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# Land use dynamics in the Planosol belt of the Gilgel Gibe catchment, South-West Ethiopia

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# Summary

In the Gilgel Gibe catchment the surface area for communal grazing on the Planosols is currently diminishing. Grazing land is being replaced by eucalyptus plots and by pits that result from brick production. This research assesses the drivers for these changes and their impact on soil quality and on future land uses.

A participatory approach, with transect walks and interviews of different stakeholders, is used to characterize current land uses and different management practices on the Planosols. Combined with Google Earth images and socio-economic data, this allows understanding the land use changes in the catchment. The physical, chemical and micromorphological soil characteristics are analysed, together with climatic data and field observations. This allows evaluating the biophysical environment of the Planosols after different management practices.

The impact of these management practices on the suitability for specific land uses is assessed with the land evaluation framework of FAO. The information on the land use dynamics is then structured and represented with the DPSIR framework. The combination of these complementary approaches allows a comprehensive assessment of the land use dynamics, evaluating specific soil management techniques on the one hand and situating this evaluation in the socio-economic context of the catchment on the other hand.

The conversion of grazing land into eucalyptus plots involves the use of a local practice for seedbed preparation, called guie. This practice comprises the burning of the upper cm of the soil before sowing eucalyptus. Both the short-term and the long-term impacts on the soil quality are evaluated, by comparing physico-chemical characteristics of soils subjected to the guie practice this year and 1, 2, 3, 5, 8 and 10 years ago. In contrast to what is reported about guie in the literature, in this research it is argued that the benefits of this practice outweigh its downsides for eucalyptus seedbed preparation on the Planosols in the Gilgel Gibe catchment.

The excavation of the bleached horizon of the vertic Planosols during brick making changes the soil type into a Vertisol. The impact of this excavation on the potential for upland rice production in the catchment is evaluated. From this evaluation it turns out that soil excavation decreases the land suitability for sustainable cultivation of upland rice.

The increased understanding of the current land use dynamics on the Planosols in the Gilgel Gibe catchment has allowed suggesting possible responses that maximize the sustainable benefits obtained from the land without increasing inequality among the farmers in the catchment.

# Samenvatting

In het Gilgel-Gibestroombekken neemt de beschikbare oppervlakte voor gemeenschappelijke begrazing op de Planosols af. Graslanden maken enerzijds plaats voor kleine eucalyptusplantages en anderzijds voor kuilen die ontstaan bij baksteenproductie na afgraving van de eluviale horizont. In voorliggende studie worden de oorzaken van deze twee trends en de impact op de bodemkwaliteit en op het toekomstig landgebruik geëvalueerd.

Aan de hand van transecten doorheen de Planosols en interviews van verschillende belanghebbenden wordt een participatief onderzoek gevoerd naar het huidige landgebruik en de lokale beheerspraktijken. Afbeeldingen van Google Earth en socio-economische data maken het vervolgens mogelijk om recente veranderingen in het landgebruik te bepalen. De biofysische omgeving op de Planosols na bepaalde beheerspraktijken wordt nderzocht met analyses van zowel chemische, fysische en micromorfologische bodemkenmerken, als klimaatdata en observaties op het terrein.

De impact van deze beheerstechnieken op de geschiktheid voor bepaalde landgebruiken wordt met de landevaluatiemethode van FAO bepaald. De DPSIR methode maakt het mogelijk om deze informatie vervolgens op een gestructureerde manier weer te geven. Dankzij de combinatie van deze twee complementaire methoden worden de specifieke beheerstechnieken geëvalueerd en wordt de evaluatie van de landgebruiksdynamieken gekaderd in de socio-economische context van het gebied.

Om eucalyptusplantages te verkrijgen leggen landbouwers in de regio zaaibedden aan door de bodem op een specifieke manier te verbranden, een lokale techniek die ‘guie’ wordt genoemd. In dit onderzoek wordt in een eerste deel de impact van guie op de bodemkwaliteit geëvalueerd op zowel korte als lange termijn. Hiervoor worden fysische en chemische eigenschappen vergeleken voor bodems die dit jaar en 1, 2, 3, 5, 8 en 10 jaar geleden aan de guie praktijk onderworpen werden. In tegenstelling tot wat eerder over guie geschreven is, wordt in huidig onderzoek beargumenteerd dat de voordelen van de guie praktijk voor de aanleg van eucalyptusplantages op de Planosols in het Gilgel-Gibestroombekken de nadelen overtreffen.

Voor baksteenproductie wordt de eluviale horizont van de vertic Planosol afgegraven. De bodem verandert dan in een Vertisol. Dit onderzoek toont in een tweede deel aan dat die afgraving ervoor zorgt dat het land minder geschikt wordt voor duurzame aërobe rijstteelt.

Dankzij de nieuwe inzichten inzake de huidige landgebruiksdynamieken in het stroombekken worden ten slotte een aantal maatregelen voorgesteld die ervoor kunnen zorgen dat de inkomsten verhogen zonder dat de sociale ongelijkheid toeneemt.

# 1. Introduction

## *1.1. Background and research significance*

According to the Food and Agricultural Organization of the United Nations (FAO) more than 75% of the people in Ethiopia directly depend on agriculture, hunting, fishing or forestry for their livelihood (FAO, 2012a). The amount of land in Ethiopia is, like everywhere, limited and is therefore subjected to competition for different (potential) land uses. Each of these land uses can yield benefits, but also has an impact on the environment. Hence, to achieve sustainable land use in Ethiopia it is important to understand the dynamics and constraints governing rural land use in the country (FAO, 1993).

Climate, soil and soil management play an important role in land use dynamics because they can influence land use allocation decisions. While climate and soil put natural constraints on the potential land uses, soil management affects the current value and long-term sustainability of a land use. Participation of local communities in an assessment of the land uses can add substantial information on these management techniques (Verburg *et al*., 2004; FAO, 2007).

In the Gilgel Gibe catchment, in southwest Ethiopia, land use and management on Planosols is currently changing. The changes involve, among others, the excavation of soil for brick making and the use of local soil management techniques for eucalyptus seedbed preparation. These techniques affect the topsoil properties and thus have an impact on current and future land use. It is therefore relevant to investigate the role of these techniques in the land use dynamics of the region.

This research has been carried out within the frame of the Soil Fertility Project of the Institutional University Cooperation programme between Jimma University and different universities in Flanders (Belgium). This programme addresses the aspects of human and animal health, ecology and agronomy in the region of the Gilgel Gibe hydroelectric dam. The "Sustainable Use of Soil Resources in the Gilgel Gibe catchment" is one of the seven research topics of the project. The main objective of this topic is to improve the land productivity through integrated soil fertility management and to extend the lifespan of the Gilgel Gibe hydroelectric power plant by reducing sediment deposition in the reservoir. The subjects that will be addressed in this research contribute to the understanding of current soil fertility management practices and potential sustainable land uses in the region.

## *1.2. Research objectives*

The major research objective is to contribute to the understanding and evaluation of the current land use practices and land use dynamics on the Planosols within the valleys of the upper Gilgel-Gibe catchment. More specifically, this thesis will try to give an answer on the following questions:

- What are the potential environmental and/or socio-economic drivers behind the observed land use dynamics and how do they contribute to pressure on the Planosols?
- Why do farmers use the guie technique in eucalyptus seedbed preparation and what are the long-term effects of guie under eucalyptus on physico-chemical soil quality?
- What is the impact of excavating the upper bleached horizons of the Planosols on their potential for upland rice production?

The findings of this thesis are expected to yield increased scientific understanding of the current land use dynamics in the catchment and their influence on future land uses. This will provide guidelines for the formulation of better policy responses and can thus contribute to the wellbeing of the local community in the Gilgel Gibe catchment.

# 2. Literature review

This chapter aims to reveal gaps in current knowledge and to provide a state-of-art regarding land use dynamics, the properties and use of Planosols and Vertisols, and guie, a specific management practice in Ethiopia. First the general concepts and principles of land use dynamics will be addressed, followed by an overview of their application in Ethiopia. The next sections focus on soil properties, soil uses and management practices that are relevant to the Planosols of the Gilgel Gibe catchment.

