conductivity (App., Pic. 25). Bonell et al. (2010) also found lower surface permeability under deforested areas by studies in the Western Ghats.

Table 5: Average hydraulic conductivity K(h) of different land use categories, measured in the field after mean time on mean soil depth; for equal size comparison, saturated conductivity $K(h)_S$ was calculated for 60 min by computed equations of a curve-fitting regression (Fig. 15).

Landuse	**K(h)** (cm h^{-1})	**time** (min)	**soil depth** (cm)	**K(h)s** (cm h^{-1})
Arable land	5.6	80	50	4.5
Forest	13.1	31	55	4.4
Grassland	3.6	43	45	2.8
Shifting area	13.1	39	53	7
Scrubland	54.8	57	74	3.5
Study area	8,5	60	55	4,3

These observations could not be confirmed by this study. Instead fire affected infiltrability and lead to higher infiltration rates than under forest vegetation. That should be caused by macropores due to destruction of roots and by that the formation of root channels, like mentioned from Zimmermann et al. (2006).

On arable land, there could be observed rates of 5.6 cm h^{-1}, on scrubland 4.8 cm h^{-1} and grassland 3.6 cm h^{-1} after one hour (Tab. 5). It can be assumed that the soil water conductivity rates can reach very different levels during the raining season with different soil moisture conditions. Nevertheless, soil hydraulic conductivity was assumed to be affected by texture and bulk density (Wahl et al. 2003). Indeed, the lowest soil bulk densities were observed under forest (0.96 g m^{-3}) and shifting area (0.97 g m^{-3}) with a significant difference ($p < 0.001$) to the D_b of arable land (1.08 g m^{-3}), scrubland (1.14 g m^{-3}) and grassland (1.12 g m^{-3}). This could explain the high rates of conductivity in during the first 30 min. Saturated conductivity stayed high for shifting area with the highest amount of clay. It seems aggregation causes porosity and by that higher rates of conductivity.

While the infiltration capacity is mainly controlled by soil depth the saturated conductivity shows a relationship between the texture of the soil profile (Adhikary et al. 2008). Simply put, the greater the sand content, the greater is the saturated hydraulic conductivity. Sandy soils or soils with stable structure like pseudo sand formation generally have higher saturated conductivities. But also, macropores and biopores, such root channels and earthworm burrows are main factors influencing the hydraulic conductivity of saturated soils (Weil & Brady 2017). In the field, some huge macropores could be observed caused by termites, earthworms or in form of snake holes (App., Pic. 28, 29).

All results of field measurements were plotted by a curve-fitting exponent regression (Fig. 15). For a uniform comparison of the saturated hydraulic conductivity values after 60 min were taken from detected graph equations given in Fig. 15. Thus, the soils of the headwater catchment at Mulshi-Lake had an average saturated hydraulic conductivity $K(h)_S$ of 4.3 cm h^{-1} and can be classified as very high after Ad-hoc-AG Boden (2005). The ANOVA null hypothesis of no land use specific differences in mean $K(h)_S$ could be rejected ($p = 0.001$). Under burned forest (shifting area) the highest $K(h)_S$ were observed (SA = 7.0 cm h^{-1}). Thereby, the soils under forest vegetation contained very high conductivity (FO = 4.4 cm h^{-1}) like the other land uses with 4.5 cm h^{-1} for arable land, 3.5 cm h^{-1} for scrubland (high) and 3.6 cm h^{-1} for grassland (high). Bhattacharyya et al. (2007) mentions a similar range between 3.4 to 7.6 cm h^{-1} for $K(h)_S$ also measured by double ring infiltrometer measurements within the first hour on tropic Alfisols and Vertisols (Fig. 15 B). In addition to that they reached values of < 0.1 to 10.1 cm h^{-1} for Black soils of semi-arid Deccan Plateau by laboratory analyses. K(h)s was assumed after three similar measurements. Pal (2017) measured different saturated hydraulic conductivity by laboratory analyses on Vertisols developed on the zeolitic Deccan basalt and under rice cultivation a range between 0.3 to 6.2 cm h^{-1} with 2.4 cm h^{-1} as weighted mean in 0-100 cm depth (Fig. 15 B). All literature values describing similar soil types approve the observed range between 2.8 to 7 cm h^{-1}. For the study area, the FAO gives K(h)s rates between 0.011 to 0.017 cm h^{-1} and can be stated as underestimated.

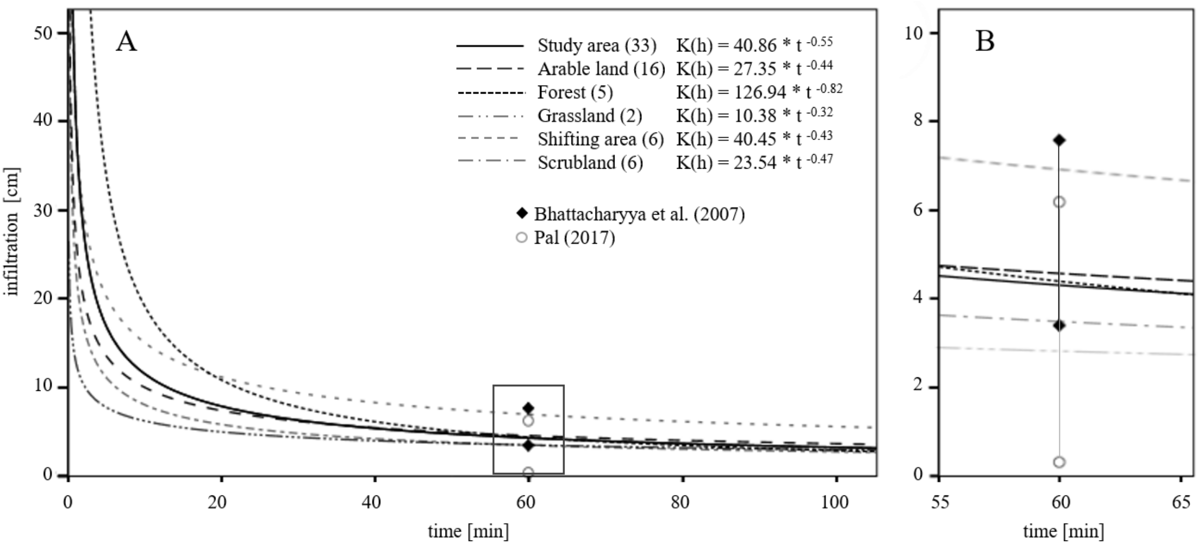


Figure 15: Adaption lines (using curve-fitting regression) of hydraulic conductivity K(h) of different land uses (A); measured by a double-ring infiltrometer; values in parentheses give the number of measurements; equations of the graphs are given; dots show literature reference values in terms of 60 min (B).

