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**SOIL DISTRIBUTION AND SOIL PROPERTIES
IN THE SUBALPINE REGION OF KAZBEGI;
GREATER CAUCASUS; GEORGIA**

INAUGURAL-DISSERTATION

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List of Abbreviations

A...	Topsoil...
AAS	Atomic absorption spectrometer
Al _{ox}	Oxalate-soluble aluminium
AMIES	Scenario development for sustainable land use in the Greater Caucasus, Georgia
a.s.l.	above sea level
B...	Subsoil...
B...	Soil profile (Auger)
b.g.l.	below ground level
BP	Bevor Present
BS	Base saturation
C...	Underground-
Cl, cl	Clay, clayey
CEC _{pot}	Potential cation exchange capacity
Ct	Total Varbon
C _{org}	Organic Carbon
DDx	DDT (Dichlorodiphenyltrichloroethane) and metabolites
E(')	East (of...)
EPSG	European Petroleum Survey Group
FAO	Food and Agriculture Organization of the United Nations
Fe _{ox}	Oxalate-soluble iron
Fe _{di}	Dithionite-soluble iron
H...	Peat...
HCH	Hexachlorocyclohexane
G...	Gleyed...
GC/MS	Gas chromatography–mass spectrometry
h	humic
ICP-OES	Inductively coupled plasma optical emission spectroscopy
Ky	1.000 years
L, l	Loam, loamy

N(')	North (of...)
n.a.	not analyzed
o	oxic
P...	Soil profile
p	plough
PAH	Polycyclic aromatic hydrocarbon
PCB	Polychlorinated biphenyl
POP	Persistent Organic Pollutants
R	Regolith
r	reduced
S(')	South (of...)
S, s	Sand, sandy
Si, si	Silt, silty
SIR	Storie-Index Rating
(M-)SQR	(Muencheberg) Soil Quality Rating
UTM	Universal Transverse Mercator coordinate system
W(')	West (of...)
WGS	World Geodetic System
WRB	World Reference Base for Soil Resources
w	weathered
XRD	X-ray diffraction

Chemical elements and units of measurement are not listed.

Abstract

Due to their characteristic properties, mountain soils require appropriate management when used for agriculture or pasture, even when climatic conditions are favorable.

To enable sustainable agricultural use, the soils of the Kazbegi district in the Mtskheta-Mtianeti region (Georgia), which located in the eastern part of the Greater Caucasus, were mapped in 2014 and 2015 and evaluated according to the Müncheberg Soil Quality Rating (M-SQR).

The soils developed mainly on sedimentary fans and on glacial and fluvial sediments. They are characterized by a low to medium yield potential, with the most productive soils being found on volcanic plateaus. Fluvisols (or at least soils with fluvial properties) are widespread in the river valleys, and bogs, histosols, also occur in the valley bottoms. Medium to very deep Cambisols or Umbrisols form on volcanic substrates. Cambisols are common on moraines, and Regosols and Cambisols are particularly common on the clayey and silty sedimentary rocks of the Jura, characterized by a high proportion of coarse fraction. The cambic horizon is not visually recognizable in these, but is clearly detectable analytically. Depending on slope inclination and exposure, Leptosols occur on the slopes and summits of sedimentary or volcanic rock.

Despite this great diversity of terrestrial and semi-terrestrial soils, a high humus content, at least in the topsoil, is characteristic of all of them. No inorganic or organic contamination was detected in relevant concentrations. However, P-sorption, mainly on amorphous Al- and Fe-oxides, could lead to increased fertilizer requirements. Due to poor accessibility, most of these soils are currently only used as pasture land. Soils on fluvial deposits, especially Fluvisols, show a very high range of M-SQR values.

Based on these results, a synthetic soil map was created combining geological and geodetic data as well as field mapping data to create a land use-management tool.

Overall, the soils of the study area have the untapped potential to optimize the basic supply of the local population as well as tourism through the cultivation of cereals. Nevertheless, variety trials on different soil-forming substrates and erosion control are important prerequisites for the successful implementation of new cultivation systems in the region. In addition, particularly rare soils, e.g. Cambisols on tephra, should be protected. The most limiting factors from an agricultural point of view are the climate

and the slope, while the low nutrient supply and low soil-pH can be counteracted by appropriate fertilization and liming.

Zusammenfassung

Aufgrund ihrer charakteristischen Eigenschaften erfordern Gebirgsböden eine angemessene Bewirtschaftung, wenn sie für den Ackerbau oder die Weidewirtschaft genutzt werden, selbst wenn die klimatischen Bedingungen günstig sind.

Um eine nachhaltige landwirtschaftlich Nutzung zu ermöglichen wurden die Böden in im Distrikt Kazbegi in der Region Mtskheta-Mtianeti (Georgien), im östlichen Teil des Großen Kaukasus, in den Jahren 2014 und 2015 kartiert sowie nach dem Münchberg Soil Quality Rating (M-SQR) bewertet.

Die Böden entwickelten sich hauptsächlich auf Sedimentfächern sowie auf glazialen und fluvialen Sedimenten. Sie zeichnen sich durch ein geringes bis mittleres Ertragspotenzial aus, wobei die ertragreichsten Böden auf vulkanischen Plateaus zu finden waren. In den Flusstälern sind Fluvisole (oder zumindest Böden mit fluvialen Eigenschaften) weit verbreitet, in den Talsenken treten auch Moore, Histosole, auf. Auf vulkanischen Substraten bilden sich mittel- bis sehr tiefgründige Cambisole oder Umbrisole. Auf Moränen sind Cambisole und auf den tonigen und schluffigen Sedimentgesteinen des Juras vor allem Regosole und Cambisole verbreitet, darunter auch solche mit einem hohen Anteil an Grobfraction. Der Cambic-Horizont ist bei diesen visuell nicht erkennbar, analytisch jedoch deutlich nachweisbar. Je nach Hangneigung und Exposition treten an den Hängen und Gipfeln von Sediment- oder Vulkangestein Leptosole auf.

Trotz dieser großen Vielfalt an terrestrischen und semiterrestrischen Böden ist für alle ein hoher Humusgehalt, zumindest im Oberboden, charakteristisch. Anorganische oder organische Belastungen wurden nicht in relevanten Konzentrationen nachgewiesen. Die P-Sorption, hauptsächlich an amorphen Al- und Fe-Oxiden, könnte jedoch zu einem erhöhten Düngebedarf führen. Aufgrund der schlechten Zugänglichkeit werden die meisten dieser Böden derzeit nur als Weideflächen genutzt. Böden auf fluvialen Ablagerungen, vor allem Fluvisole, weisen eine sehr hohe Bandbreite von M-SQR-Werten auf.

Auf der Grundlage dieser Ergebnisse wurde eine synthetische Bodenkarte erstellt, in der geologische und geodätische Daten sowie Daten aus der Feldkartierung zusammengeführt wurden, um ein Instrument für ein Landnutzungsmanagement zu schaffen.

Insgesamt haben die Böden des Untersuchungsgebietes das bisher ungenutzte Potential, die Grundversorgung der lokalen Bevölkerung sowie den Tourismus auch durch den Anbau von Getreide zu optimieren. Dennoch sind Sortenversuche auf unterschiedlichen bodenbildenden Substraten sowie Erosionsschutz wichtige Voraussetzungen für eine erfolgreiche Umsetzung neuer Anbausysteme in der Region. Darüber hinaus sollten besonders seltene Böden, z.B. Cambisole auf Tephra, geschützt werden. Die am stärksten limitierenden Faktoren aus Sicht der Landwirtschaft sind das Klima und die Hangneigung, während der geringen Nährstoffversorgung und dem niedrigen Boden-pH-Wert durch eine angemessene Düngung und Kalkung entgegen gewirkt werden kann.

Chapter 1 Extended summary

1. Introduction

Mountain regions cover one quarter of the Earth's terrestrial surface and are both valuable and vulnerable areas with complex human-environmental interrelationships. Furthermore, mountainous ecosystems are likely to be especially responsive to changing environmental conditions such as global warming, acid deposition or nutrient cycling. Although alpine soils, which are quantitatively almost negligible on a worldwide scale but important for Central Europe, prove to be essential from the point of view of detecting qualitative transformations [sic!] (Egli et al., 2003a, p. 81). This statement can also be applied to the Caucasus region in general and to Georgia in particular. Hence, mountain regions are both valuable and vulnerable areas with complex human-environmental relationships. In this coupled system, land use changes induced by political or socio-economic transformations have consequences for ecological landscape functions such as soil productivity and species richness, with sustainable land development achievable based on integrative land use concepts. In the Kazbegi region of the central Greater Caucasus of Georgia, land use changes have led to landscape structure changes and to population marginalization (Theissen et al., 2019). Alongside the climate, soil quality is a fundamental determinant of the prosperity and development of a rural population. Therefore, assessments of soil quality, yield potential and soil ecological functions were essential parts of the interdisciplinary AMIES II-project, implemented to support rural development in the Kazbegi district of the Greater Caucasus. The project focuses on the human-environment interface and comprises ecological and socio-economic research aimed at the development of sustainable agriculture (Hanauer et al., 2017). Soils are also of interest from a geoscientific point of view, as surficial processes acting on alpine and subalpine landscapes vary at small temporal and spatial scales and may thus be difficult to conceptualize in landscape evolution models. In such cases, soils can provide valuable information about landform genesis, sedimentology and age (Johnson et al., 2015). Therefore, the aim of this study was to obtain solid pedological data for the above-mentioned points.