## *2.1. Land use dynamics*

### *2.1.1. Concept and objectives*

Land use has been defined as "the arrangements, activities and inputs people undertake in a certain land cover type to produce, change or maintain it" (FAO, 1997). According to this definition, land use describes the interaction between human activities and land cover. Although sometimes land use and land cover are mixed, there is a clear distinction between both. While land cover can be directly observed, as it is the upper layer on the surface of the earth, comprising soils, biomass and human structures, land use cannot. Land use is an inherently dynamic concept that is a function of both biophysical parameters, affecting the potential land cover, and socio-economic parameters, affecting the actual land cover at a certain moment in time (Verburg *et al.*, 2009). The land use on a piece of land thus affects the goods and services provided by that land. These goods and services not only comprise those expected from the intended land use, but also a broader range of services, called ecosystem functions (MEA, 2005).

The study of the land use dynamics recognizes the dynamic nature of land and aims at assessing the different, changing land uses, and the causes and effects of those changes. The objective can be to increase scientific knowledge regarding the key processes relating the biophysical environment of the land, the land use and the socio-economic environment, or to help policy-makers and land managers to formulate the appropriate responses (Lambin *et al.*, 2000; Reidsma *et al.*, 2011). The first objective can be a necessary step to reach the second objective and often no clear distinction is made between the two.

### *2.1.2. Different scales, purposes and approaches*

The concept of land use dynamics is very broad and its dynamics can be assessed at different scales, with diverse purposes and from the viewpoint of different disciplines. Various approaches have been designed that often focus on a specific aspect of the general dynamics (Veldkamp and Lambin, 2001; Verburg *et al.*, 2004).

The approach used strongly depends on the scale at which the dynamics are to be evaluated, which can range from very low, at global level (e.g. Dale, 1997), to large, at farm or even plot level (e.g. Duguma and Hager, 2011). As the type of data and the variables relevant for the assessment differ from one scale to another, it is important to take into account the scale at which the dynamics are to be assessed (Veldkamp and Lambin, 2001). Only the approaches relevant for the regional, landscape and farm level will be discussed here. These approaches will be broadly categorized into two, non-exclusive, groups, depending on the purpose of the assessment.

On the one hand, the purpose can be to analyse the driving forces and the effects of land use change in the past or in the present. The data needed for such an analysis range from remote sensing data and aerial photographs to socio-economic data and information obtained from interviews. The relationships and trends can be discerned statistically with Geographic Information Systems (GIS) (e.g. Feoli *et al*., 2002b) or by directly formulating hypotheses using information on climate, soil and socio-economic environment (e.g. Reid *et al.*, 2000).

With respect to environmental change, acquired knowledge can be structured with the Drivers–Pressures–State–Impacts–Responses (DPSIR) framework, illustrated in figure 2.1. This framework can be useful to categorize and share information, but should not be used for modelling or to elaborate cause-effect relationships. Critics of the DPSIR framework say that it simplifies reality by assuming a linear unidirectional causal chain, that it doesn't always generate neutral knowledge and that it neglects the importance of local, aggregated and informal responses to address the drivers and pressures (Carr *et al*., 2007; Svarstad *et al*., 2008; Gregory *et al*., 2013). It has been argued that the DPSIR framework should only be used to categorize information at the local scale (Carr *et al*., 2007).

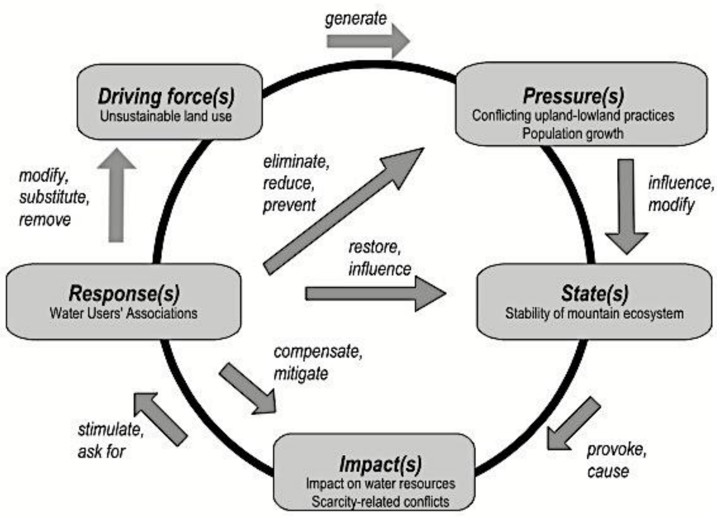


**Figure 2.1: Illustration of DPSIR for a case study in Mount Kenya (Odermatt, 2004)**

On the other hand, the focus can be on the comparison of different (potential) land uses or land management techniques in a region. This can be done with regard to the production functions of land, such as agricultural production, or to the broader functions for the environment, such as ecosystem services. The impact of different land uses can be compared, either directly or by means of indicators (Bockstaller *et al*., 2008). Different ways to compare land uses, related to different points of interest, will be discussed in the following section. The Framework for Land Evaluation, published by the Food and Agriculture Organization of the United Nations in 1976 (FAO, 1976), will be used as the basis for this discussion because that approach is considered to be relevant for this dissertation. The Framework for Land Evaluation was not the first attempt to create a method allowing for the comparison of land and land uses, but it can be used as a reference because it was published by FAO and aimed at a standardization of the procedures applied (FAO, 2007).

In short, a land evaluation consists of the evaluation of different (potential) land uses, called land utilization types, for a specific land, called land unit (FAO, 1976), and vice versa. The data in such an evaluation are used to match the soil, climate and topography on the one hand to information about the requirements of a land utilisation type (e.g. a crop type) on the other hand (Sys *et al*., 1991a). At the origin, comparison of land utilization types was mere qualitative, but after time more quantitative methods, for example to predict yields, have evolved. Both the qualitative and the quantitative approaches are still useful, depending on the context and the purpose of the evaluation (Van Lanen *et al*., 1992). Developments in computer science have made it possible to incorporate the dynamic nature of land and quantitatively model biophysical processes related to various land uses (Rossiter, 1996; Costantini, 2009). This makes the framework to be a strong tool for matching (potential) land utilization types with land units and for the formulation of guidelines for decision makers (FAO, 2007).

Yet, the framework for land evaluation has been criticized for its lack of a practical assessment of the socio-economic environment of the land (Samranpong *et al*., 2009). Although it is explicitly stated in the framework that a land utilization type can only be suitable if it fits the economic, social and political context of the area, the framework fails to explain how those parameters have to be taken into account (FAO, 2007). This problem has been tackled in what has been called an economic approach to land evaluation, which incorporates market mechanisms, like the production cost and the rate of return, into the assessment. The economic land evaluation tries to combine both the biophysical and micro-economical functions (Johnson and Cramb, 1994). It enables decision-makers to get a more comprehensive assessment of the impact of different land utilization types, but also renders the conclusions of the evaluation more ephemeral, since the socio-economic environment is often more changeful than are biophysical parameters.

The land evaluation framework has also been criticized because it fails to assess all the functions and services of land. For a systematic and general assessment of land use functions, also ‘unintended’ functions, such as replenishment of the water table or prevention of erosion (e.g. Bastian and Röder, 1998), as well as cultural functions, should be taken into account (MEA, 2005). An evaluation of land uses will only yield the maximum benefit for the community if all the criteria, categorized as economic, social and ecological, are taken into account. Adoption of a participatory approach has been recognized as of critical importance to discern the relevant social, but also ecological and economic, parameters (Duguma and Hager, 2011; Fagerholm *et al*., 2012). A revised framework for land evaluation will try to take the wider functions of land and the important role of stakeholders into account, while keeping in mind the biophysical limitations of the environment (FAO, 2007).