5.2 Soil water retention characteristics

Four different Pedotransfer Functions (PTFs) were tested to valid the most applicable model for the studied soils. The plotted results of the PTFs are presented in Fig. 16 providing an impression of hydraulic properties calculated by basic soil parameters of the study area. The models show conspicuous differences in volumetric soil water content at same water potentials. Expect of Tomasella & Hodnett (1998) all models are based on the US Soil Survey Database (USA, nationwide and central) for which the PTFs of Rawls et al.

(1982 resp. 1983) and Saxton et al. (1986) were indicated as most suitable (Kern 1995). But for the tropic soils of the Western Ghats the model of Rawls et al. (1983) showed higher water contents compared to Saxton et al. (1986). The sampled soils of the Indian Deccan Plateau are different in physical and hydraulic properties and are subjected to different pedogenetic processes compared to the USDA soil database.

5.2.1 Model validation

Soil water retention values for Vertisols of Peninsular India (with 60 % clay, D_b around 1.5 g cm^{-3} and a total soil depth of 150 cm) the volumetric soil water contents range between 40-48 % for field capacity FC (-330 hPa) and 20-26 % for permanent wilking point PWP (-15 000 hPa) (Pal 2017). The PTFs of Gupta and Rawls reached 37 % for PWP and did not at all fit into the expected range of 20 to 26 %. The equation of Rawls et al. (1983) is known to overestimate water contents for tropical soils (Tomasella & Hodnett 1998) and seems also to react sensible to high amounts of organic carbon. While the other models can deal with outliers of organic carbon (> 10 %), the PTFs of Rawls et al. (1983) produced outliers with unrealistic water contents of more than 100 % (Fig. 16). Because of that, the PTFs of Rawls et al. (1983) were excluded for

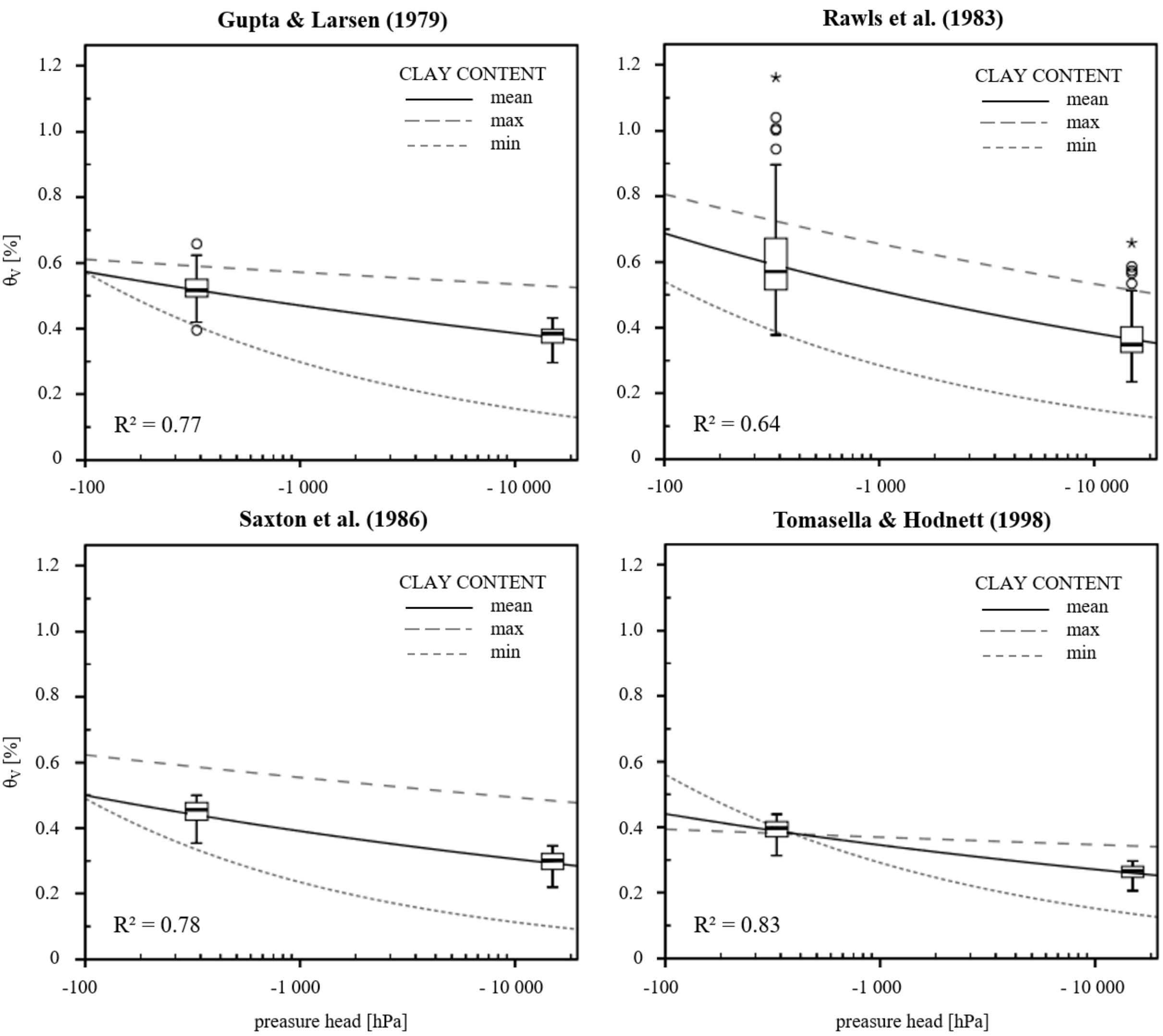


Figure 16: Soil water retention curves calculated after the pedotransfer functions of Gupta & Larson (1979), Rawls et al. (1983), Saxton et al. (1986) and Tomasella & Hodnett (1998); black line shows the retention curve for the study area plotted by the mean values; two boundary curves show mean soil water retention for maximal (100 % - sand %) and minimal (0 %) amount of clay; R^2 gives the coefficient of determination for curve-fitting regression; box-plots show volumetric soil water content θ_v at field capacity (-330 hPa) and permanent wilking point (-15 000 hPa); boxes show the median and the 1. and 3. quartile, whiskers give the minimum and maximum; circles represent outliers (≤ 95th percentiles) and stars represents extreme outliers (> 95th percentiles).

further valuations. The PTFs of Gupta et al. (1979) did not produce outliers, but showed similar overestimated mean water contents and was equally not considered for the ongoing work.