2. State of knowledge

Soil development in the high mountains has several peculiarities. Catena studies on Holocene and Pleistocene moraines in the Rocky Mountains provided a model of soil development on slopes over time. Aspect was shown to influence soil development in the canyons because it strongly influences their bioclimatic zones. S-facing slopes are relatively warm, and N-facing slopes relatively cool, with the differences reflected in the vegetation (Birkeland et al., 2003, p. 334). Boxleitner et al. (2017) suggested that, in geomorphologically active regions such as the Alps, soil development is often non-linear over time but instead characterized by stages of progressive and regressive evolution caused by build-up (formation, profile deepening) and erosion (profile shallowing). They described several phases of progressive and regressive soil development in the Central Alps that could be correlated with Holocene cold and warm phases. Human impact is increasingly detectable after ca. 2.4 ka BP, based on the appearance of new plant species. These processes can be assumed for the study area as well. Soil age and lower elevation do not necessarily mean more developed soils. For example, Birkeland et al. (2003) showed that that some 12-ky alpine tundra soils can be just as well or even better developed than 20-ky soils at lower elevations in the forest. This was explained by a greater eolian influx in the alpine region (as also observed by Douglass and Mickelson, 2007), which promoted the greater availability of fines, greater soil moisture in some parts due to wind redistribution of snow, the potential for flushing by large amounts of water through the soil during melt-season and possibly a greater local disturbance of soils by tree throw in forested areas. Johnson et al. (2015) found that, in the subalpine post-glacial San Juan Mountains, some typical chronosequence soil properties (e.g. pH, structure, color) did not correlate with time over short time scales while the correlation of extractable iron ratios was relatively strong (late-Pleistocene and Holocene time scales) and the maximum profile clay content was characterized by a weak but statistically significant relationship with age. However, differences in the texture of the initial parent material and dust inputs seem to be the most significant complicating factors in elucidating the temporal relationships of soil.

Additionally, Johnson et al. (2015) found that the occurrence of acumulic soils in the subalpine landscape rendered weathered depth ineffective in determining soil age, as some of the youngest soils were also the thickest. Zollinger et al. (2017) used a non-steady-state conceptual approach to determine the rates of chemical weathering, soil

erosion, soil formation, soil denudation and soil production in the alpine (tundra) and subalpine (forest) ranges of the Eastern Swiss Alps. The authors determined annual soil formation rates of 8.8–86.7 t km⁻², annual chemical weathering rates of 17.23 ± 6.17 t km⁻² (for non-permafrost sites) and a trend towards higher rates of chemical weathering with increasing soil erosion. In the Italian Alps, extensive mineral weathering has resulted in significant leaching losses of major base cations (up to >80% of the initial content), as well as Al and Si, with element denudation most pronounced in subalpine forests near the timberline, the product of the influence of temperature, the percolation rate and the vegetation (Egli et al., 2003b). As water fluxes increase with altitude, due to higher precipitation and decreasing temperatures, net element export may also increase (Egli et al., 2004). Soil formation was shown to decrease with increasing denudation, with denudation rates predominately determined by the erosion rates, which account for 97% of the denudation in permafrost soils and 79% of the total denudation in non-permafrost soils (Egli et al., 2003b). Soil formation rates decline with increasing soil age. Egli et al. (2003a, p. 98) reported that extensive mineral weathering resulted in significant losses of chlorite and mica, via their transformation to smectite. Annual formation rates at the start of soil formation and after about 7000 years were of a similar order of magnitude although the primary lithologies (parent material) differed. The latter is of high relevance for this project, because the study area has a wide range of parent materials (see below). In two soil sequences in northern Italy, Egli et al. (2004) observed that element leaching was greatest at 1400–1900 m a.s.l. under subalpine forest and that weathering rates decreased at both higher and lower elevations, despite differences in lithology and precipitation. Furthermore, the amounts of produced clay were similar at the two elevations.

In the Caucasus region, Molchanov (1999) concluded that mountainous soils do not form continuous vertical soil zones over considerable areas but instead show winding and discontinuing boundaries, due to lithological, geomorphic and bioclimatic conditions, based on observations made using small, mostly heterogeneous soil mapping units. This results in multilevel structures. In the Northern Caucasus, microstructures with respect to genetic type and transitional character are typically present over small areas (typically <0.1 ha, rarely >0.5–0.8 ha) that form rounded or extended shapes along the slope (Molchanov, 1999), leading to different soil types within tens or even several meters (Molchanov, 2010). Good drainage conditions with

unidirectional water flows oppose reciprocal geochemical conjunctions and, due to the steepness of the slopes, only very weak unilateral genetic links are evident. Furthermore, extensive non-soil formations, such as outcrops and profiles deformed by impact (e.g., landslides) or natural processes of swamping and waterlogging, also increase soil heterogeneity (Molchanov, 1999). Molchanov distinguished three types of soil cover structures for the Northern Caucasus: (1) structures developed under normal conditions of pedogenesis, (2) denudation structures and (3) erosional structures mainly conditioned by anthropogenic impacts. Microcombinations of soil types differing in thickness, stone content and texture are mainly associated with the heterogeneity of the parent material and a differentiation of the microrelief. Mesocombinations (soil districts) of similar composition occupy certain elements of mountain ridges (slopes, summits) while vertical sequences of these mountain soil districts comprise vertical soil zones that form macrostructures related to mountain ridges with no genetic links (Molchanov, 1999). Skeletal weathering crusts of the alpine belt of the Northern Caucasus are characterized by free profile drainage and strong surface run-off, leading to a predominance of oxidative conditions as well as leaching (Molchanov, 1999; Molchanov, 2010). Molchanov (2010) also distinguished two types of mountain meadow soils in the Western Caucasus: alpine and subalpine. More favourable bioclimatic conditions in subalpine mountain meadow soils lead to more profound topsoil and subsoil horizons than in alpine mountain meadow soils, especially on southern slopes.

Egli et al. (2003b) proposed that, with rising temperatures, mountain organisms will be able to live at higher altitudes, citing evidence from the European Alps. However, the upward movement of those organisms to many of the natural and managed ecosystems at higher elevations may be limited by factors that include the availability of suitable soils and differences in biotic factors. According to those authors, a rise in temperature and a shift of coniferous forests to higher elevations (currently still above the tree line) could increase weathering rates there. Conversely, weathering rates in the montane to subalpine region could decrease, due to the advance of deciduous forests.

Benedict (1970) measured average maximum ground motions of 0.4 to 4.3 cm per year in an alpine region in Colorado above timberline and found an average rate of 1.9 mm per year for the past 2340 years. This is the resultant of potential frost creep, solifluction, and retrograde displacement. These values are comparable to those

measured in other alpine and arctic regions and higher than values measured on grassy and forested slopes in temperate and semiarid regions and lower than values measured on stony, unvegetated slopes in temperate and semiarid climates. Furthermore, rates of downslope soil movement are largely determined by the depth to groundwater at the beginning of the autumn freeze and under comparable moisture conditions, movement increases as a direct function of slope angle. While differences in soil texture and temperature affect movement indirectly, by influencing the availability of moisture, they otherwise have little control upon rates of downslope movement. Frost creep is generally associated with upper slope and solifluction with lower slope positions. However, sorted landforms characteristic of frost creep are often superimposed upon landforms characteristic of solifluction.

A further aim of this study was to evaluate the agricultural potential of these mountain soils. However, a multitude of approaches exist to quantify agricultural soil quality resp. the production function. Soil rating focuses on the evaluation of soil fertility, e.g. yield potential of arable soils (Stahr, 2010). Due to Müller et al. (2010) three natural limits to growth can be distinguished (1) temperature and moisture regime of the soil, (2) internal soil deficits, e.g. a substrate hindering root growth and nutrition supply, and (3) the relief. For example, the FAO developed at first the Land Suitability Classification (LSC) in 1960, focusing on natural conditions limiting the yield potential: Thermal and moisture regime, nutrient supply, and relief as well as socio-economic factors of the site, but with more emphasis on rating of climatic and edaphic factors than soil rating itself. In a second project, the 'Agro Ecological Zones', agro-climatic zones were combined with the already existing Soil Map of The World (1:5.000.000) to get suitability classes for different crops (Stahr, 2010). To get an international consistent rating scheme the Soil Quality Assessment was developed in the USA. It focuses on small data sets of the evaluated soils to determine soil quality by only a few measurements (USDA, 2001).

A method explicitly accounting for the soil productivity of arable land as well as grassland is the Muencheberg Soil Quality Rating (M-SQR) (Müller et al., 2007). Its practicability and reliability was already confirmed by field tests in several countries and the rating scores are well correlated with crop yields, especially at a moderate level of farming intensity (Müller et al., 2012), as it is typical for the study area. Hence, M-SQR was chosen for the purpose of this study.

3. Study area

The following text passage was taken from our joint publication of the AMIES II project team (Theissen et al., 2019).