Closely related to these broader functions of land is the aspect of sustainability. While the original framework for land evaluation explicitly states that a specific utilization type is only termed suitable if it can be sustained, it fails to explain how the sustainability of a land use is to be assessed. Therefore, the framework for evaluating sustainable land management was published by FAO in 1993 (FAO, 1993). An important step towards sustainability assessment is to understand the impacts of different land uses or land management techniques. These impacts can be evaluated according to socio-economic parameters, such as the impact on farmers' income, or environmental parameters, such as the impact on physical soil quality (Reidsma *et al*., 2011). The overall sustainability of a specific land use can be assessed once its different impacts are known. Different approaches exist to assess the overall sustainability. A sustainable development appraisal, for example, makes use of the participatory approach to evaluate the sustainability of different practices in a region (Hurni, 2000), while a trade-off analysis approaches the matter from a more economic point of view (Stoorvogel *et al*., 2004).

From this literature review, it is clear that a wide variety of approaches does exist and that different approaches focus on different aspects of land use dynamics. The structural complexity of the matter makes it difficult, if not impossible, to cover every aspect of the problem. It is clear, however, that an integration of the different aspects of land use dynamics discussed in the previous paragraphs will yield a more comprehensive understanding of the problem (Verburg *et al*., 2004). A description of land use changes, for example, requires some understanding of the potential driving forces and an assessment of the impacts of a specific land use cannot go without keeping the concept of sustainability in mind.

This research in the Gilgel Gibe catchment doesn't claim to be fully comprehensive, but will take the abovementioned concepts into account when assessing selected aspects of these land use dynamics.

### *2.1.3. Land use dynamics in Ethiopia*

During the second half of the 20$^{th}$ century, the Ethiopian highlands have faced significant land use changes. Aerial photographs and remote sensing images proved useful to quantify the extent of these changes at catchment level. The interpretation of these changes, however, required additional information such as climate data, data obtained from the Ethiopian Central Statistical Authority, and technical, social and environmental knowledge collected through participatory approaches and field surveys, sometimes including soil sampling. This allowed the identification of the driving forces behind the changes (e.g. Reid *et al*., 2000; Feoli *et al.*, 2002b; Amsalu *et al*., 2007; Gebresamuel, 2010). The driving forces that have been discerned for land use change in the Ethiopian highlands are, among others, an increase in population pressure (Kidanu, 2004), soil degradation and water shortage (Amsalu *et al*., 2007), the land use policy (Feoli *et al*., 2002b; Kamara *et al.*, 2004), new technologies and pest control (Reid *et al*., 2000). As land use is a dynamic concept, the consequences of previous land use change can become driving forces for following changes. This is especially the case for soil degradation (Amsalu *et al*., 2007).

Though land use change doesn't automatically imply land degradation, in Ethiopia the latter has often be a consequence of the former. Different types of land degradation encountered in Ethiopia are, among others, soil erosion, decrease in organic matter content, nutrient depletion, salinization and soil compaction (Solomon *et al*., 2002; Girmay *et al*., 2008; Haile and Fetene, 2012). Land degradation can have both on- and off-site impacts. The former directly affects the utility for the land manager, while the latter affects others in society. Soil erosion can, for example, not only directly reduce soil depth and crop yield on the affected plot (Mekonen and Tesfahunegn, 2011), but also increase the downstream sedimentation (Bewket, 2003). This is of particular relevance in the Gilgel Gibe valley, as the lifespan of the hydropower plant is being reduced by excessive sedimentation (Devi *et al*., 2008).

While abovementioned researches investigated the extent of land use changes, their causes and their consequences, other authors assessed the options to reduce land degradation and increase yields at farm level. The impacts of local techniques, such as the Maresha plough (e.g. Biazin, 2011) and the guie practice (e.g. Sertsu and Sanchez, 1978), have been subjected to scientific inquiry and alternative farm and plot management practices have been investigated (e.g. Abegaz and Van Keulen, 2009; Araya *et al*., 2011). Soil and water conservation measures have been suggested to fight land degradation caused by soil erosion (Mekonen and Tesfahunegn, 2011).

It has been stated, however, that a lack of participation and top down planning caused several conservation programmes to be inefficient in the past (Shiferaw and Holden, 1999; Nyssen *et al*., 2010). Several studies therefore attempted to approach the matter from a farmer's perspective. This has contributed to new insights regarding soil management and land use dynamics at farm level (e.g. Astatke *et al*., 2003; Nyssen *et al*., 2010). There is a growing recognition of the importance to include local knowledge and inputs from all stakeholders in the evaluation of a land use (Elias and Scoones, 1999; FAO, 2007; Duguma and Hager, 2011; Tesfahunegn *et al*., 2011).

One publication of particular interest for this dissertation is from Reid *et al.* (2000), because it investigates the causes of land use changes in the Gibe catchment. The Gibe valley is located northeast and downstream from the Gilgel Gibe catchment. The landscape consists of upper plateaus cut by the valleys of the rivers. Seasonally flooded Vertisols under wooded grasslands are commonly found. The driving forces of land use changes in this valley have been investigated with a combination of aerial photographs and ecological timelines. Several changes have occurred in the period between 1957 and 1973, including both intensification and extensification of the land use. The major driving forces that have been discerned for these changes were combined effects of drought, migration, changes in the severity of *trypanosomosis*, and changes in settlement and land tenure policy. The impact of those driving forces on the land use varied from site to site. This illustrates the complexity of the matter and the need for a site-specific approach that allows relating causes and consequences of land use change. The next sections of the literature review will therefore focus on more specific aspects of the site under investigation.

## 2.2. Classification, properties and use of Planosols

### 2.2.1. Characterization and classification

According to the World Reference Base (IUSS Working Group WRB, 2007), Planosols are soils that have an abrupt textural change within the upper 100 cm of the soil. This abrupt textural change separates an overlying surface horizon that is bleached, is light-coloured and shows signs of periodic water stagnation, from a more dense and less permeable subsoil that contains significantly more clay (Driessen *et al*., 2001).

In the past the soils currently recognized as Planosols were described as being pseudogley soils or podzolic soils. The abrupt textural change, which currently is a diagnostic feature of Planosols, was not taken into account at that time (Dudal, 1971). The US Soil Classification was the first to introduce the Planosols as a Great Soil Group in 1938 (Baldwin *et al*., 1938). Currently, not only the revised legend of the soil map of the world and the WRB classify soils with an abrupt textural change and periodic water stagnation as Planosols, but also national systems such as the French and Brazilian soil classification systems (EMBRAPA, 2006; AFES, 2008). One important soil classification system not using the term Planosols is the USDA Soil Taxonomy, even though the US Soil Classification was the first to coin the name. Most of the Planosols are currently included in the Great Soil Groups of the Albaqualfs, Albaquults and Argialbolls (Soil Survey Staff, 2010).

It is recognized that an understanding of the soil-forming processes contributes to a better characterization of soils (IUSS working Group WRB, 2007). Three different, non-exclusive processes have been suggested that could be at the base of the abrupt textural change in Planosol (Driessen *et al*., 2001). Those are

- geogenetic processes that result in a coarser fraction covering a finer fraction, like the selective sedimentation or colluvial deposition of a sandy layer on a more clayey layer, selective erosion of the finer soil fractions in the upper part or sheet wash of a lighter textured soil over a layer with more clayey soil;

- physical pedogenetic processes like selective eluviation-illuviation of fine fractions in a soil with a low structural stability; and
- chemical pedogenetic processes, like the ferrolysis process that was first proposed by Brinkman (1970) to explain abrupt textural changes in acid, seasonally wet soils.

In general the weathering of clays, as such, cannot change the texture of a soil because it involves the transformation of one clay type into another. However, it is stated that a complete destruction of the clay minerals is possible in an acidic environment by successive oxidation and reduction of iron if the reduced solution is being evacuated (Brinkman, 1970; Barbiero *et al*., 2010). This process is called ferrolysis and has been suggested several times as to be one of the processes involved in the formation of a Planosol (e.g. Feijtel *et al*., 1988; Baize, 1995; Barbiero *et al*., 2010). It has, however, also been questioned by several authors (e.g. Eaqub and Blume, 1982; Rossignol, 1985; Boivin *et al*., 2004; Van Ranst *et al*., 2011).