The soil water contents of 44 % at FC and 29 % for PWP, produced by the PTFs from Saxton et al. (1986) fitted into the expected range (26-48 %). But the retention equation was usually not developed on soils of high amount of clay. Partial, the texture of the studied soils lies outside of the valid range of the model. Instead, the proposed relationship of the PTFs of Tomasella & Hodnett (1998) were based on Brazilian soils with high amounts of clay (without lateritic soils). The model also fits into the expected range (20-48 %) with soil water contents of 39 % at FC and 26 % at PWP. Furthermore, the PTFs contained the steadiest ranges of produced outputs. By that the highest R-squared for curve-fitting regression ($R^2 = 0.83$) can be explained.

Interesting was the behavior of the PTFs of Tomasella & Hodnett (1998) due to the two boundary scenarios of maximal (100 % - sand %) and minimal (0 %) amount of clay (Fig. 16). While all other models stolid raised the soil water content with an increasing amount of clay (and vice versa), the tropical model presented more natural behavior. Due to water-stable soil aggregates soils of the tropics with high clay contents show high infiltration capacities like sandy textured soils (Bremer 1995). Consequently, larger amounts of water drain from clayed soils under low tensions (-100 and -1 000 hPa) compared to soils of temperate clay soils (Tomasella & Hodnett 1998). Tropic clayed soils can contain retention characteristics of sand at high pressure heads but hold water like typical clays at low water head. Thus, in this case soils of less clay can hold more water compared to clay enriched pedons.

5.2.2 Field capacity and permanent wilking point

After the PTFs of Tomasella & Hodnett (1998) the θ_V at FC reached mean contents of 37.5 % for arable land, 39.5 % for forest, 40.6 % for grassland, 38.4 % for shifting area and 41.2 % for scrubland (Tab. 6). For the PWP the mean water contents were 25 % for arable land, 26.5 % for forest, 27.3 % for grassland, 26.3 % for shifting area and 27.7 % for scrubland (Fig. 17). Between the different soil layers D30 to D90 the water content had a maximum change of 16 % at FC and a maximum range of 4.5 % at PWP (Fig. 17). In Fig. 17 FC and PWP were plotted into the measured soil water content (given as volumetric soil water content) at the time of the field study. In July, at the end of the dry season the water content of the topsoil (30 cm) of all land use categories was below the PWP. In the second soil depth just forest and scrubland contained soil moisture above PWP. Arable land and grassland contained least of all soil moisture for the first and second soil layer. In the last soil depth, arable land also contained plant available water across the PWP. Shifting area reached similar low moisture contents as arable land at the first soil depth D30 but contained more

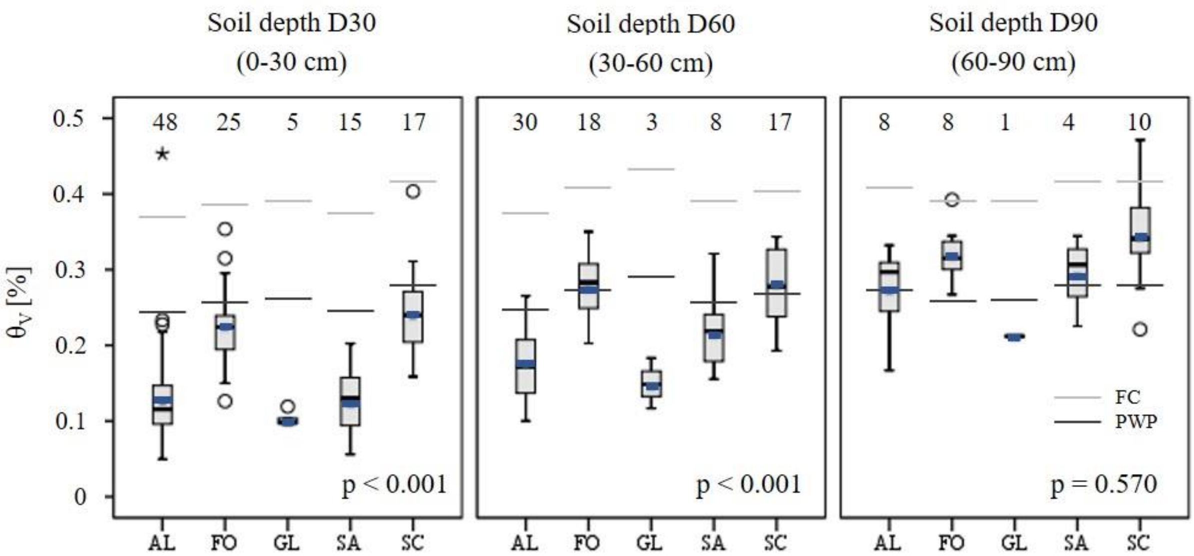
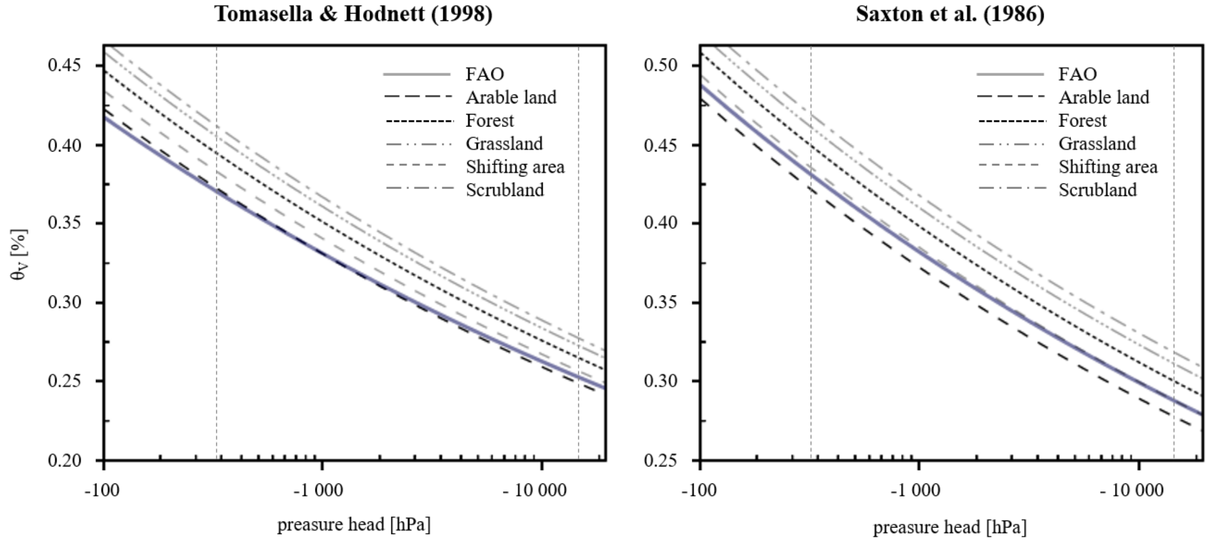