The study region is part of the Kazbegi district (1070 km², GeoStat, 2011) in the Mtskheta-Mtianeti region, located in the eastern part of the central Greater Caucasus. The district (population in 2014 approx. 3800, Census 2014; GeoStat, 2016), as an administrative unit, is situated in the northern slopes of the Great Caucasian Ridge, between the Jvari crosspass and the Russian border. The study area is embedded in the upper catchment of the river Tergi, which originates in the glacier area of the Mount Kazbek and drains to the north in the Caspian Sea. Selected settlements and their surrounding land located along the Tergi and Snotskali valley are the focus of this study (Figure 1), with Stepantsminda (2014 pop. approx. 1300) being the main town in the district.

The geomorphological situation of the study region is diverse and shaped by quaternary fluvial and glacial sediments, tertiary and quaternary volcanic rocks and Jurassic sedimentary rocks (Hanauer et al., 2017). Dominant soils are Leptosols, Cambisols, Gleysols and Histosols (Kirvalidze and Petriashvili, 1999). Whereas the productive Cambisols are mainly spread in the lower subalpine zone, the shallow Leptosols primarily occur in the lower subnival belt, which reaches up to approx. 3200 m a.s.l.. Both soils are characterized by acid and weak acid reactions, a high content of humus as well as deep humus penetration (Urushadze and Ghambashidze, 2013).

The climate in the study region is moderately humid and continental. In the subalpine belt (1700 - 2400/2500 m a.s.l.), the mean annual temperature is 4.7 °C and the mean annual precipitation is about 800 mm, approx. 70% thereof falls during the six-month growing season (May–October) (Lichtenegger et al., 2006; Nakhutsrishvili et al., 2005). Mean air temperature in July and August, the warmest months, averages to 15 °C (maximum around 30 °C). The daily mean air temperature in January, the coldest month, is -11 °C (with a minimum of -30 °C), and stable snow cover persists from November to May (Akhalkatsi et al., 2006). Besides gorge winds, northerly and southerly winds are typical (Nakhutsrishvili, 2003). A diverse pattern of land cover and land use characterize the study area from the montane belt (< 1700 m a.s.l.) to the alpine belt (2400/2500–3050/3100 m a.s.l.). Within the village catchments, pasture (57% of all catchments), forest and scrubland (12%), as well as meadow (8%)

characterize this mosaic. Inside or close to the villages (covering 3% of the whole study area) we find gardens and orchards (2%) as well as small-scaled parcels of arable land (1%). Agriculture and tourism are the main sources of income in the district. The industrial sector has never been important in the region (TJS, 2009). The local agrarian food production is primarily located in the subalpine belt. Under the Soviet Union, agriculture in Kazbegi was dominated by sheep transhumance, a system that has been replaced by semi-stationary and stationary variants with cattle since the independence, mainly for private supply (Didebulidze and Plachter, 2002). Since the middle of the 1990s, the number of cattle has risen because cattle provide meat and milk, the latter of which can be processed into several dairy products (Haerdle and Bontjer, 2010).

The tourism sector has been growing in recent years, with rising participation of the local population in touristic services (Gugushvili et al., 2017; Hüller et al., 2017). The Kazbegi district is a major tourist destination in Georgia, however the tourists are almost exclusively concentrated in the settlements Stepantsminda, Gergeti and Juta (GeoWel Research, 2015). Further touristic infrastructure in the district is incomplete, with shortcomings in regulations and restrictions leading to uncontrolled tourism (Heiny, 2017) – a similar situation as in other regions of Georgia (Oedl-Wieser et al., 2017). Today, the appeal of the region for Georgian (70% of all visitors in the district) and international tourists mainly originates from nature, sport activities and cultural sites (Heiny et al., 2017). With the rising number of tourists, who spend about two-third of their daily expenditures on food (Bélisle, 1983), the demand for food in the region increases.

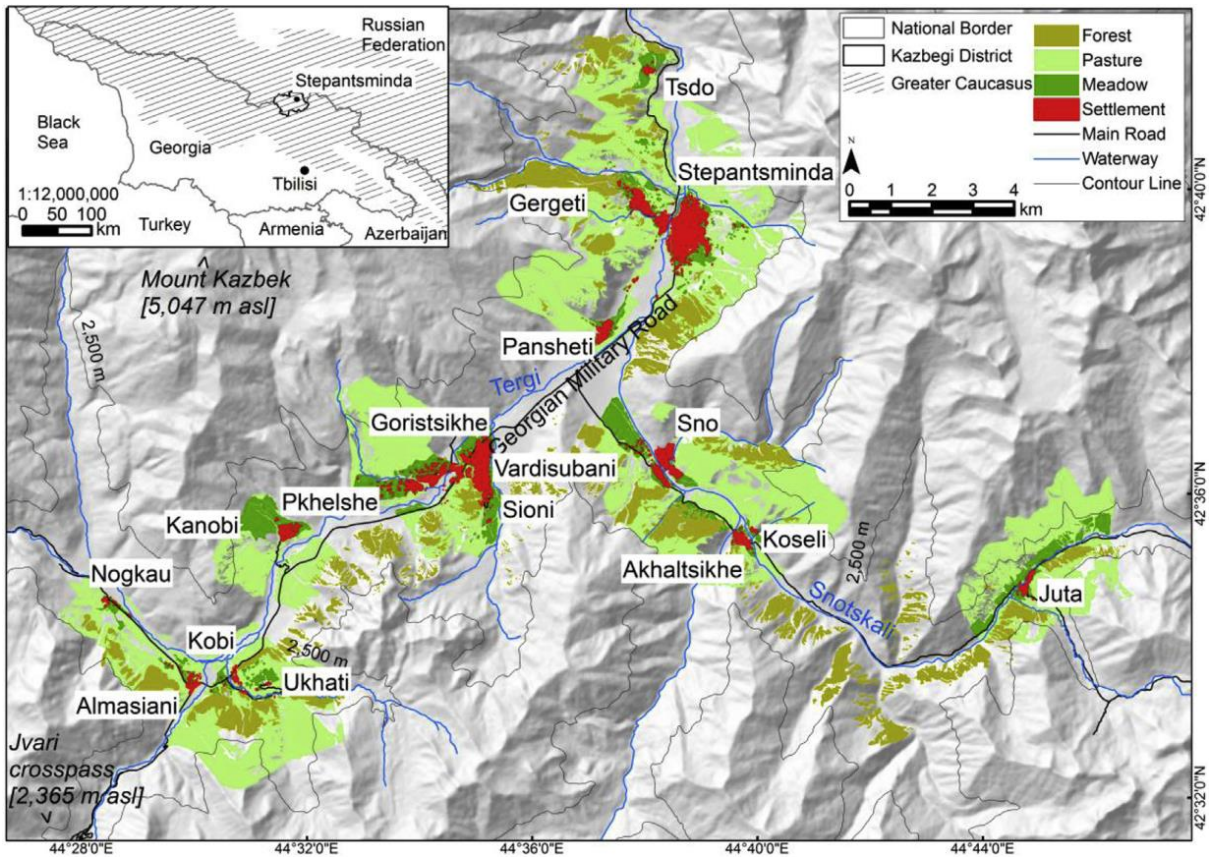


Figure 1 The Kazbegi region in the eastern part of the central Greater Caucasus (Georgia), with Stepantsminda the main settlement (Theissen et al., 20019 p. 312).

4. Geological and pedological features of the study area

In addition to the statements already made above, the following should be added from a geoscientific perspective: The study area is located in the geomorphological zone of the Tergi-Arguni interridge isoclinal depression (Kazbegi-Khevi intermontane basin) and is characterized by high tectonic and geomorphologic activities. The mountainous regions of the Caucasus are situated in a zone of magnitude 8–9 earthquakes, with previous events leading to block landslides and glacier drifts and to the occasional formation of lakes from rivers. The Kazbegi volcano is recognized as being potentially active and its reawakening cannot be excluded (Bondyrev et al., 2015a). The landscape morphology is diverse and has been shaped by quaternary fluvial and glacial sediments, Tertiary and Quaternary volcanic rocks and Jurassic sedimentary rocks (K38-54-A, 1983; K38-54-B, 1983; K38-54-G, 1962; K38-54-V, 1983). The Kazbek neovolcanic center was still active from the late Quaternary until <50,000 a B.P. The last satellite volcano, Tkasrsheti, erupted during the middle Holocene, approx. 6000 a BP. The stratovolcano Kazbek became a center of eruption, with lava flows extending up to 15 km. Its lavas were of a mixed mantle-crustal origin that deposited mainly porphyritic, rarely aphyric, rocks that vary from basaltic andesites (basaltic trachyandesites) to dacites, with a leading role for dacite lavas (Lebedev et al., 2014). Three small volcanic structures of explosive origin are located in the study area: near Pkhelshe, downward from the town of Sioni and at the mouth of the Chkheri River, NE' Stepansminda (Lebedev et al., 2014; cf. Figure 1). The second most important bedrocks in the study area flysch terrigenous and carbonate sediments of the complete Jurassic (Bondyrev et al., 2015a) (primary clay slates but also marlstone) and lower Cretaceous (limestone) (K38-54-A, 1983; K38-54-B, 1983; K38-54-G, 1962; K38-54-V, 1983). Quaternary fluvial and glacial deposits are composed of both of these bedrocks, giving rise to a sediment cascade typical for alpine geosystems, comprising rock face, valley head (regolith), slope (debris/ talus fan), and valley plain (alluvial sediments, terraces) (cf. Zepp, 2002). Pediments are formed by sediment fans (e.g., talus) of Jurassic sediments or by slope loam and the debris of volcanic rocks. The shape and composition of the pediments indicate weathering by solar radiation, although they are not restricted to south-facing slopes and rock fall, from the boulder sediments that typically result, which in turn build scree slopes (accumulation slopes) (Huddart and Stoot, 2010). However, the morphology of some pediments, e.g. east exposed pediments north of the village of Pansheti, suggest a higher proportion of