The definition of Planosols not only comprises an abrupt textural change, but also periodic water stagnation. Periodic water stagnation is a key feature of both Planosols and Stagnosols and a major feature of Solonetz and Albeluvisols. Those soils differentiate from Gleysols in the sense that Gleysols show signs of reduced conditions caused by prolonged periods of water saturation, while Planosols and Stagnosols are periodically drained. Planosols clearly differentiate from Solonetz and Albeluvisols because they neither have a natric horizon or albeluvic tonguing respectively. The distinction between Planosols and Stagnosols is based on the presence or absence of an abrupt textural change. Both Planosols and Stagnosols show redoxymorphic features in the topsoil caused by a perched water table during some period of the year, but as Planosols rank first in the key, they are differentiated on the basis of abovementioned property (Driessen *et al*., 2001; IUSS working Group WRB, 2007). It has been suggested that an overlap exists in the WRB between Planosols and Stagnosols (Van Ranst *et al*., 2011).

### *2.2.2. Position in the landscape, properties and use*

Planosols typically can be found in seasonally waterlogged areas in flat lands, at the lower end of slopes or in the lower parts of highlands in sub-tropical, temperate, semi-arid and sub-humid regions. The natural vegetation consists of grasses and herbs or light forest. This rather sparse vegetation is a consequence of both the physical and chemical characteristics of the soil. Physically, the conditions are difficult for root growth. The abrupt textural change and compactness of the subsoil foster water stagnation and prevent their penetration. Water stagnation induces oxygen deficiency, which also prevent a good development of the roots. The bleached horizon typically has a weak structure of low stability. If it has a silty texture the bleached horizon can become very hard in the dry season and muddy when waterlogged in the wet season. Also the chemical soil conditions aren't optimal. Planosols can be chemically strongly degraded when mature, having a low ion exchange capacity in the upper horizon. Acidity and aluminium toxicity are also problems frequently faced in Planosols (Driessen *et al.*, 2001; IUSS Working Group WRB, 2007).

As they are both chemically and physically difficult to manage, land use is less intensive on Planosols than on other soil types under similar climatic conditions. They can be left for extensive grazing or for the production of dryland (fodder) crops. In regions with warm and wet summers, inundated Planosols are used for the production of wetland rice. The production of dryland arable crops requires draining and loosening of the soil. Wood production is also an option on Planosols, but only with species that have an extensive and shallow root system and are capable of withstanding severe drought and periodic waterlogging (Driessen *et al.*, 2001). Eucalyptus has been reported to grow on Planosols, but not as good as on other soil types in similar climatic conditions (Castro *et al.*, 2010). The bleached horizon of Planosols can also be excavated and used for pottery craftworks and brick making (Alves *et al.*, 2005; Van Ranst *et al.*, 2011).

### *2.2.3. Properties and use of the Planosols in the Gilgel Gibe catchment*

Planosols in the Gilgel Gibe catchment are found in an association with Vertisols in the lower parts of the landscape. In Borè, a village in the catchment, the average thickness of the bleached horizon is 37.3 cm and the transition between the two horizons is sharp (Dumon, 2010). A sketch of the distribution of the soils in the landscape is given in figure 2.2. This kind of soilscapes, in which a bleached horizon covers a vertic horizon, is common but not unique for Ethiopia (Driessen *et al.*, 2001). Similar associations have also been reported in other parts of the world, like in Uruguay and Colombia (Rossignol, 1985; Faivre and Chamarro, 1995).

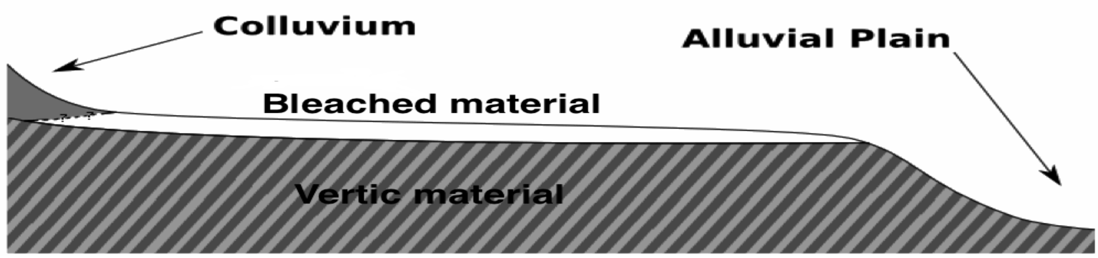


**Figure 2.2: Simplified illustration of the position of the bleached layer in the landscape (Adapted from Dumon, 2010)**

It is hypothesized that the Vertic Planosols in the catchment are formed by the deposition of volcanic ash on the top of a Vertisol. The iron nodules at the boundary between the upper layer and the lower horizon are remnants of a selective lateral erosion of the Vertisol before deposition of the ashes. Subsequent weathering and mixing of the soil material by biological activity and infilling of the cracks explains the geochemical similarities between the bleached and the vertic materials (Van Ranst *et al.*, 2011).

The chemical and physical properties of the bleached horizon are relatively constant throughout the catchment. The textural class of the bleached horizon ranges between silt loam and silt clay loam. The pH (KCl) ranges from 4.2 to 4.9, but measured values for exchangeable aluminium remain low. The CEC is generally low, varying between 7 and 14 $cmol_c$/kg, while base saturation is around 60%, but varies from site to site. The organic carbon content of the bleached horizon can strongly vary, ranging between 0.4 and 4.7 % (Vandemeulebroeke, 2012).

The Planosols in the catchment are commonly kept under extensive grazing. At some locations, the bleached horizon is being extracted for brick making and covering of walls. This process has a great impact on the soil as it involves the removal of the bleached horizon and thus the uncovering of the underlying vertic horizon (Van Ranst *et al*., 2011; Vandemeulebroeke, 2012). Therefore, the characteristics of Vertisols and vertic horizons will be discussed in the next section.

## *2.3. Vertisols: classification, distribution and use*

According to the World Reference Base (IUSS Working Group WRB, 2007), a vertic horizon is a subsurface horizon that is rich in expanding clays and that has slickensides (polished and grooved ped surfaces) and wedge-shaped structural aggregates (sphenoids) as a result of swelling and shrinking. When dry, vertic horizons have a hard consistency and show cracks of at least 1 cm wide. Vertisols have such a vertic horizon relatively close to the surface and have high clay content in the upper 20 cm. Other soils can have vertic properties, but those are not so pronounced as in Vertisols. The concept of Vertisols has been widely accepted among soil scientists soon after it was first coined because of its wide distribution in the world (AFES, 2008). The formation of Vertisols has been intensively studied in the past and will not be discussed here.

Most Vertisols can be found in the semi-arid tropics with distinct wet and dry seasons. They cover an area of 335 million hectares worldwide of which less than half is estimated to be potential cropland. Vertisols are typically situated in lower landscape positions like dry lake basins and lowlands that are periodically wet, but they can also be found on lower foot slopes or even on gently sloping hillsides, depending on the parent rock and environmental conditions. The natural vegetation can be grasslands, savannah or woodland (Driessen *et al*., 2001; AFES, 2008).

Vertisols are considered to be very fertile soils, but have a still underused potential for agriculture because they require adapted management techniques. These management techniques mainly relate to the physical characteristics of the soils. Physically, Vertisols are very hard while dry and plastic and sticky while wet. Water infiltration upon precipitation after a dry period will be initially high, as water easily percolates through the cracks, but will decrease to close to zero when the cracks are closed because of wetting. Therefore Vertisols are easily flooded and erosion can be a problem. Management of Vertisols requires special attention to the cracks in order to allow replenishing the water content in the lower horizons and preventing moisture excess at the surface. Several practices, like alternating broad beds and furrows and the use of microdams for water harvesting, have been developed to cope with these problems. Chemically, Vertisols are ‘good’ soils in the sense that they have a high CEC and a high base saturation. Vertisols usually have a low amount of organic matter and can be deficient in nitrogen. The availability of phosphorous can also be a problem. The use of sufficient (organic) fertilizers can help for maintaining the fertility status of the soil (Driessen *et al*., 2001).