Figure 17: Box-plots of volumetric soil water content θ_v in the different soil depths and under different land use (AL = Arable land, FO = Forest, GL = Grassland, SA = Shifting Area, SC = Scrubland); boxes show the median and the 1. and 3. quartile, whiskers give the minimum and maximum; circles represent outliers (≤ 95th percentiles) and stars represents extreme outliers (> 95th percentiles); blue crossbars show mean values; lines show θ_v at field capacity (FC, grey) and permanent wilking point (PWP, black); values above boxes give number of samples; p gives significance value of the ANOVA.

soil water of forest in the last soil depth D90. This distribution was seen in the field. While grassland areas and the fields of arable land were completely dried out, vegetation on forest plots and scrubland appeared still green due to deep-rooted vegetation (App., Pic. 5, 18).

The PTFs of Tomasella & Hodnett (1998) do not consider bulk density but showed high significant correlation between measured and estimated water content at selected water potentials by the soil data of Brazil. For the headwater catchment, the PTFs of Saxton et al. (1986) showed similar retention characteristics but takes D_b into account. On an average, the PTFs of Saxton et al. (1986) showed 5 % higher water contents at FC and 3 % higher water contents for PWP, but did not change the ranking between the different land use categories. The PTFs ranged on an average θ_V between 44.2 % (FC) and 29.5 % for the study area. For tropical soils texture seems to be the dominant factor. For the volumetric soil water content and soil texture, there could be observed a significant positive correlation with silt and clay content ($p < 0.001$). Saxton & Rawls (2006) mentions texture and organic matter as primary variables. OM generally improves the water holding capacity and conductivity of soils due to the proportions of textural components (Rawls et al. 2003; Saxton & Rawls 2006). Rawls et al. (2003) observed a higher influence of OC on soil water retention at -330 hPa than at -15 000 hPa. After Pirastru et al. (2013) water retention is mainly affected by slope and soil texture. In this study, slope as well as elevation could be identified as important terrain attributes with



a significant influence in the second soil layer (see paragraph 5.4). It seems like the dry-out effect prevails in the topsoil while a consistent soil moisture in the subsoil at D90 makes an indication of terrain impacts impossible.

Figure 18: Soil water retention curves of different land use categories calculated after the pedotransfer functions of Tomasella & Hodnett (1998) and Saxton et al. (1986); blue line shows soil water retention curve for adapted values from FAO et al. (2012) with 20 % for sand, 30 % for silt, 50 % for clay, 1.3 g cm $^{-3}$ and 1 % for organic carbon; broken lines mark the volumetric soil water content θ_v at field capacity (-330 hPa) and permanent wilking point (-15 000 hPa);

5.2.3 Available water capacity

Table 6: Volumetric soil water contents θ_v at field capacity (FC) and permanent wilking point (PWP) of the different soil depths (D30 = 0-30 cm, D60 = 30-60 cm, D90 = 60-90 cm) and under different land use categories; values are estimated by pedotransfer functions of Tomasella & Hodnett (1998), AWC gives the available water capacity.

		Arable land			Forest			Grassland			Scrubland			Shifting area			Study area		
		D30	D60	D90	D30	D60	D90	D30	D60	D90	D30	D60	D90	D30	D60	D90	D30	D60	D90
θv at FC	(%)	0.37	0.38	0.41	0.39	0.41	0.39	0.39	0.43	0.39	0.42	0.40	0.42	0.37	0.39	0.42	0.38	0.39	0.41
θv at PWP	(%)	0.25	0.25	0.27	0.26	0.28	0.26	0.26	0.29	0.26	0.28	0.27	0.28	0.25	0.26	0.28	0.25	0.26	0.27
AWC	(%)	0.12	0.13	0.14	0.13	0.13	0.13	0.13	0.14	0.13	0.14	0.13	0.14	0.12	0.13	0.14	0.13	0.13	0.14

Based on the PTFs developed by Tomasella & Hodnett (1998) the range of available water content (AWC) stored in the soil was estimated separately for the different land use categories and soil depths. There could be observed a significant difference between land use categories as well as in soil depth if only on the decimal place ($p < 0.001$). In general, the volumetric water content at FC ranged between 31 % and 44 %, for PWP between 21 % and 30 % (Tab. 6). The AWC of all soil samples ranged between 11 and 14 % with a mean AWC of 13 % (Tab. 6). Therefore, the soil depth is essential for differences of the available water holding capacity (AWHC) of a total sampled profile. For estimations of the total AWHC of a soil, the single AWCs of all soil depths had to be summed up. AWHC reached different values of 58.9 mm for arable land, 71.3 mm under forest, 59.6 mm for grassland, 59.5 mm for shifting area and 100 mm for Scrubland (Tab. 7). It was interesting to see, that forest showed a high AWHC but got on the same level as arable land after fire process.

Table 7: Calculated available water holding capacity (AWHC) for different land uses and FAO values for measured and unified soil depths.