debris flows compared to rock fall, which is more typical for shade slopes. These show both the typical basal accumulation of fine sediment and channels (cf. Huddart and Stoot, 2010). As the study area is situated at the hypsometric level associated with (peri)glacial processes of the middle belt, which includes alpine to subalpine landscapes (1750–2300 m a.s.l.), both slope (solifluction, rock streams, snow avalanches, talus trains and mudflows) and plane (polygonal-structural) processes associated with periglacial morphogenesis prevail (Bondyrev et al., 2015b). Mudflows are a common natural hazard in Georgia (approx. 37 occurrences in the past 200 years) and are mainly due to intensive precipitation and consequent flooding, as described in the Tergi river basin (Bondyrev et al., 2015b). Landslides are frequent as well, with 2700 basins or 55,000 landslide-collapsed areas (20% of the whole territory) located in Georgia. Those coherent-loose deposits of active areas of weathering crust (Bondyrev et al., 2015b) are of particular interest for soil science. According to (Bondyrev, 2015), the study area is located in a zone of only medium landslide hazard, but with >70% of the territory of the Terek river basin subject to avalanches (Bondyrev, 2015c). On the other side of the Caucasus, on the northern slope of the Kazbeck massif in North Ossetia, in 2002 the Kolka-Karmadon rock and ice avalanche, triggered by the partial collapse of the Kolka glacier, severely hit two villages and killed 125 people (Huddart and Stoot, 2010).

Dominating soil types are Leptosols, Cambisols, Gleysols and Histosols (Urushadze, 1999). As reported by Urushadze and Ghambashidze (2013) mountain meadow soils (Leptosols) are distributed across the study area (1800–3200 m a.s.l.), bordered by Leptosols (upper zone) and Cambisols (lower zone). Among the characteristics of these soils are their acidic and weakly acidic reactions, a high humus content and deep humus penetration (Urushadze and Ghambashidze, 2013). Soil-climatic conditions in the study area are a soil temperature at the surface to 20 cm depth of 0–10°C during the growing season as well as a reserve of productive moisture in the 1-m layer of 100–200 mm year⁻¹ (Elizbarashvili et al., 2007).

5. Physicochemical properties and distribution of the soils

Soils on solid rocks (bedrock) or regolith

As a result of the diversity of bedrock in the study area, the chemical soil properties strongly differ depending on whether the parent material is clay slate, volcanics, sandstone or limestone. Due to limited accessibility and very restricted land use (pasture may be possible only if the slope is not too steep), these soils were not the focus of this study. Nevertheless, three common features must be mentioned. First, due to the harsh climatic conditions, the mineralization of litter is hindered and very humic topsoils as well as subsoils (if present) have developed, but litter horizons are mostly missing. Second, the coarse fraction increases rapidly from topsoil to subsoil, reaching >75%, due to the transition from substratum to not weathered or not chemically weathered regolith; hence, the field capacity is very low. Third, if vegetation cover is disturbed (e.g., by overgrazing or tourist activity), these soils will be at risk of erosion, owing to the steepness of the slopes and the intensive rainfall in the study area. These soils are located typically at the convex creep slope or even the fall face of the slope (cf. Huddart and Stoot, 2010). Two profiles (P13 and P28) on different parent materials were chosen to demonstrate the main characteristics of these soils in the Kazbegi region: Profile P13, a *Skeletal Leptosol (Humic)* obtained near Holy Trinity Church, at an elevation of 2187 m a.s.l. on a SE-exposed slope with 15° inclination, can be considered representative of the shallow soils on the steep slopes of non-calcareous, weakly weathered bedrock in the study area. In this shallow profile, the very humic topsoil is followed by a transitional horizon that also has a very high humic content and is rich in stones. The transitional horizon already shows an increase in pedogenic oxides, indicating an incipient brunification. The C horizon, attributable to physical weathering, already starts at about 15 cm b.g.l. The soil pH is in the weakly acidic range and the CEC_{pot} is very high, due to the high C_{org} content of the horizons. Despite the high (usable) field capacity in percentage terms, the water-holding capacity is low, due to the shallowness of the soil.

Profile P28, a *Calcaric Skeletal Regosol (Humic Fulvic)* between the villages Sno and Achkoti on a 30° steep south exposed slope, is representative of soils on calcareous bedrock in the study area. The almost decalcified sandy-loamy, moderately humic topsoil horizon merges into a diffuse transition zone at 10 cm b.g.l. and then into the underlying horizon (BwC) with a loamy texture. Here only minor signs of soil

development are evident, such as a lower soil pH and a higher C_{org} than in the underground. At approx. 30 cm b.g.l. a diffuse horizontal boundary with the underground is present. The underground is characterized by a significantly higher coarse fraction and is very slightly humic. Despite the medium C_{org} content, the Ah horizon shows a very narrow C:N ratio of 7.6. The soil acidity of the profile is at the level of the carbonate buffer. The CEC_{pot} of the profile is in the medium to high range.

Soils on debris of Jurassic sedimentary rocks

On the clay and silt-rich debris of Jurassic sedimentary rocks, Regosols and Cambisols have primarily developed. These soils are located typically at the transportational midslope or even to some degree at the colluvial footslope (cf. Huddart and Stoot, 2010). Regosols are young, weakly developed, but sometimes (as in the Kazbegi region) profound mineral A-C soils. If the fine earth content is <20 vol%, then the soils belong to the Leptosols. Accordingly, the coarse fraction of Regosols can be high and the field capacity very different. Their rootability is high, but nutrient stocks and the humus content are usually low (Zech et al., 2014). However, the latter does not apply to the Kazbegi region, where C_{org} may nearly reach 12%. In the topsoil it never falls below 2.4% and even the subsoil contains a medium amount of C_{org} .

The formation of pedogenic oxides is analytically detectable but is visually masked by the very dark color of the parent material (Jurassic shale). Hence, transition horizons (BwC) can be distinguished in the study area, in contrast to the typical A-C profile of Regosols. The texture is dominantly loam, with differing proportions of silt, clay and sand. The soil pH is in the weakly acidic or neutral range in all horizons, with a strong dependence on the parent material or bedrock. The CEC_{pot} in topsoil is high but rapidly decreases with depth due to the weak differences along the profile and the decrease in humic sorption sites. Base saturation also decreases with depth in non-calcareous parent material (possibly due to the so-called base pump effect, which would fit well with the high humus content of the topsoil). Biological activity can be high in case of base saturation and high humidity. As in the case of Leptosols, the physicochemical properties of Regosols are strongly dependent on those of the bedrock (Zech et al., 2014).

Cambisols are relatively young, moderately developed and relatively weakly weathered Ah-Bw-C soils. They are often developed on non-calcareous parent rock and in mountainous regions are commonly associated with Leptosols (Zech et al., 2014). In the study area, the diagnostic, usually brown, cambic horizon is not visually apparent due to the dark, blackish parent material, although it is clearly analytically

detectable. Johnson et al. (2015) mention a similar difficulty in subalpine soils on deposits, where the differences could not be qualified using a Munsell chart but only based on the extractable iron content. Cambisols are characterized by a moderate to good nutrient supply, a moderately acidic to neutral pH and a moderate to high CEC_{pot} . Rootability and aggregate stability are good. Porosity and field capacity are high and biological activity is medium to high at Cambisols in the study area as well. The mean C_{org} value and the C:N ratio are slightly higher than the corresponding values of Regosols, at least for the very humic topsoil and medium humic subsoil. The CEC_{pot} is high even in the subsoil, due to the formation of pedogenic oxides and vermiculite. Base saturation of the topsoil and subsoil is higher than in the Umbrisols from the same parent material (see below). The decrease in non-swelling illite, due to a finer texture of the silt fraction, as its main source, or to other alterations (see below), in favor of smectite partially offsets the decrease in C_{org} . However, the exchange capacity depends strongly on C_{org} . The $Fe_{ox}:Fe_{di}$ ratio for both Regosols and Cambisols in the study area is in the normal range (0.2 - 0.4) for humid temperate soils in glacial and periglacial regions (Chestwort, 2008).

In a few cases, even Umbrisols have developed. They are characterized by their typical low base saturation in the topsoil and subsoil. The difference in the C_{org} content compared to the parent material is significantly higher than 0.6%. For example, for P32 (*Skeletal Mollic Umbrisol*), the C_{org} content decreases with depth, from 8.1% to 3.5% to 0%. Notable, the CEC_{pot} is unusually high for Umbrisols, probably due to the high humus content. However, since only one profile (P32) was mapped on Jurassic debris, it is difficult to make general statements for the study area.