## *2.4. Guie: a traditional soil management technique*

### *2.4.1. Technical aspects*

Guie is a local soil management practice in the Ethiopian highlands that comprises the burning of the upper centimetres of the soil. The term ‘guie’ is phonetically derived from the Amharic word ‘gaje’, which means ‘burning’ or ‘smoking’. Local farmers apply this technique on plots that have been left fallow for several years before bringing them into use again (Wolde-Yohannes and Wehrmann, 1975). The practice fits into a cycle of shifting cultivation comprising as much as 15 years of fallow for every 2 years of cultivation (Abebe, 1981).

At the end of several years of fallow, just after the main rainy season, the farmer ploughs the plot in different directions. The topsoil is then left to dry until January. Before the onset of the small rainy season, the fields are ploughed once again for several times in different directions in order to dislodge the sods into smaller pieces. Those pieces are then piled into small heaps with a diameter and a height of 1,6 m and 0,8 m respectively. Around 900 heaps per hectare are created by this means. Burning cow dung is then inserted at one side of every heap in order to set it on fire. The heaps are left burning for one or two weeks during which a temperature gradient develops inside. At the onset of the main rainy season, in June, the burnt soil is spread out over the plot and ploughed in. Farmers commonly plant barley or wheat after guie and get relatively high yields for two years. Yields up to 3 tonnes of barley have been reported (Wolde-Yohannes and Wehrmann, 1975; Roorda, 1984).

As a temperature gradient develops inside the heaps, not all the soil is affected in the same way. Four distinct zones inside the heap have been described (figure 2.3). The inner part of the heap, which has been termed the burned part, can face temperatures up to 650°C. Organic matter is completely removed, the colour of the soil turns into yellowish reddish (Munsell colours are 5 YR 6/8 while dry and 5 YR 4/6 while wet) and soil particles are aggregated into brick-like granules. A carbonized zone covers the burnt soil and has a black colour (Munsell colour is 5 YR 2/2). This layer is covered by a heated zone (Munsell colour is 5 YR 4/3 when dry), which is, on its turn, under an unaffected cover layer. The topsoil below the heap is also slightly affected by the temperature and by the deposition of ashes (Wolde-Yohannes and Wehrmann, 1975; Abebe, 1981).

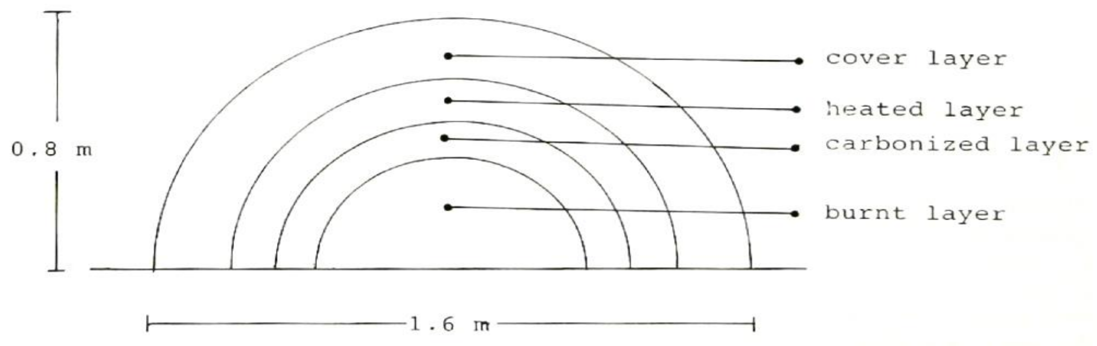


**Figure 2.3: Cross-section of the guie heap with the different layers described (Pulschen and Koch, 1990)**

### *2.4.2. Distribution*

Different studies have identified the guie practice in several zones in Ethiopia, comprising Keffa, Arsi, Semien Shewa, Shoa, and others. These are all located around central and Southwest Ethiopia. Guie soils are said to occur at an altitude between 2,000 and 3,000 m above sea level in regions receiving between 1,100 and 1,500 mm of annual rainfall. The yearly average temperature in those highlands is around 14.5°C. The regions where guie practice has been described have two different soil types, called Pseudogleys and Vertisols. In general, however, guie is only applied on the pseudogleyic soils. Those soils are hydromorphic, don't swell and shrink like Vertisols and are poor in bases. The natural vegetation of those soils is grassland (Wolde-Yohannes and Wehrmann, 1975; Roorda, 1984). Though several publications have described those soils as pseudogleyic, sometimes with vertic properties, they might be currently called Planosols according to present WRB classification system (IUSS Working Group WRB, 2007). As mentioned in previous chapter, Planosols have sometimes been called Pseudogleys in the past. Also, Sertsu and Sanchez (1987) refer to an Ethiopian soil that had been under guie in the Shoa zone, as having a low ECEC and probably being from volcanic origin. This description is in line with the hypothesis mentioned above regarding Planosols in some parts of Ethiopia.

At the time of writing, Wolde-Yohannes and Whermann (1975) reported that about 540 000 ha was under guie practice in Ethiopia every ten years. No information about the current extent of the practice in Ethiopia is available, but the technique has been mentioned in recent publications. Holden and Shiferaw (2004) mention guie (called gaay) as a practice in use on Andosols in the North Shewa zone in Ethiopia. Though 'guie' specifically refers to a practice in Ethiopia, similar techniques have been reported in Western Kenya. People that are called Kipsigis also burn heaps of piled slices of topsoil before spreading it out and mixing it with the rest of the soil (Kitur and Frye, 1983). This practice, as a part of seedbed preparation after a period of fallow of only 4 years, has recently been confirmed on Vertisols in the Bomet District in Kenya (Nafuma *et al*., 2010).

### *2.4.3. Impact on soil and crop*

Soil management with guie affects the topsoil in several ways. The practice destroys the organic matter, affects the soil mineralogy and modifies the physical and chemical properties of the soil. Soil burning also sterilizes the soil and kills seeds of weeds.

Heating or burning can alter the mineralogy of the soil, depending on the original mineralogy and the duration and intensity of the heating (Giovanni *et al*., 1988). Heating up to 200°C doesn't affect soil mineralogy, but from temperatures of 300° to 400°C, the crystal lattice of the clays starts to dehydrate and dehydroxylate. This can cause the crystal lattice to break down (Nishita and Haug, 1972; Abebe, 1981). At that temperature clay particles also start to aggregate into coarser particles. This has been attributed to calcination, with iron and aluminosilicates playing a role. These modifications upon burning have been compared with the slow process of laterization in tropical soils. The progressive hardening of the aggregates, combined with the progressive decrease of the plasticity of the soil during laterization is similar to the much faster modifications upon burning (Giovanni *et al*., 1988). These findings correspond to field observations after guie (Wolde-Yohannes and Wehrmann, 1975).

As burning affects the mineralogy and destroys the organic matter in the soil, the physical characteristics of the soil are also altered. The particle size distribution is altered in such a way that soil texture changes from clayey to sandy loam after heating at 400°C. The amount of coarse aggregates also increases (Sertsu and Sanchez, 1978). This might be surprising, as one of the cementing agents, organic matter, is removed. It has to be attributed to the abovementioned processes of dehydration. The increased sand fraction enhances the porosity of the soil. This might increase soil aeration and the permeability of the roots. Yet, as only the upper centimetres of the soil are affected, the impact on soil drainage is minimal. As a matter of fact, the increase in sand fraction has been reported to last for only one year after guie. The sand particles and the aggregates formed are not resistant to the impact of wetting and mechanical disturbance. Therefore, it is believed that the physical soil quality might increase directly after guie, but is negatively affected in the long run. The aggregate stability is decreased because initial aggregation is not long lasting and organic matter is removed, which renders the soil more sensitive to erosion during heavy rains (Wolde-Yohannes and Wehrmann, 1975).