Landuse	AWHC (mm)	
	real soil depth	**90 cm**
Arable land	58.9	109.0
Forest	71.3	103.2
Grassland	59.6	86.3
Shifting area	59.5	116.5
Scrubland	100.5	114.1
Study area	68.3	105.8
FAO	-	108.0

Referred to the study area the soil map of the world (FAO et al. 2012) gives soil water contents of 37 % for FC and 25 % for PWP after the PTFs of Tomasella & Hodnett (1998) and 43 % (FC) and 26 % after the PTFs of Saxton et al. (1986). FAO soil properties were taken from FAO et al. (2012) with 50 % clay, 30 % silt and 20 % sand (see Tab. 8). Bulk density was 1.3 g cm^{-3} and for organic carbon content 1 %. In both models, the FAO soil water retention was most close to the retention characteristics of arable land and shifted area. That means in large scale models adapted FAO values mainly represent degraded land use forms. Depending on the soil depth FAO AWHC values range between 50 to 150 mm. To compare FAO and estimated AWHCs all values were calculated for an equal soil depth of 90 cm. In that case the AWHC of the studied soils reached values between 86.3 mm to 116.5 mm with a mean capacity of 105.8 mm (Tab. 7). The FAO reaches a similar content of 108 mm for the same soil depth. Concerning the individual soil depths of the land use categories the AWHC changed to mean content of 68.3 mm, causing a relevant difference of 37 % compared to the FAO (Tab. 7). Grassland is assumed to be overestimated due to chosen sampling location.

Table 8: Soil properties of the two stated dominant soils of the study area adapted from FAO et al. (2012)

Mapping Unit	Soil Group & Soil Name	Layer	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Bulk Density (g cm^{-3})	OC (%)	AWHC (mm)
6669	PH-Phaeozems	Topsoil	0-30	20	30	50	1.23	1.43	150
	Vertic Cambisols	Subsoil	30-100	20	29	51	1.38	0.6	
3711	NT-Nitisols	Topsoil	0-30	21	28	51	1.3	1.4	150
	Chromic Cambisols	Subsoil	30-100	18	28	54	1.46	0.45	

5.3 Specific explanatory terrain attributes

Under all land uses elevation and slope had the biggest explanatory power on stone content (SC), especially for the subsoil. Under arable land most important was elevation in soil depth D60 with a low leveled significant correlation. Slope could not be tested for AL because of the leveled terraced fields. In the forest soils elevation was the dominating factor in soil depth D60 (Tab. 9). Under Grassland no significant correlation could be observed. Under shifting area and scrubland highly significant relations with the terrain attributes only occurred in the soils deeper soil depths D60 and D90. In general, the effects of the terrain attributes seemed to important for the second soil layer D60.

For texture, there could be observed no significant correlation with terrain attributes. The topographical wetness index (TWI) could be identified as the most important attribute on grain size distribution in the second soil depth D60 under forest ($p < 0.1$) (Tab. 9). For sieving analysis, composite samples were taken to reduce working process. But because of the reduced number of samples no linear regression analysis could be realized for different land uses. For arable land and forest enough samples were available but for them as well as the whole catchment no significant correlation could be observed. Sand content is the only soil property which seemed not be affected by a relation of the three terrain attributes elevation, slope and TWI.

Table 9: Correlation coefficients and significance levels of a linear regression analysis relating soil properties (sc = stone content, Texture; D_b = bulk density, SOC = soil organic carbon, SOC stock = soil organic carbon stock, Sand content, θ_v = volumetric water content, f = infiltration capacity) of different land uses and soil depths with terrain attributes of elevation, slope and topographic wetness index (TWI).

	Arable land			Forest			Grassland	Scrubland			Shifting area		Study area		
	D30	D60	D90	D30	D60	D90	D30	D30	D60	D90	D30	D60	D30	D60	D90
SC															
Evelation	0,16	-0,08	0,27	-0,13	**-0,46** *	-0,31	0,20	**0,19**	-0,03	-0,65	0,34	**-0,65** **	0,26	**-0,11** *	-0,17
Slope	0,02	-0,11	**0,45**	**-0,37**	**-0,08**	-0,09	0,67	-0,01	-0,18	**-0,97** **	0,10	**0,23** **	0,22	**0,13** **	**-0,32**
TWI	-0,08	0,25	-0,09	0,13	0,08	-0,51	0,80	-0,16	0,09	-0,26	-0,19	**0,80** *	-0,16	0,07	-0,15
Sand															
Evelation	-0,22	0,16		-0,76	-0,15	0,63							-0,37	-0,50	-0,22
Slope	0,02	-0,01		-0,94	0,56	-0,46							-0,42	-0,28	-0,28
TWI	-0,13	0,25		0,75	**-0,73**	0,06							0,12	0,37	0,50
Silt & clay															
Evelation	0,22	-0,16		0,76	0,15	-0,63							0,37	0,50	0,22
Slope	-0,02	0,01		0,94	-0,56	0,46							0,42	0,28	0,28
TWI	0,13	-0,25		-0,75	**0,73**	-0,06							-0,12	-0,37	-0,50
Db															
Evelation	-0,17	0,17	-0,38	-0,30	-0,19	0,13	0,45	0,33	-0,08	**-0,53** **	-0,45	-0,39	**-0,35** **	**-0,27** *	-0,23
Slope	0,15	0,14	0,13	-0,36	-0,41	-0,01	0,06	0,45	0,08	**0,04** **	0,03	0,17	-0,21	-0,12	-0,12
TWI	0,04	-0,11	0,23	-0,02	0,10	-0,18	-0,80	0,17	0,06	0,39	0,22	0,06	0,15	0,04	0,17
SOC															
Evelation	0,21	-0,20	0,37	0,30	0,20	-0,18	-0,45	-0,30	0,09	**0,54** **	**0,55**	0,40	**0,38** **	**0,25** *	0,19
Slope	-0,18	-0,17	-0,17	0,37	0,46	0,01	-0,05	-0,43	-0,06	-0,02	0,04	-0,20	0,23	0,11	0,09
TWI	-0,07	0,08	-0,26	-0,04	-0,15	0,14	0,81	-0,12	-0,06	-0,38	-0,25	-0,04	-0,17	-0,05	-0,16
SOC-stock															
Evelation	0,18	**-0,34**	0,38	0,37	0,39	0,30	-0,55	-0,34	0,16	0,61	-0,03	0,27	**0,26** *	**0,28** *	0,10
Slope	-0,13	0,01	-0,18	0,39	0,41	0,26	-0,32	-0,45	0,03	0,33	-0,15	0,07	0,14	0,13	0,04
TWI	-0,06	0,20	-0,24	-0,77	-0,25	0,35	0,56	-0,16	0,08	-0,38	0,01	-0,10	-0,13	0,00	0,00
θv															
Evelation	-0,22	0,13	0,26	-0,16	-0,92	-0,73	**-0,11** *	0,03	0,43	0,57	0,25	0,67	0,62	**0,62** ***	0,34
Slope	0,09	0,01	-0,55	0,10	-0,01	-0,19	**-0,13** *	-0,04	0,47	0,67	**0,71** *	-0,69	0,28	**0,28** *	0,25
TWI	0,25	-0,13	-0,12	-0,11	-0,04	-0,40	**-0,64** *	0,12	-0,08	-0,05	-0,38	-0,36	-0,24	**-0,24**	-0,12
f															
Evelation	0,30	-0,21	0,38	0,25	0,25	0,57	-0,45	-0,33	0,20	0,36	**0,43**	**0,83** **	**0,26** *	**0,23** *	0,04
Slope	-0,07	0,13	-0,13	0,06	0,16	0,26	-0,06	-0,45	0,14	**0,63** *	-0,15	**-0,67**	0,14	0,09	0,00
TWI	-0,02	0,25	-0,23	-0,16	-0,26	0,37	0,80	-0,17	0,29	-0,09	-0,20	**-0,25** *	-0,16	0,06	0,16