Profile P11 [*Skeletal Cambisol (Humic)*], above the village of Stepanzmina (cf. Figure 1), located at an elevation of 1961 m a.s.l., on a WSW-exposed slope of 19°, can be considered representative of soils developing on the debris of Jurassic sedimentary rocks. The very humic topsoil (Ah) has a high CEC_{pot} and due to its bedrock is free of any carbonate. The second horizon, the still humic Bw, is pocket-shaped and extends over a depth range of 18 and 22 cm. The humus content shows a sharp decrease at deeper horizons but is still 1.4% C_{org} at CBw. The coarse fraction increases from 16% at Ah to 25% at Bw and to 38% at CBw. Texture is Cl for topsoil, L for subsoil and SL for both underground horizons. Due to the good rootability and water conductivity of the debris fans, the C horizon might be slightly weathered for several meters. As for most of the soils developed on Jurassic slate, the visual identification of pedogenic

oxides (weathering) is hindered by the dark color of the bedrock (see above). However, amorphous and crystalline iron oxides (ferrihydrite, goethite) were proven analytically as well as mineralogically. The decrease of illite with depth might be due to the decrease of the silt fraction (in which illite is most abundant, cf. above). The relative increase in chlorites can be attributed to the increase in unweathered sedimentary rocks. Accordingly, the chlorites are assumed to be primary chlorites. The relative increases of quartz, kaolinite, smectite and albite with depth are also due to the increase in unweathered sedimentary rocks. Feldspar as well as the decreases in Fe_{ox} and Al_{ox} also evidence poorly weathered material. The somewhat lower proportions in topsoil of illite than in the subsoil suggest a transformation from illite to smectite. However, the conditions in the CBw and BwC horizons are consistent with a similar transformation. Whether and to what extent a clay transformation took place in situ or was overburdened by a rearrangement is therefore unclear. Higher precipitation rates and the production of chelating compounds in the soil are believed to promote the appearance of smectites, and presumably in P11 as well. However, in the investigated profiles of the study area, vermiculite, which would actually be expected for illite weathering (see, among others, Egli et al., 2003a), was not detected.

Soils on glacial sediments

The most prominently developed soil type on glacial sediments in the study area is Umbrisol. These soils are characterized by a thick, dark, humic, well-structured topsoil and often develop on siliceous weathered material. They have a high field capacity and good water conductivity. Redoximorphic features are found, if at all, in the subsoil even when the topsoil is constantly wet (due to high annual precipitation). Nutrient supply and biological activity in Umbrisols are low (Zech et al., 2014). These features were confirmed on the non-calcareous glacial sediments of the study area. The Ah horizon of Umbrisols can be >0.4 m deep and tends to be even more humic, with a C_{org} of 10.5% (median), than in the case of Cambisols on Jurassic. The highly decomposed organic matter is well mixed with the mineral soil, leading to a crumbly structure of the Ah horizon. The subsoil has a medium to high humic content, but the difference compared with the topsoil is somewhat more pronounced than in soils on Jurassic sediments previously described and even in the underground a C_{org} of 0.5% (median) is detectable.

By contrast, CEC_{pot} and base saturation are much lower in Umbrisols than in Cambisols on Jurassic rocks, related to the above-mentioned nutrient deficits of Umbrisols. The (available) field capacity is very high (cf. above) in the topsoil due to the higher C_{org} and smaller coarse fraction but decreases with depth. On calcareous glacial sediments, Regosols have developed and in case of a more fine-grained texture of the parent material Cambisols are also possible. For Regosols as well as for Umbrisols and Cambisols, the $Fe_{ox}:Fe_{di}$ ratio is low and in the range of that of humid temperate soils in glacial and periglacial regions (0.2 - 0.4) and glacial sediments (Chestwort, 2008; Johnson et al., 2015). However, as the soil pH in the study area is moderately acidic to acidic, aluminium toxicity is possible.

The most important soil type on this parent material, Umbrisol, can be described in detail based on a representative profile (P22) near the village of Jutta (cf. Figure 1). Profile P22 shows this typical soil on non-calcareous glacial sediments. The topsoil has a very high humus content and is thus designated as *Cambic Umbrisol* due to IUSS Working Group WRB (2015). The textures vary strongly in their clay and silt contents (Cl, Si, CL, L and SL, from topsoil to underground). The coarse fraction is about 20 vol% and the majority of soil aggregates are smaller than 2 cm. Due to the texture, an effective rooting depth of 1.2 m can be assumed. Sporadic earthworm burrows were found in the profile. The decrease in the illite content with depth is partly due to the decrease in the silt fraction (where illite is most abundant) from 36% (topsoil) to 28% (underground). The relative increase in chlorites is due to the increase in unweathered rocks. Accordingly, these chlorites are considered to be primary chlorites. The increase in unweathered rocks also explains the relative increases of quartz, kaolinite, smectite and albite with depth. An increase in dolomite with depth also evidences an increase in unweathered rocks and corresponds well with an increase of the base saturation from 7% (topsoil) to 70% (underground). The above considerations regarding clay transformation also apply here. However, it must be noted that even minor mineralogical variations in the parent material lead to different weathering paths and thus also to different end products. The lower smectite content of the topsoil of P22 than of P11 (cf. above) fits well with the correlation between smectite and altitude shown by Egli et al. (2003a). An inverse relationship between smectite and chlorite from the subsoil to the topsoil also characterizes P22.

Soils on volcanic unconsolidated rock

As mentioned above, the substrates of the study area are partly of volcanic origin. Therefore, andesite dacite or lava and tuff of andesite dacite, or residual loam thereof, are common parent materials of the soils in the Kazbegi region. These volcanic products may be mixed with or buried by glacial sediments or vice versa. This is the case, for example, on the Uckhati plateau (cf. Figure 1), where volcanic ejecta near the surface are overlain by meltwater sands, which in turn are buried under colluvium consisting of clay residues from andesite weathering. The soils developed here can be comparatively profound under these conditions. These soils are located nearly at all slope segments except the alluvial toeslope (cf. Huddart and Stoot, 2010) in the study area. *Cambisols (Humic)* and *Umbrisols (Protoandic)* have developed with similar characteristics in terms of (available) field capacity and texture class. A very humic Ah horizon up to 15 and 25 cm thick, with a C_{org} of 7.5% and 10.2%, respectively, is detectable in the subsoil in proportions of 2.1% and 3.2%, respectively, but even in the underground at 0.5% (median). The Umbrisols are thus characterized by a slightly higher humus content but a similar C:N ratio and a lower base saturation. Pedogenic oxides are formed in the Umbrisols as well. However, these considerations apply only to the topsoil and subsoil, since underground the influence of the parent material dominates over pedogenic features.

CEC_{pot} and base saturation are 26 [$cmol_c kg^{-1}$] and 89% in the topsoil of the Cambisols and 41 [$cmol_c kg^{-1}$] and 16% in that of the Umbrisols. In the subsoil, they decrease to 11 [$cmol_c kg^{-1}$] and 77% and 27 [$cmol_c kg^{-1}$] and 6%, respectively (median). The $Fe_{ox}:Fe_{di}$ ratio is 0.2 - 0.4 and thus in the range of that of humid temperate soils in glacial and periglacial regions (Chestwort, 2008), except for the subsoil and lower depths of P09 [*Rhodic Cambisol (Humic)*], obtained close to Pkhelsche, which developed on the residual loam of lava and tuff from andesite dacite volcanism.

These soils are considered relatively favorable for agricultural use. Even if the skeletal content can reach up to 40% in the subsoil, at least vegetable cultivation should be possible. At the Uckhati plateau, several potato fields have already been established. However, mowing is much more widespread and is favored by the gentle morphology of the volcanic plateau.

Soil profile P04 is representative of soils on volcanic unconsolidated rock in the study area. The profile was obtained from the 14° middle-slope exposed to the SW, close to

the village Ukhati, at 2206 m a.s.l. (cf. Figure 1). The site is used as grassland. According to the IUSS Working Group WRB (2015) it is a *Eutric Cambisol (Humic)*, which is assigned to the mountain meadow soils in the Russian soil classification (still in use in Georgia as well; see, for instance, Kvirivshvili et al., 2018). In the subsoil and underground, oxidative features indicated by a very low ochre to light rust coloration and very weak bleaching appear. Singular iron concretions are also found in the C horizons, but only in a proportion of $\leq 2\%$, hence the profile lacks any stagnic properties. This is mentioned because hydromorphic features conditioned by stagnant soil water are rare in the study area. The profile is comparatively profound and suggests the better suitability of this location for agriculture than elsewhere in the study area. In contrast to the previous profiles, the changes in the mineral content of P04 with depth are much less pronounced. The relative increase of smectites in the two subsoil horizons can be attributed to the formation of secondary clay minerals, consistent with the decline in K-feldspars in these horizons.