Guie also affects the chemical characteristics of the soil. As organic matter is destroyed, nutrients are released and become more available to the plants (and for leaching). Upon heating, the availability of nitrogen increases up to a temperature of 200°C, after which it starts to decrease again. This is attributed to the destruction of organic matter, followed by a volatilization of ammonium at higher temperatures (Kitur and Frye, 1983). This results in decreased concentrations of nitrogen in the burnt layer and increased concentrations in the carbonized layer (Roorda, 1984). The availability of phosphorous generally increases as a result of the destruction of organic matter. The availability of Ca and Mg decreases due to the formation of insoluble oxides and carbonates. The pH is reported to decrease with increasing temperatures up to 200 °C after which it start to increase again. The increase in pH at temperatures above 200 °C can be partially attributed to the formation of oxides and carbonated. The availability of potassium and some micronutrients temporarily increases after burning. This is attributed to the decrease in CEC due to the destruction of the organic matter and the dehydration and aggregation of the clay particles (Nishita and Haug, 1972; Wolde-Yohannes and Wehrmann, 1975; Sertsu and Sanchez, 1978; Kitur and Frye, 1983; Roorda, 1984). Availability of micronutrients has also been reported to decrease due to the formation of stable oxides (Abebe, 1981).

One of the potentially positive impacts of guie might be the effect of burning on the growth of weeds. Seeds of weeds are destroyed during burning of the heaps and this gives crops a competitive benefit during the first weeks. This effect is, however, only notable on the locations of the heaps and is rather negligible for the entire field (Wolde-Yohannes and Wehrmann, 1975; Pulschen and Koch, 1990).

Farmers apply the guie practice because they believe it has a positive effect on crop growth. Several studies have assessed the impact of soil burning, and of guie in particular, on the growth of crops. Heating of a soil to about 100°C is reported to increase the yields, while higher temperatures have a negative impact (Kang and Sajjapongse, 1980; Kitur and Frye, 1983). As both temperatures below and above 100°C are being reached with the guie practice, it can have a negative or a positive impact. The guie practice is said to increase the yields during the first two years after the practice, but has a detrimental effect on soil quality in the long run. As only the upper centimetres of the soil are affected, the effect of guie (both positive and negative) on the fields should not be overestimated. It is argued that other practices, like the use of fertilizers, might yield better results with less effort and without a period of fallow (Wolde-Yohannes and Wehrmann, 1975; Abebe, 1981).

## *2.5. Eucalyptus production in Ethiopia*

The guie practice is also used as a technique for seedbed preparation for eucalyptus. Therefore this chapter will discuss the production of Eucalyptus in Ethiopia.

### *2.5.1. Role of eucalyptus in Ethiopian land use*

The role of eucalyptus in the Ethiopian land use cannot be addressed without reference to the problem of deforestation. During the last century, the search for timber and fuel wood has been driving deforestation and subsequent soil degradation. In order to meet demands for wood without compromising the remnants of the natural vegetation, planting eucalyptus species, and especially *Eucalyptus globulus*, could be part of the solution. The species was first introduced in Ethiopia at the end of the 19$^{th}$ century and is now one of the most popular tree species among farmers. Its popularity is due to its high mean annual increment (MAI), its coppicing behaviour and its capacity to produce good fuel wood. As the leaves of the trees are not palatable by cattle or sheep, eucalyptus trees do not require additional fencing and can be used for boundary planting along the fields. This is especially useful because of the free grazing practice that is common during the dry season (Pohjonen and Pukkala, 1990; Jagger and Pender, 2001; Kidanu *et al*., 2005).

### 2.5.2. Requirements and growth of eucalyptus

Though several species of eucalyptus are planted in Ethiopia, *Eucalyptus globulus* is the most common one. The species originates from Tasmania, which is a region with a climate similar to the climate in the Ethiopian highlands. The bimodal rainfall pattern with mild frost during the cold months in the central Ethiopian highlands fits the tree requirements well (Pohjonen and Pukkala, 1991). Eucalyptus stands in Brazil have been reported to perform less if grown on soils that are insufficiently drained. The performance of the trees also strongly depends on the nutrient availability in the soil (Castro *et al*., 2010). This might be a problem in Ethiopia, as some soils can be seriously waterlogged and also the fertility of the soils strongly varies. Soils that are commonly found in Ethiopia, like Vertisols, are, however, sufficiently fertile for the growth of eucalyptus. Mean annual increment of the best sites can be up to 44 $m^3$ $ha^{-1}$ $year^{-1}$ in seedling stands and even more during the first two coppice rotations. The rotation that maximizes wood production is between 14 and 19 years (Pohjonen and Pukkala, 1990).

### 2.5.3. Impacts and benefits in the Ethiopian highlands

Though the eucalyptus species grows well in the Ethiopian highlands and is very popular among farmers, it is not without controversy. Regional governments, such as the governments of Tigray and Oromia, try to discourage farmers from planting eucalyptus on their land. They fear the potential environmental impacts associated with the production of eucalyptus and are worried that its production might be at the expense of agricultural crops (Jagger and Pender, 2003; Kebebew and Ayele, 2010). Eucalyptus species are purported to outcompete crops and degrade soil quality causing the irreversible loss of agricultural land (Michelsen *et al*., 1993).

*Eucalyptus globulus* has a high demand for nutrients and releases allelopathic substances. As eucalyptus cannot fix nitrogen, the continued harvest of biomass will deplete nutrients if no input is provided. Nutrients mainly accumulate in the leaves, and therefore recycling the leaves back to the soil can slow the process of nutrient depletion (Kidanu, 2004). Nutrient depletion and allelopathy is said to negatively affect the future use of the soils because, on the one hand, it prevents successional transition towards indigenous forests, while on the other hand it prevents the use of the soil for agricultural production. However, regarding the first, evidence exists that successional transition is possible in old eucalyptus plantations (Michelsen *et al*., 1993). Regarding the future use of the soil for agriculture, some studies report that the yields of subsequent crops are affected by allelopathic substances remaining in the soil (e.g. Michelsen *et al*., 1993), while others state that these substances do not stay active in the soil for a time long enough to prevent subsequent crop production (Davidson, 1985; Kidanu, 2004).

Besides its impact on the chemical and biological soil quality, eucalyptus has also been criticized for its excessive water use. Its high water consumption and deep rooting system provide eucalyptus with a competitive advantage over other plants. This is especially relevant in dry areas and when the eucalyptus is planted along the borders of the fields. Crops up to 15 meters from the eucalyptus line can suffer from increased water stress during periods of drought. Excessive water use by eucalyptus may also affect the hydrology of the watershed (Kidanu *et al*., 2004). Yet, rows of eucalyptus trees also have a positive impact because they can function as windbreaks, reduce water run off and increase water use efficiency by using water from deeper horizons. Moreover, precipitation outside the growing period, which is usually not available for crop growth, is used by eucalyptus for biomass production (Kidanu, 2004).

Several recent studies advocate that the advantages related to the production of eucalyptus outweigh the above-mentioned problems. They argue that regional governments should encourage small farmers to plant eucalyptus, rather than prevent them (e.g. Duguma, 2013). The production of wood by means of eucalyptus plantations in woodlots or along the borders of fields has several important benefits. First, it reduces the pressure exerted on the remaining natural forests by providing an alternative source of wood. Secondly, it can replace dried dung and crop residues as a major source of energy. This should allow dung to be returned to the fields and could slow the nutrient depletion of the soils. Thirdly, cost benefit analyses have demonstrated that the production of eucalyptus yields a high rate of return and could thus provide an important source of income to poor, rural families. Finally, eucalyptus also offers some other ecological benefits, like a reduced run-off and erosion and a potential for succession towards natural forest (Menz and Grist, 1997; Jagger and Pender, 2003; Kebebew and Ayele, 2010). It is thus clear that, in the current situation, the production of eucalyptus in some regions of Ethiopia is beneficial to both farmer and society. One should realize, however, that the financial return from eucalyptus as calculated in the current situation, would decrease if more eucalyptus were planted. Also one should keep in mind that overall food production should not be endangered.