Significance levels: $p < 0.1$ (·), $p < 0.05$ (*), $p < 0.01$(**), $p < 0.001$ (***); missing values are caused by a too small sample number

For soil bulk density, no significant correlation with terrain attributes could be observed under arable land, forest, grassland and shifting area. Under scrubland elevation and slope plays an important role (significant, $p < 0.01$) in soil depth D90 (Tab. 9). Referred for the complete catchment elevation was the significant attribute for soil depth D30 ($p < 0.01$) and D60 ($p < 0.05$). Bulk density decreased with height by neglecting land use.

In the studied headwater catchment, the variability of soil organic carbon was only affected by elevation and the most explanatory power was given for the topsoil (D30) (Tab. 9). Individually correlations between the different land uses resulted in no effective relations for SOC under arable land, forest and grassland. In the subsoil (D90) of scrubland the terrain attributes elevation seemed to be a reasonable predictor for SOC contents. On the burned field plots (shifting area) elevation represented the most influential variable in the first soil layer D30 (Tab. 9). When the soil organic carbon was represented as carbon stock, a segmentation in land use categories did show no significant correlation with any terrain attribute. For the study area, instead a variability in the stock of SOC seemed to be affected by elevation into a soil depth up to 60 cm (D30 and D60). In the second soil depth D60 slope got significant important as well.

In terms of volumetric water content (θ_V), the terrain attributes elevation, slope and the topographic wetness index (TWI) could not explain the variation under arable land, forest and scrubland (Tab. 9). Under grassland all terrain attributes showed significant correlations in soil depth D30. The TWI was most important, followed by slope and elevation (all $p < 0.05$). For the second and third depth, no regression analysis could be performed because of not enough sample numbers. Under shifting area, the slope had a significant correlation in soil depth D30. In general, the WC of the whole study area elevation was the most important attribute. Correlations on high significant levels could be detected for the soil depths D30 and D60 ($p < 0.001$). In D60 slope also have a significant effect on θ_V (Tab. 9).

In general, the soil properties of the headwater catchment were most controlled by elevation. Elevation caused a statistical significance difference in specific soil properties like θ_v ($p < 0.001$), D_b ($p = 0.006$), SOC (p = 0.033) and SOC stock (p = 0.043). No significance difference could be observed for stone content (p = 0.516). Equal mean values of D_b (p = 0.076), SOC content (p = 0.108) and SOC stock (p = 0.180) under different slope levels could not be rejected. Instead, there could be observed a statistical significance difference of mean values for θ_v (p < 0.001) and SC (p = 0.014) under different slope levels. Surprisingly, the TWI as a hydrological value seemed not to be an important factor for infiltration capacity (Tab. 9).

The most correlations were found in the second soil depth increment D60. The deeper subsoil D90 seemed not to have a significant relation to terrain attributes. These connection, could not be approved by determination of the single land use categories. The variability of the soil properties did not correlate with elevation, slope or TWI. The biggest impact of the terrain attributes could be identified for scrubland (D_b, SC, SOC) for the deepest soil layer D90. The analyses of specific explanatory terrain attributes mostly got significant for considering the whole study area. For example, elevation seems to be important for water content for the study area. Regarding the single land use categories, no such significance for elevation could be indicated. It is assumed, that for the study area the terrain attributes show an indirectly reflection of land use. Significant differences in water content could be measured for different land use categories. For the whole catchment, the effect of land use distribution was not dismissed (arable land in the flat area, forest on the slopes) As a consequent the terrain attributes got significant for the whole area. Hence, differences in land use could be identified as dominating influencing variable of spatial variability of soil properties. To be sure a partial correlation was ruled out by controlled land use where no significant correlation between soil properties and terrain attributes could be observed.

6 CONCLUSION

A field study was carried out to quantify small scaled variability in hydrological soil properties of different soil depths (0-30 cm, 30-60 cm, 60-90 cm) and land uses (arable land, forest, shifting area, scrubland and grassland) in consideration of different terrain attributes (elevation, slope and topographical wetness index) in a headwater catchment of the Indian Western Ghats. Based on 235 soil samples and 33 double-ring infiltration measurements, differences in soil water retention and hydraulic conductivity at field saturation could be identified. The knowledge about zeolites provides a smectite persistence in the clay soil formation of the Indian Deccan basalt and prevents the loss of soil productivity even under a humid tropical climate and intense leaching conditions. Because of this improvement in soil properties, a group of SOC-rich and clayed soils can develop in the Western Ghats of Maharashtra. Maybe this Red Soils should not be treated as completed weathered tropical soils, but should be seen still in a developing process.

By the terrain attributes, elevation presents the most important attribute for the bulk density of the topsoil and affects differences in soil texture and stone content. Referred to different slopes a significant dependence for texture and stone content could be observed. For the water content and retention characteristics slope seems to play a primary role in the second soil depth (30-60 cm). The topographical wetness index could not be identified as an explanatory terrain attribute. In contrast, all observed soil properties and hydrological characteristics show a significant correlation with land use and soil depth between D30 and D60. No significantly differences could be detected in the last sampled soil depth D90 (60-90 cm). There was a strong correlation between the terrain attributes and land use.