Soils on fluvial sediments [Fluvisol, Gleysol (fluvic Regosol or Cambisol as well as Anthrosol [fluvic])]

These soils are located in the alluvial toe slope (cf. Huddart and Stoot, 2010) in the study area. Soils on the fluvial sediments of the study area are characterized by a high diversity, due to the different watersheds or the heterogeneous geology thereof. In the studied soils, the C_{org} content in the topsoil is significantly lower than that in the rest of the study area, ranging from 2.6% to 6.8%, and the soil pH is neutral to slightly acidic, at least in the topsoil and partly in the subsoil. The wide ranging CEC_{pot} and base saturation values do not allow generalized conclusions whereas the very high $Fe_{ox}:Fe_{di}$ ratio indicates a very low degree of weathering and crystallization of the oxides. Together, these properties indicate a relatively young age of these soils. However, their rough subdivision into two classes of different parent material, depending on their catchment area, is possible. P03 is a *Calcaric Gleysol*, representative of the calcareous parent material. The profile was obtained along a branch of the Terek River, the Truso, at an altitude of 2000 m a.s.l. Furthermore, non-calcareous fluvial sediments in the study area are due to tributaries, e.g., those in the Sioni valley, and are exemplified by profile P40, a *Skeletal Dystric Fluvisol*.

Histosols

Histosols are rare in the study area and are either groundwater- or slope-drainwater-induced (*rheic*) fens, such as occur on a slope eastward of Kobi (cf. Figure 1), or the result of a high groundwater table in alluvial sediments. In higher areas, rainwater-influenced raised bogs (*ombritic*) are also likely, but they were not mapped. Therefore, these soils are typically located on the intermediate and seepage slopes or on the colluvial footslope and alluvial footslope, possibly also on the transport-related middleslope (cf. Huddart and Stoot, 2010) in the study area. The soils are partly used for pasture and even meadow mowing.

Synthetic soil map

A further aim of the study was to create a synthetic soil map to provide an overview of the soil distribution as well as an instrument for land use-management in the study area. In accordance with Jenny (1980), soil is defined as the result of the action of several factors, including climate, organisms, primarily vegetation, slope or topographic setting, parent material, time and others. In the study area, the large variations in the factors parent material and topographic setting give rise to a wide range of soils. Hence, geological and geodetic data were merged, matched, and adjusted with the field data to obtain a spatial distribution of the predominant soil types. Hence, the resulting synthetic soil map (see Figure 2) was derived from a solid map base (according to geology and terrain morphology) supported by empirical findings. For the elevation levels that were mapped, the map provides a good planning reference for socio-economic or agronomic as well as geo-scientific purposes in the Kazbegi region. Moreover, it can be used as a model for similar areas in the alpine regions of the Greater Caucasus.

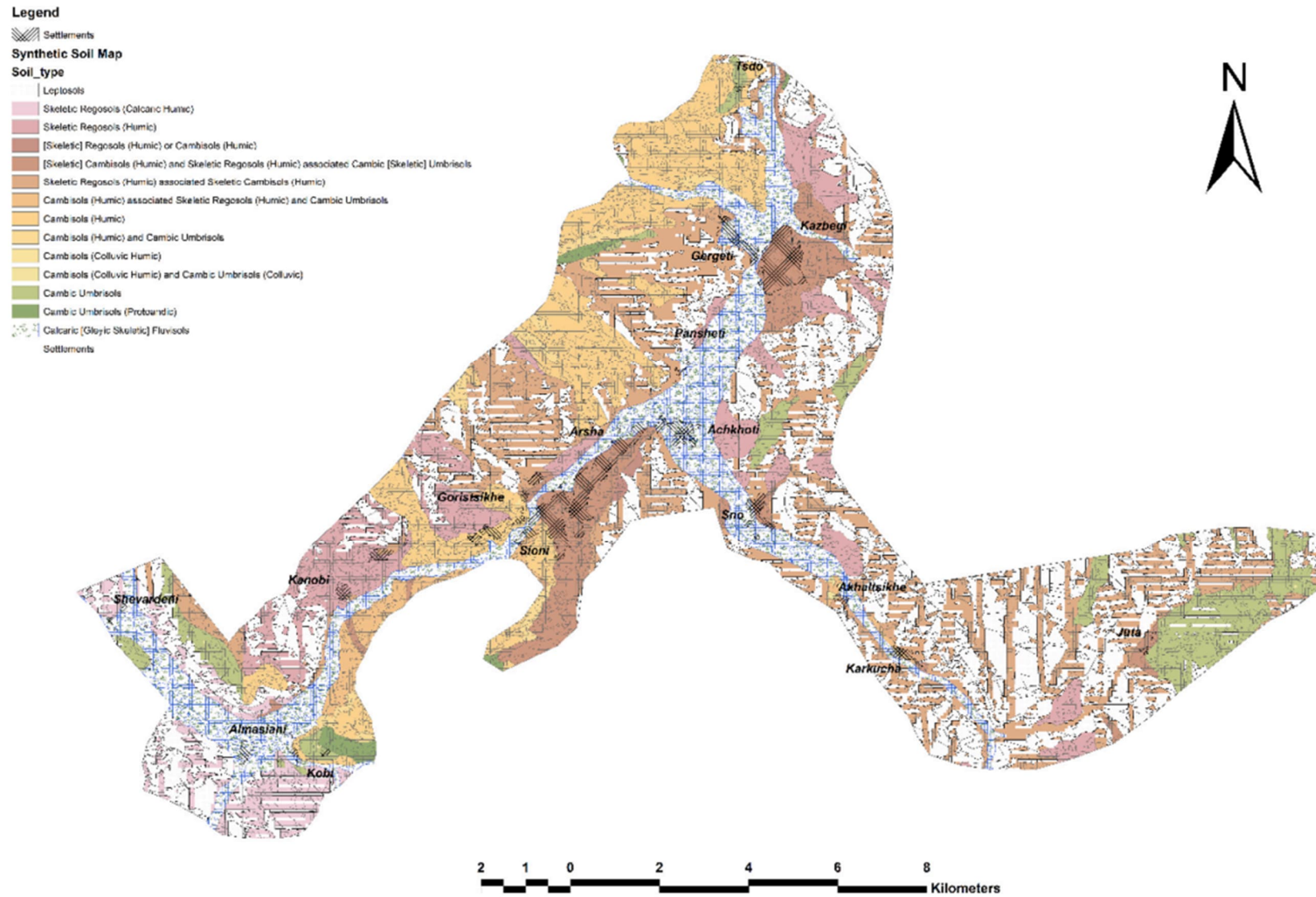


Figure 2 Synthetic soil map of the study area; total size of the study area: 154.94 km². [cf. Chapter 3]

6. Soil quality rating

For the purpose of evaluating and classifying soil quality, a classification by soil types due to IUSS Working Group WRB (2015) proved difficult, because Cambisols and Umbrisols developed on stony sediments fans as well as on volcanic influenced substrates with very different properties and yield potentials. However, due to the dependency of soil quality from soil substrate (see below) a rough classification due to the six main parent materials of pedogenesis of the study area was developed. The general term 'parent material' is used, because different substrates might be included, e.g. loam or even gravel in case of fluvial deposits. For practical reasons and for sake of clarity, such a simplification is appropriate and similar but not identical to the classification given in section 4. The results were also summarized in a map, the basis of which has already been explained in section 5.

M-SQR

The M-SQR applied in this study bases on the evaluation of properties of the rooting zone for cropping and uses indicators concerning the natural yield-potentials. These indicators are distinguished in 8 so called "basic soil indicators" (weighted of 1 up to 3) and 13 "soil hazard indicators". While the basic indicators concerning criteria for plant growth (texture, rooting depth, wetness, and ponding...) and range from 0 (poorest) to 2 (best); , hazard indicators concerning potential yield-limiting factor (contamination, acidification, drought...) and range from 0.1 (maximum limitation) to 3 (no limitation). All basic indicators are summed up and multiplied by the lowest resp. most limiting hazard indicator to get the final soil score (M-SQR score) between 0 (poorest) to 100 (best). Additionally, the M-SQR-score can be abstracted in five classes from very poor (<20) up to very good (>80) and pedon rating can be transferred to landscapes. All basic indicators can be determined in field preferably by a regular soil pit or otherwise a small soil pit and auguring at the bottom of the pit down to at least 1.4 m below surface. While some hazard indicators can be determined in field (e.g. soil depth above hard rock, steep slope...) others must be determined by evaluating the regional climatic data or laboratory data of soil analyses (e. g. salinity, total nutrient status). Hence, the final M-SQR-score depends on field work, rating the pedon as well as the topography, climate data research and results of the laboratory work (Müller et al., 2007).

Soils of the alpine ecosystem are regarded to be shallow, rocky, and mostly used as pasture. Indeed, we find such soils largely extended in the study area (see above).

However, they are not as characteristic for the Kazbegi region as they seem to be at the first sight. On very steep slopes with an inclination $>30^\circ$ or on exposed slope areas soils above solid rock, maybe underlain by a shallow regolith layer only, are widely spread (45.55 km² resp. 29% of the study area) especially in higher elevations at the transition zone from pediment to the open rock surface. Obviously due to the shallow root zone and steepness that influence further soil parameters, e.g. water capacity or thermal regime, an agricultural potential is strongly limited or non-existent. Due to limited access and the assumption of a spatially homogenous soil development from such parent materials, only one example profile (P44, close to Akhaltsikhe, cf. Figure 1) was classified with M-SQR, resulting in only 11 points or 'Very Low'. Even if in some areas site conditions are slightly better, e.g. a deeper regolith layer, it can be assumed that these soils belong to the M-SQR-class 'very low' due to steepness, shallow profile, low nutrient status as well as small water capacity. Hence, only fallow, extensive pasturing or the use of extensive forestry is possible, strongly connected to accessibility and steepness, but erosion control must have highest priority, because the unconsolidated rocks at steep slopes of the study area are exposed to mud slides like in case of the mud slide in Mleta in 2010 (Keggenhof et al., 2011).