## 2.6. *Rice: a potential land use in Ethiopia*

Rice (*Oryza sativa*) cultivation is currently not extensive in the Gilgel Gibe catchment. Yet, its importance in Ethiopia is increasing, and the potential of upland rice cultivation in the catchment is currently under investigation.

### 2.6.1. *The role of rice in Ethiopian land use*

The cultivation of rice is a recent phenomenon in Ethiopia. It was probably initiated on the plains of Fogera and Gambella in the early 1970s and some consider it now as one of the best options for Ethiopian farmers to efficiently use water and land in swampy and flooded regions. Its high appreciation among farmers explains the current rapid expansion of the practice (Gebrekidan and Seyoum, 2006). In 2009 already 155 886 ha in Ethiopia was under rice cultivation and this has been projected to increase even further in the coming years. This increase will be fostered by recent government initiatives to promote research and development activities throughout the country. The government now recognizes the importance of rice as a food security crop and as a source of income to small farmers, as well as an opportunity to increase employment on the countryside. Though the yields of both upland and lowland rain-fed rice are still lower than in other countries, improved technologies and varieties could increase the yields in the coming years (Negussie and Alemu, 2011).

### 2.6.2. *Climatic requirements*

A wide array of rice varieties, adapted to a wide range of climatic conditions, exists. Broadly, rice varieties are subdivided into upland and lowland (bunded) rice. Upland rice is cultivated under aerobic conditions, while lowland rice is produced under flooded and thus more reduced conditions (Naklang, 1996). Only the upland varieties will be discussed here. Long periods of sunshine are usually important because yields increase with increasing incidence of solar energy in the last months before harvest. High yields are obtained if the mean temperatures range between 25° and 35°C during growing cycle. Precipitation during crop cycle should range between 800 and 1200 mm (Sys *et al*., 1993). These values are indicative and aim at an optimal yield. Less optimal conditions can still be suitable depending on the specific socio-economical context.

### 2.6.3. *Soil requirements*

Upland rice can grow on a wide array of different soil types, with soil textures ranging from heavy clays to sandy loams. Though the optimal pH for rice production lies between 5.5 and 7.5, soils with pH values as low as 4.5 and as high as 7.9 are still considered as suitable (Sys *et al*., 1993). Optimal rooting depth of upland rice is 120 cm, but as the majority of the roots are situated in the upper 20 cm, all soils with a depth larger than 20 cm can be cultivated. The major problem related to small soil depths is moisture stress due to low available water content (Yoshida, 1981; Sys *et al*., 1993). Yields increase with increasing availability of nutrients. Especially the availability of nitrogen and phosphorous is important to obtain high yields. Soils with a high CEC, a high base saturation and a high organic carbon content therefore perform better. Fertilization with phosphorous and nitrogen, in different splits to avoid leaching, is usually necessary (Yoshida, 1981; Mae, 1997; Krik *et al*., 1998).

### *2.6.4. Management problems*

Two major problems related to upland rice cultivation are the competition of weeds and the increased erosion risk. Some conservation agriculture practices, which are normally promoted to prevent soil erosion, don’t seem to be appropriate for upland rice in cold conditions. This might be caused by a delayed crop emergence under mulched soils and difficulties to take up nutrients in a cold environment (Dusserre *et al*., 2012). Other solutions will have to be found if upland rice production is to be practiced on a sustained base in Ethiopia. As upland rice usually produces lower and less predictable yields than lowland rice, major attention has been given to the latter in the past. Recently, however, the former has been recognized as a promising production system for Africa and Latin America because it might bring into production lands that are currently underexploited (Ahmadi, 2004).

# 3. Materials and methods

## 3.1. Description of the study area

### 3.1.1. Location, geology and topography

The Gilgel Gibe catchment is located in southwest Ethiopia at about 260 km of the capital, Addis Ababa. The catchment covers an area of about 5,500 km$^2$ with an altitude that varies between 1,096 and 3,259 m above sea level (figure 3.1). It is approximately located between 7° 22’ 72’’ and 7° 34’ 84’’ latitude N and between 37° 21’ 05’’ and 37° 28’ 80” longitude E. The bulk of the catchment is located in the south of Jimma zone, which is one of the zones of Oromiya region. This zone is subdivided in districts, called woredas, of which several, such as Kersa (major village is Serbo) or Dedo (major village is Dedo), cover part of the catchment. The main city in the catchment is Jimma, located at an altitude of approximately 1,800 m above sea level. The Gilgel Gibe is the main river of the catchment and is cut by the Gilgel Gibe hydroelectric dam.

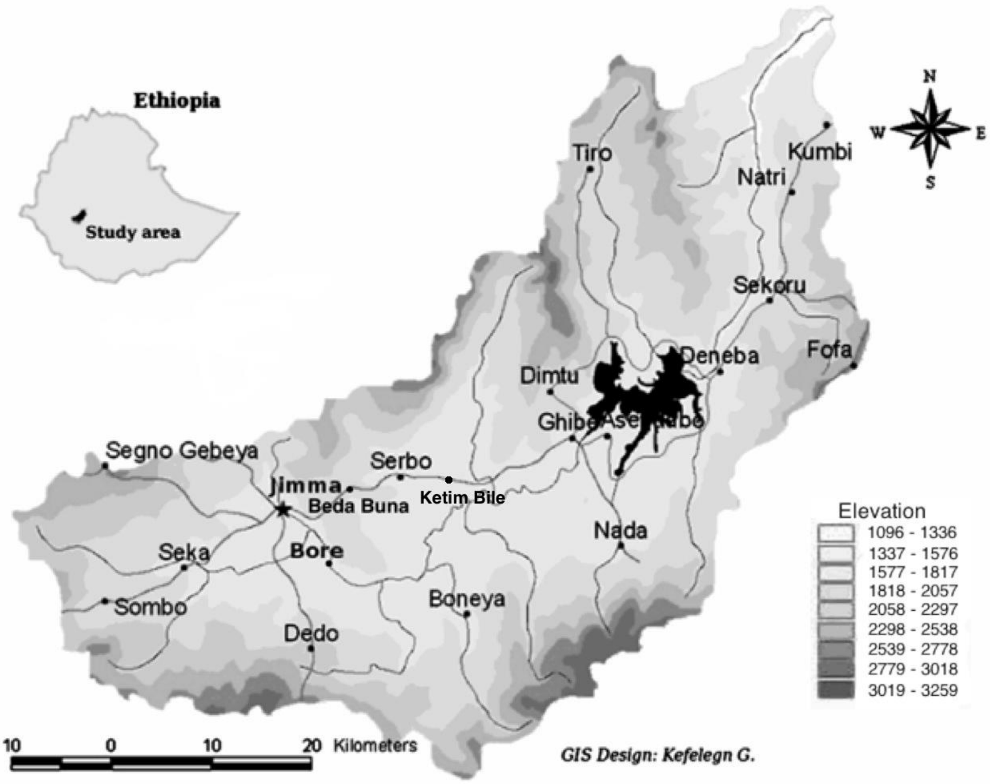


**Figure 3.1: Location of the study area with the main cities and location of the villages where transect walks have been performed: Borè, Serbo, Beda Buna, Ketim Bile and Dimtu (adapted from Van Ranst *et al.*, 2011)**

The geology of the catchment is related to the uplifting of the East African rift valley in the Upper Eocene (Tadesse *et al*., 2003). It is therefore dominated by Eocene and Paleocene volcanic materials, like basalts, tuffs, rhyolites, ignimbrites, trachytes and ash deposits (Van Ranst *et al*., 2011). Remnants of volcanic landforms, like plugs and cone structures can be discerned in the landscape.

The topography is heterogeneous, with upper plateaus that are cut by deep V-shaped valleys in the flanks and flat river terraces around the Gilgel Gibe river in the centre of the catchment. Several reference soil groups can be found, the most important being Nitisols, Ferralsols, Acrisols, Vertisols and Planosols. The associations of Planosols and Vertisols are located on the river terraces in the lower landscape positions (Van Ranst *et al*., 2011).