Thus, summarizing the results of this study it was clearly detected, that the observation of small scale differences in physical and hydraulic soil properties can be focused on differences in land use as dominant factor (Fig. 19):

(i) Regarding texture, the sand content in the studied headwater catchment ranged between 3.3 % and 33.8 % in total with a mean sand content of 15.3 %. For the distribution of soil particle size there were detected differences within the soil depths and land use categories despite of the same parent material. The highest mean sand content was under arable land (20 %) and is assumed to be related to the rainfed cultivation management, where aggregated fine soil particles can get in solution and removed by water erosion during the raining season, while they stay as stable fractions on the slopes. Lowest sand content of 10.5 % was observed under scrubland. Fire influences the soil texture whereby the intense of heating seems to play an important factor.

(ii) The organic carbon sequestration with a mean SOC content of 3.5 % and maximum values more than 10 % seems very high. In general, the mean SOC at soil depth D30 was significantly higher than in D60 ($p = 0.001$) and D90 ($p < 0.001$). The highest SOC contents were found under natural forest and shifted area with mean SOC values of 5.69 % and 6.15 %. Again, the fire intensity can affect the amount of accumulated SOC. Arable land with an average SOC level of 3.47 % was maintained at an outstanding high level after some decades or even centuries of deforestation ago. It is assumed that these soils can reach a steady-state in OC content due to the low-level management of local cultivation. Under arable land the mean SOC contents were slightly higher than grassland and scrubland. Consequently, arable land stored more SOC than scrubland in sum.

(iii) Soil inorganic carbon was only observed on shifting area with the highest mean rates in the first sampled soil depth D30 (1.1 %). It is hypothesized that intensive forest fire is causing a self-chalk-fertilizing effect by a chemical reaction of abundant Ca^{2+}-minerals with HCO_3 of the soil water. For the process a certain amount of soil moisture seems to be required.

(iv) A significant higher calculated average soil bulk density of 1.08 g cm^{-3} was found on cultivated soils compared to natural soils with the lowest bulk density of 0.96 g cm^{-3} under forest. For the topsoil, even bigger deviations could be observed compared to measured D_b in the field by a core cutter which an average Db of 1.19 g cm^{-3} under agriculture land and 1.01 g cm^{-3} under forest. Unnatural soil compression of human activity seems not able to be certainly predictable with Equation 2.

(v) The highest mean infiltration capacity was observed under scrubland with a total average water absorption of 410.8 mm followed by forest, arable land, shifting area and grassland with respectively 324.4 mm, 268.3 mm, 263.1 mm and 262.8 mm. After the dry season, the soils of the headwater catchment can absorb first monsoon rainfalls more than 250 mm.

(vi) The highest $K(h)_S$ of 7.0 cm h^{-1} was observed on shifting area. The soils under forest vegetation contained very high conductivity of 4.4 cm h^{-1}, followed by 4.5 cm h^{-1} for arable land and again less values were reached under scrubland 3.5 cm h^{-1} and grassland 3.6 cm h^{-1}. Soil depth could be identified as the most important impact on the water movement in the soil.

(vii) Soil water content increased with increasing soil depth. In the subsoil, there was stored the double amount of water (31 %) compared with the topsoil (16.6 %). An impact of different land uses and soil depths could be detected. At the time of sampling the water content of the topsoil (30 cm) of all land use categories was below the permanent wilking point. In the second soil depth forest and scrubland contained soil moisture above PWP. In the last soil depth, only grassland did not contain any plant available water. Soil water retention takes place over wide ranges of spatial and temporal scales with great impact on model simulations. There could be observed large differences in saturated hydraulic conductivity within soils of similar texture, organic matter and bulk density. Maybe a time-dependency of hydraulic conductivity should be investigated further, by infiltration measurements taken under different soil moisture conditions of the year.

As a limitation of the investigations of that study should be mentioned the different numbers of samples due to the different land use categories and the missing sieving procedure until the clay fraction. In future research, more detailed and constant measurements on the soil texture should be made. In addition to that, stone content is certainly underestimated due to the sampling method by the Pürckhauer soil auger (App., Pic. 30). As a result, the SOC-stock and $INCA_d$ might be slightly overestimated. Referred to hydraulic measurements simpler methods could be considered for future studies due to some difficulties encountered using the double-ring infiltrometer on the slopy terrain. The falling-head technique described by Bagarello et al. (2004) could offer a simplified measurement, requiring short duration experiments, small water volumes and easy transportable equipment. Another option for soil studies with a hydrological context could be the BEST-method for estimating both hydraulic conductivity and soil water retention (Lassabatère et al. 2006).

In the literature, differences in soil hydrology are focused on soils under forest and agriculture, while the function of other land cover areas are hardly observed. But the results of this study show the problem of still limited know-ledge about spatial distribution of small scale patterns under different land uses and in different soil depths. Compared to the FAO mean values of different properties show similar values which are mostly representing the characteristics of degraded land use forms. Consequently, large scale models with adapted FAO values mainly represent reduced soil qualities underestimating SOC and soil water content. In this study was shown the uncertainty of estimated soil characteristics. For modelling purpose, mostly PTFs validated from soils of temperate regions are used for the soils of tropical areas. This should always be handled with a questioning context. Maybe it is necessary to derive more specific PTFs to predict hydraulic properties of tropical soils. In general, more basic pedological research should be done to understand the development of the tropical Red Soils of the Deccan Plateau under different land use managements. Therefore, further field measurements are essential. To improve the representation of hydraulic modeling, land use types next to forest and cultivated areas should get more attention due to the variability of soil hydraulic properties.