Hence, below the Leptosols above solid rock deeper soils can be found on weathered debris. It has to be distinguished between soils formed on accumulated debris from the Jurassic sedimentary rocks and soils formed on parent material, which was more or less mixed with pyroclastic materials. The soils mentioned first are very rich in stones with up to 75% coarse fraction in the subsoil resulting in a low water capacity combined with limited nutrient supply and difficult conditions for cultivation (see above). However, due to the loose substrate, roots can be found down to more than 1 m. Most of the settlements in the study area, e.g. Stepantsminda itself, are built on these debris fans. Hence, main SQR-hazard indicators are, beside the thermal regime that is a problem for all soils in the study area, 'high percentage of coarse soil texture fragments' and 'steep slope'.

Under intensive cultivation in house gardens or fields close to the settlements, Hortisols have developed as well. They are characterized by a high content of C_{org}, accumulated in the topsoil. However, the blackish color is not only the result of humus accumulation but results also from lithogenic carbon of the Jurassic silt stones and clay slates. These soils cover 5039 ha or ca. 32.5% of the study area. The agricultural potential due to SQR ranges from very poor in case of steep slopes and/or a high proportion of coarse

fraction, to moderate on lesser steep parts of the sediment fans. Concentrations of primary nutrients differ, while (in non-cultivated soils) potassium and phosphorus reserves of the profiles are low (Blume et al., 2011), nitrogen reserves as well as available nitrate and ammonia are mostly (very) high due to the high humus content, high mineralization rates and low leaching rates during the dry phases of the vegetation period. Therefore, most of these soils, even with a good accessibility, are used as pasture, hay meadow or small potato fields. At least in case of soils on the lower parts of the sediment fans, this kind of land use is far below their potential. This also becomes evident if the former land use is taken into account: In the second half of the last century barley was grown on a large scale on the lower parts of the sediment fans close to Stepantsminda (Regional Museum in Stepantsminda, oral communication 2015).

The third main group of soils has developed on pediments and plateaus from Andesite-Dacite and other pyroclastics (e.g. tuff). This parent material ('volcanic influenced unconsolidated rock') covers 2518 ha or ca. 16% of the study area. It is obvious that in case of steep slopes also on this substrate only very low or low SQR-rated soils developed, e.g. P17 (19 points). But on smooth slopes or in flat areas moderate to good SQR-classes are distributed. These are by far the best soils of the study area, especially if they have developed on colluvial loam in accumulation areas (e.g. slope toe) as already mentioned in section 5. For example, P05 roughly in the middle of the volcanic plateau close to the village Ukhati gets 79 points, that is on the upper edge of the SQR-class 'good'. Except of the thermal regime acidification could be problematic in a few cases, because soil pH in most profiles is > 4.5 . Furthermore, phosphorus availability might be limited (referring to SQR-hazard indicator 'low total nutrient status') if the soils show *protoandic* properties (IUSS Working Group WRB, 2015). These result in an increased phosphate-fixation by allophanes and metal-humus complexes, due to a high anion exchange capacity.

Phosphorus-sorption is a common feature of Andosols as well as soils with *andic* properties, due to their high ion exchange capacity (Zech et al., 2014; Brady and Weil, 2016). Hence, P-sorption was expected in the Kazbegi region as well, and selected soils formed on volcanic-influenced and not-influenced parent material were therefore investigated. As a soil profile with the highest probability of P-fixation, P07, a *Cambic Umbrisol (Protoandic)* developed on (residual) clay with coarse soil components of andesite dacite, was chosen for further investigations. Profile P16 is a *Eutric Cambisol (Humic Tephric)* formed from pyroclastics that also consists of coarse soil components

of andesite dacite. The control soil profile (P11) is a *Skeletal Cambisol (Humic)* formed from slope debris of Jurassic sedimentary rocks, described above. Indeed, the *Cambic Umbrisol (Protoandic)* (P07) had the highest P-sorption, with a maximum of 84% in the AhBw horizon. By contrast, P-sorption of the Humic Cambisol was much lower: 27% in the Ah horizon. The *Eutric Cambisol (Humic Tephric)* had the lowest P-sorption, with a maximum of 7% in the C horizon. The strongest factor influencing P-sorption in the investigated profiles is the proportion of amorphous Al- and Fe-oxides, but the humus content, clay content and soil-pH also play a role. Hence, P-fixation might be a problem for more intensive land use in the study area, although the Umbrisols would in principle be appropriate due to their depth and good rootability. However, even in Andosols, this problem can be managed with adapted fertilization practices and the incorporation of crop residues (Brady and Weil, 2016). This could also be a problem for other anionic nutrients (e.g. nitrate or chloride) (Arnalds, 2008). Hence, cropping may need an increased phosphorus-fertilization combined with liming to increase soil-pH and to decrease anion exchange capacity.

Within the Pleistocene major parts of the study area were covered by glaciers, as it is easy to conclude from the shape of valleys and the distribution of end and side moraines, e.g. in the Truso valley. But soils developed on glacial deposits are partly covered by Holocene deposits. For example in the Chkheri valley, WNW' Stepantsminda, a groundmoraine is buried beneath lateglacial fluvial sediments or at the Ukhati plateau by colluvium (P05, P36, cf. Figure 1). Hence, only in for 398 ha, or less than 3% of the study area, various glacial sediments are the parent material of the complete soil. However, in other soils they participate as layers in deeper parts. A typical hazard indicator for these soils is a 'high percentage of coarse soil texture fragments' due to bed load of the moraines.

Fluvisols or soils with fluvic properties cover 2.081 ha or ca. 13% of the study area. These soils are formed on a variety of substrates, depending on source area of the watercourse as well as distance to the water divide (see section 5). Due to dominating calcareous sedimentary rocks in the south of the study area, most alluvial sediments are calcareous. Water logging and ponding up to paludification is a problem in case of the braided river beds of the Truso river (below Ukhai) and the Snotskali river (SE Akhothi), resulting in the SQR-hazard indicator 'flooding and extreme waterlogging'. However, the main hazard indicator 'high percentage of coarse soil texture fragments'

is a result of postglacial outwash as well as mass movements on slopes in the study area, especially at the low terraces.

Histosols occur in isolated and small areas in abandoned braided river beds, e.g. between Achkhoti and Sno (ca. 2 ha in size), or slope flattenings above an aquiclude, e.g. at the counter slope S' Ukhati. Bogs are not taken into account of the SQR-map due to the small size of the areas. Generally, similar restrictions for cultivation apply as in case of the Fluvisols with an extreme water regime as mentioned above. For reasons of climate protection and their rarity in the region, these soils should not be used anyway.

Due to the aim of the study to supply information for a sustainable agricultural and horticultural land use particular care has been given to the hazard indicator 'contamination'. For this purpose, trace metals as well as organic pollutants/chemicals were measured in selected samples. Trace metals increase in soils on bedrocks containing high lithogenic amounts. This is the case for sedimentary resp. metamorphic as well as volcanic rocks (Mansfeldt, 2011). These are more or less the sources of all soil-forming substrates in the study area. The andesite and dacite lavas of the Kazbek neovolcanic center show e.g. Ni and Cr concentrations of 15-150 resp. 30-270 [mg kg⁻¹] (Lebedev et al., 2014). In a few case total concentrations of As, Cu, Ni and Zn exceed Georgian thresholds (Ministry of Labour Health and Social Affairs of Georgia, 2003). However, mobile forms are relevant for risk assessment. Due to this 10% of the samples, covering the range of metal concentrations, were extracted with 1 M NH₄NO₃-solution to evaluate mobile species. As expected, only a very small part of total concentrations belongs to the mobile fraction. Hence, elevated trace metal concentrations can be traced back to lithogenic background concentrations which cause only a very small risk for a translocation into food chain.

A further task was the evaluation of POPs in topsoils due to industrial and traffic emissions or application of plant pesticides. In topsoils of three (former) glass houses in Kazbegi region we found residues of DDT and HCH resp. their metabolites, presumably due to application in Soviet times. In one case the Georgian threshold for DDT was exceeded (Ministry of Labour Health and Social Affairs of Georgia, 2003). Due to this, 22 topsoils of the investigated profiles were chosen for a screening on POPs. However, in the investigated soils, all measured substances were below the quantification limit of the screening method used. Hence, neither inorganic nor organic

pollutants can be found in relevant amounts in outdoor topsoils of the study area. Due to this, the hazard indicator ‘contamination’ can be excluded for all investigated soils. Nevertheless, for precautionary reasons the still intensively used topsoils of the (former) glass houses should be investigated in more detail.

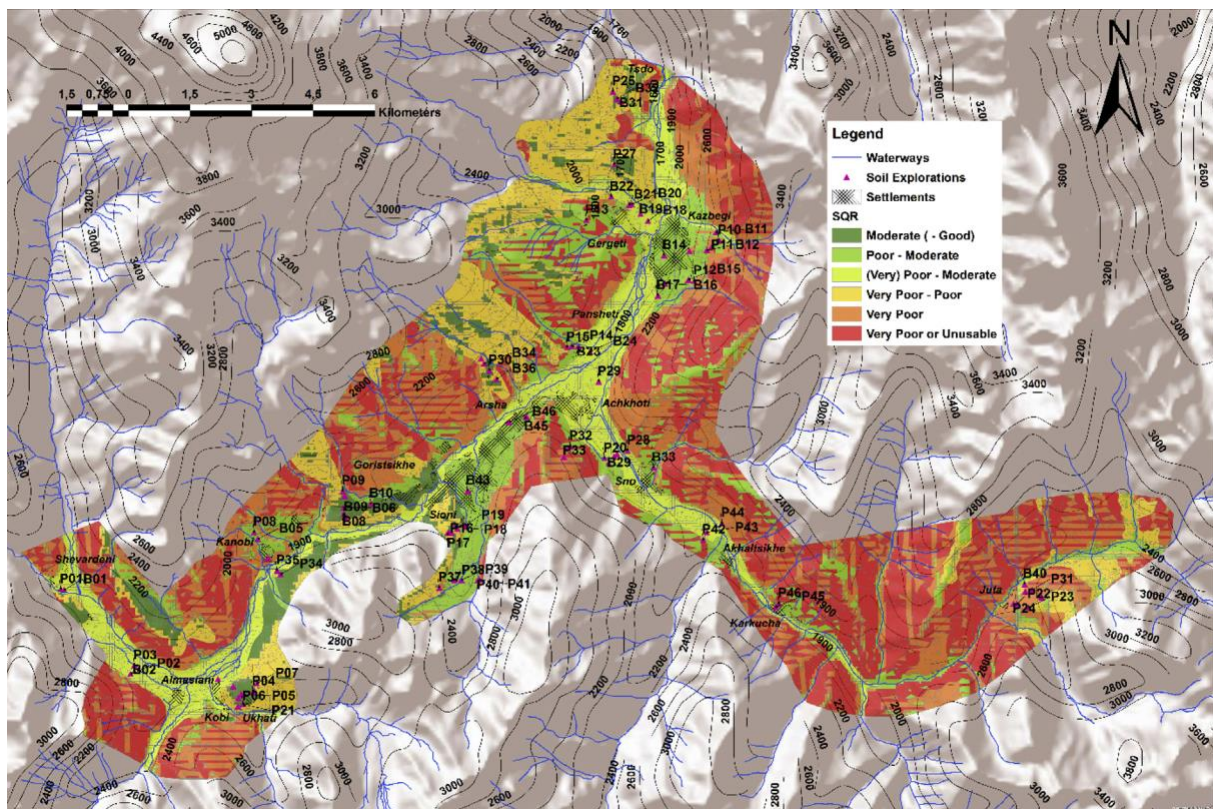


Figure 3 Map of the SQR-Score (due to Müller et al, 2007) of the study area, in case of the Jutistkali River no fluvial parent material is shown separately, due to dominating slope processes in the steep gorge. [cf. Chapter 2]

Yield potential and appropriated crops

Soils with a poor (or even very poor) yield potential are rated with less than 20 and up to 40 M-SQR-points. From all 39 soil explorations 21 fall into this category. These soils are suitable for grassland and (if at least 20 SQR-points) for crops adapted to local conditions for subsistence farming (Müller et al., 2007). Due to hazard indicators like ‘soil depth above hard rock’, ‘flooding and extreme water logging’ or ‘steep slope’ cropping is strongly limited. While excess water is limited to the soils in floodplains resp. Histosols, inclination of slopes and soil depth pose a problem to all soils. But due to the further hazard indicator ‘high percentage of coarse soil texture fragments’ soils on ‘debris of Jurassic sedimentary rocks’ are disproportionately represented (7 of 10) in this class. Sites not that much restricted by inclination are suitable for cropping in

case of an adequate soil management (erosion control, fertilization). Suitable soils with a low yield potential for cropping, developed from 'volcanic influenced unconsolidated rock' are distributed e.g. on the smooth to middle steep slopes above Ukhati. Soils from 'debris of Jurassic slates' are distributed on the unforested slopes N' and S' Stepantsminda. If these soils are deep enough cereals could be cultivated to improve local food supply as well as local markets e.g. for sustainable tourism. Many abandoned terraces indicate where grain was formerly grown in the Khevi region (Kazbegi) due to Bussmann et al. (2017). Arable crops adapted to local conditions could be Oat (*Avena sativa* L.), Summer-Barley (*Hordeum vulgare* var. *distichon* L.) and *Solanum tuberosum* L. (Alsing et al., 1995) (list is not exhaustive; variety trials are necessary). Nevertheless, erosion control must have highest priority. Furthermore, particularly rare soils, like the Cambisols on Tephra close to Sioni (P 16), should be protected e.g. in form of geotopes.

Soils with a moderate yield potential are rated between 40 and 60 M-SQR-points. From all 39 soil explorations 17 fall into this category. These soils, mainly developed from glacial sediments or volcanic influenced unconsolidated rock. Due to Zech et al. (2014) the strongly represented Umbrisols can be improved drastically by erosion control, fertilization (N, P, K, Mg) as well as adapted cropping (potatoes, cereals).

Secale cereale shows the broadest ecological adaptability, due to its few demands on soil quality and climate (Bussmann et al, 2017; Hanus, 2008; Alsing et al, 1995). Caucasian rye (*S. cereale* L.) used to be cultivated in high mountain regions of Georgia (1.800-2.200 m) for bread and beer production (Bussmann et al, 2017). However, heavy rainfall, typical for the vegetation period in the study area, could be a problem for the stability of the long haulms of *S. cereale* (Bussmann et al, 2017).

Hordeum vulgare var. *distichon* is a summer culture due to the limited frost hardiness of winter barley but for summer barley the climatic preconditions, as vernalization temperature (5-10 days of max. 10 °C) and frost hardiness (-6 °C) are fulfilled (Schönberger and Kropf, 2000). Nevertheless, soil-pH should be above 6, because summer barley is sensible to a lower pH (Alsing et al., 1995). This might be a problem for most of the soils and therefore liming would be unavoidable. *Hordeum vulgare* is an ancient agricultural crop in Georgia and had particular importance in beer production (Bussmann et al, 2017). *Avena sativa* could be a further alternative cereal, but it has only a limited functionality for food supply. Its frost hardiness is similar to *H.*

vulgare but it is less sensitive to low soil-pH (Schönberger and Kropf, 2000), also its root system is more effective (Alsing et al, 1995). From a farmer's point of view, oats are considered a “healthy crop” (“Gesundungsfrucht”), as they are not a host plant for many pathogens that cause cereal diseases. It also has the best weed suppression among summer cereals and is suitable for extensive cultivation thanks to its low need for pesticides. This high performance in extensive cultivation is also a reason for the popularity of the crop in organic cultivation (Farmnet, 2024).

Solanum tuberosum could be an alternative on shallower soils or soils with a higher part of coarse fraction. It is highly adaptable to soil quality and climate and grows on soils with a pH-value down to 3.7. Cultivation is possible up to 2.000 m a.s.l. and soils from sandy loam or loamy sand rich in humus are most suitable, while a higher clay content reduces yield (Alsing et al, 1995). It is already cultivated to some degree in the study area, even on the volcanic plateau of Ukhati >2.000 m a.s.l.

In addition to the above notified crops, cropping of *Triticum aestivum* L. or other *Tritium* species might be possible in a few cases, e.g. on Fluvisols from alluvial loam in the Truso valley. However, *T. aestivum* needs a dry period for grain maturity. Hence, due to only short dry periods during vegetation period yield could be less than regular. Wheat fields were planted throughout Georgia at elevations from 300 m to even 2.160 m a.s.l. Almost none of these traditional wheat varieties and species occur in the territory of Georgia, actually. Nevertheless, endemic *T. carthlicum*, that is adapted to high elevations, is still grown in the mountainous area of Meskheta (Akhalkatsi et al., 2012). However, cropping is restricted to the lower areas of the study area. Furthermore, liming is necessary for most soils as well as an appropriate erosion control. Soils on higher areas should stay pastures or meadows, even in case of a moderate yield potential e.g. soil on glacial sediments around the village of Jutha.

Soils with a high yield potential are rated between 60 and 80 SQR-points. From all 39 soil explorations only 1 site falls into this category. These high-quality soils are restricted to loamy colluvium at the volcanic plateaus in the study area, e.g. Ukhati, Toti or Tsdo. Despite their altitude (>2.000 a.s.l.) and difficult accessibility, these soils are predestined to improve productivity of the local agriculture. Due to their location in the landscape (accumulation area), erosion is less problematic, but amelioration (liming) is still necessary due to the low soil-pH.

In addition to the points made above and discussed in Chapter 3, the following restrictions should be made: The production potential for field crops is offset by the inevitable CO₂ release associated with grassland ploughing. Furthermore, the different contribution margins of crop production, either for human consumption or for processing, and grassland management for animal husbandry should be considered, taking into account regional characteristics.

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Chapter 2

Soil distribution and soil properties in the subalpine region of Kazbegi; greater Caucasus; Georgia: Soil quality rating of agricultural soils

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Chapter 3

Soil distribution and soil properties in the subalpine region of Kazbegi, Greater Caucasus, Georgia: Physicochemical properties, distribution and genesis

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Dr. Thomas Hanauer