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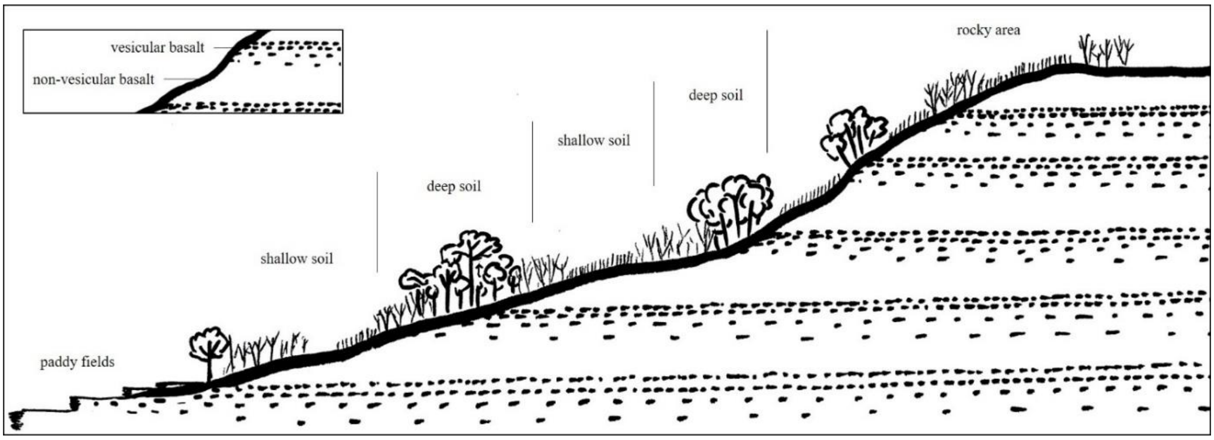
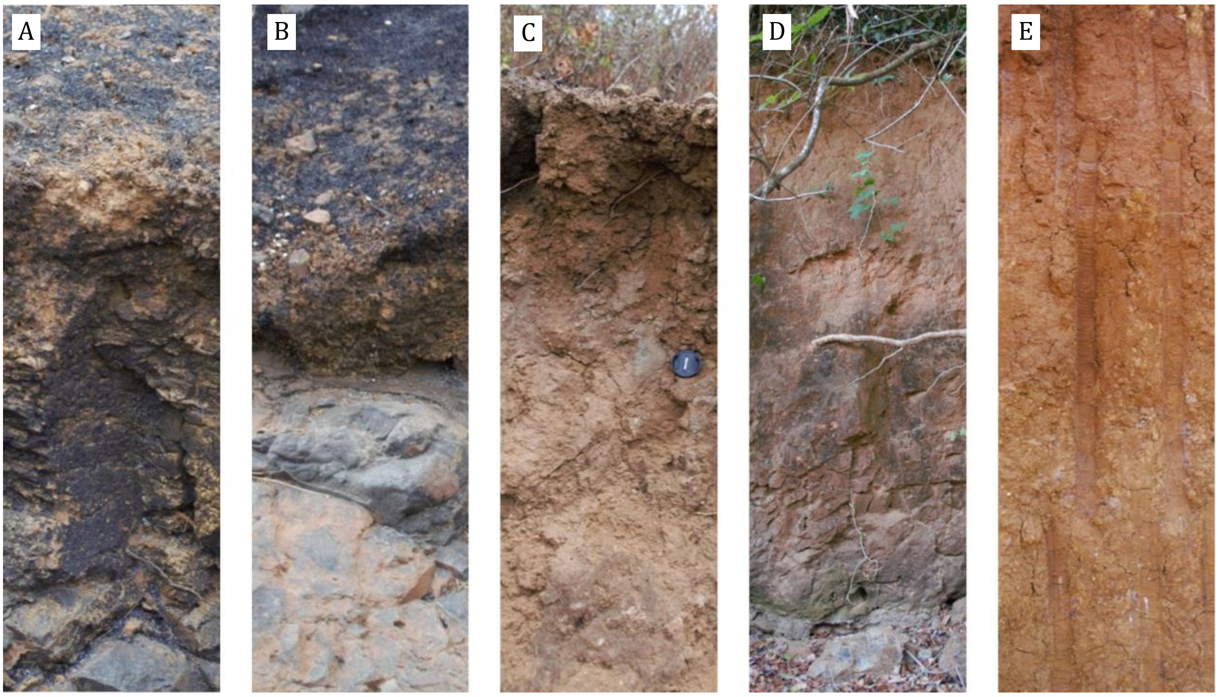
APPENDIX



Scheme: Charting of the spatial distribution of land cover and soil depth in the study area in relation of the geology. Deeper soil depths are assumed to be related with the vesicular basalt layers while shallow soils and rock outcrops are supposed to be found on the non-vesicular foothills.

Picture 1: View over the studied headwater catchment draining into the Mulshi-Lake with forest and scrubland on the slopes, spare forests and grassland on the shallow soils and arable land on the valley bottom.



Picture 2. Different steps of soil development discovered in the study area: (A) weathered rock surface; (B) shallow colluvium soils on bare rock; (C) weathered soils containing zeolitic minerals; (D) deep in-situ weathered soil and saprolite formations under forest cover, (E) well developed loamy clay soils on gently slopes

Picture 3: Steady slopes on granite rocks southern of Mahabaleshwar.

Picture 4: Marked basalt traps in the northern parts of the Western Ghats

Picture 5: Changes in vegetation are interpreted as a sign for the dependency of soil development on vesicular and non-vesicular rock layers.

Picture 6: Dense and dark rock formations of the non-vesicular basalt layers.

Picture 7: Tholeiitic basalt formation of the vesicular layers.

Picture 8: Quartz crystal found in the study area. No quartz gravels could be identified in the soils.

Picture 9: Zeolite formation in the study area.

Picture 10: Weathered zeolite sheets. After Bhattacharyya et al. (1999) some soils can contain zeolites half of their mass in the C-horizon.

Picture 11: Mollisols were observed western of the study area with 4.4 % of SOC in the topsoil.

Picture 12: Soil samples contained primary minerals but calcite was missing.

Picture 13: Trees and scrubs growing on weathered rock formations outside of the sampling area.

Picture 14: Rock outcrops and grass covered shallow soils on the steep slopes.

Picture 15: Cracked clay soils on the valley bottom.

Picture 16: Shrink and swell Vertisols on the fields.

Picture 17: Both, evergreen and deciduous forest formations could be observed in the study area

Picture 19: Green scrubland with dried out shallow rooted grassland.

Picture 18: Terraced and ploughed paddy fields.

Picture 20: Stable dam formations due to fire.

Picture 21: Burned and water stable worm casts covering the dams between the rainfed rice fields.

Picture 22: A numerous amount of snail shells could be found on the burned shifting areas.

Picture 23: *Strobilanthes (kunthianus)* covers large areas of the mountain ranges of the Indian Western Ghats.

Picture 24: Tillage depth is assumed not to reach more than 30 cm because of the mechanic plough.

Picture 25: Shifted area in the studied catchment with ash residues and red colored topsoil due to oxidation processes caused by forest fire.

Picture 26: Superficial leaf residues and litter under forest (about 10 cm).

Picture 27: Natural fertilizers are added in form of farmyard manure, green manure and cattle dung.

Picture 28: Termites could be observed in small numbers under forest and scrubland.

Picture 29: A snake hole represents an example for macropores by macro fauna.

Picture 30: Certainly underestimated stone content due to the sampling method by the Pürckhauer soil.

Picture 31: Soil formation in the study area included red and yellowish-red soils (A) and well developed Bt-horizons (B).