### *3.1.2. Climate*

Though geographically Ethiopia lies in the tropical region, several factors give the country a particular set of different climates. The altitude, rift valley and Inter Tropical Convergence Zone (ITCZ) influence both the temperature and precipitation patterns across the country. Minimum and maximum average temperatures vary from less than 10 to over 40 °C and the mean annual rainfall ranges from 100 to 2,800 mm, depending on the site. Also the temporal rainfall patterns differ throughout the country. In some regions in Ethiopia the majority of the precipitation is distributed over two separate rain seasons (Belg and Kiremt), while other regions only have one (CSA, 2006; FAO, 2012c).

The rainfall pattern in the Gilgel Gibe catchment is distributed over only one season. Contrary to what has been reported in previous theses (e.g. Dumon, 2010), no distinction between Belg (March-May) and Kiremt (June-October) season can be discerned in this region (CSA, 2006). Figure 3.2 represents the average annual distribution of the precipitation and of the mean temperature at the meteorological station of Jimma Airport, calculated with daily data from 1981 to 2005. The average minimum and maximum temperature are 11.5°C and 27.5°C respectively, while the average precipitation is 1,521 mm. The meteorological station is located at an altitude of 1,890 m above sea level.

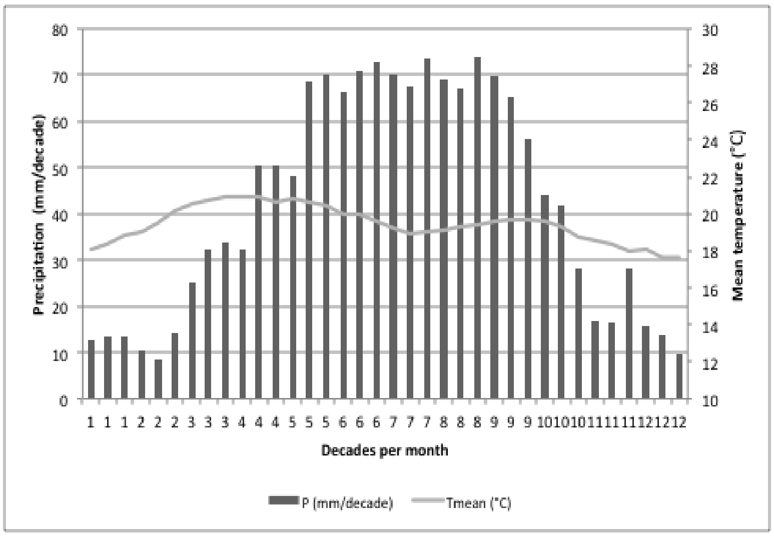


**Figure 3.2: Average decadal (10 days) precipitation and mean temperature in Jimma Airport, based on daily data from 1981-2005**

It is important to notice that abovementioned values are from Jimma and may differ at other locations in the catchment. Precipitation, for example, ranges from 1,300 mm in the lower parts of the catchment to 2,000 mm in the higher regions. In Dedo, which is located at a higher altitude than Jimma, annual precipitation is 2,097 mm. Mean minimum and maximum temperatures in Dedo are 11°C and 25.1°C respectively (Regassa, 2009). Care should thus be taken when using the climatic data obtained of the Jimma meteorological station for other locations in the catchment. Yet, as the Planosols under investigation in this thesis are located at an altitude comparable to the one at Jimma meteorological station, it is assumed that those climatic parameters can be used.

### *3.1.3. Land use*

Land use statistics are an important source of information for the assessment of the land use dynamics in a region (FAO, 1993). However, the values for land use described in this chapter are indicative and should therefore be interpreted with care. Personal communication with experts of the Office of Agriculture of Jimma zone has revealed that land use is estimated visually in the field and that no other inputs are used to check the validity of these data. Also, as the Gilgel Gibe catchment overlaps with several woredas, no land use data are available for the whole catchment. The Gilgel Gibe catchment (about 550,000 ha) is situated in Jimma zone (1,828,327 ha), which is divided in several woredas, like Kersa or Dedo, that cover part of the catchment.

Land use in Jimma zone for the years 2009 and 2012, and in Kersa woreda for the year 2012, are given in table 3.1. The values for Jimma zone were obtained from the Office of Agriculture of Jimma zone in Jimma, while the values for the Kersa woreda were obtained from the Office of Agriculture and Rural Development of Kersa in Serbo. Three out of five sites under study, namely Serbo, Beda Buna and Ketim Bile, are situated in Kersa woreda. Agricultural land in Jimma zone has increased from 2009 to 2012, replacing forest and grazing land. The percentage of land covered by forest is higher in Jimma zone than in Kersa woreda, which could be explained by the presence of state forests in other parts of the zone.

**Table 3.1: Land use in Jimma zone for the years 2012 and 2009 as compared to land use in Kersa woreda in 2012**

| **Land use** | **Jimma zone** | | | **Kersa woreda** | |
|---|---|---|---|---|---|
| | Area in 2012 (ha) | Area in 2009 (%) | Area in 2012 (%) | Area in 2012 (ha) | Area 2012 (%) |
| **Agricultural land** | 948,814 | 46 | 52 | 62,693 | 64 |
| **Forestry** | 356,818 | 25 | 19 | 8,809 | 9 |
| **Grazing land** | 164,888 | 12 | 9 | 11,216 | 12 |
| **Urban settlements** | 266,334 | 14 | 15 | 4,830 | 5 |
| **Others** | 85,679 | 3 | 5 | 10,321 | 10 |

### 3.1.4. *Population statistics and land tenure policy*

The most recent population census in 2007 revealed that total population in Jimma zone was 2,486,055 (figure 3.3) and had increased with 27% in comparison to the previous census in 1994. In 2007, 94.5 % of the people lived in rural areas. More than half of the people were less than 18 and the average household size was 5 persons. In rural areas, more than half of the people have never been to school and literacy rates are therefore very low. However, differences between urban and rural population are great (table 3.2). Less than 10 % of the households has access to electricity, while around 50 % has access to a protected water source. The main fuel type used is firewood (88 %), followed by fossil fuels (6 %) and dried dung (4 %). The road density is low, with only one asphalted road between Jimma and Addis Abeba (CSA *et al*., 2006; CSA, 2010).

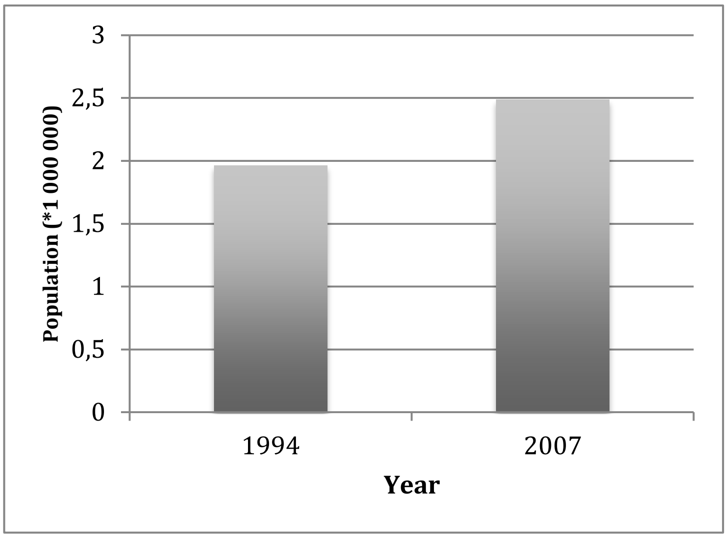

**Figure 3.3: Population in Jimma zone (CSA, 1996; CSA, 2010)**

**Table 3.2: Population, age and literacy in urban and rural areas of Jimma zone (CSA, 2010)**

| | Urban | Rural |
|---|---|---|
| **Population** | 137,668 | 2,348,487 |
| **Children under 18** | 46 % | 55 % |
| **Persons that are literate** | 70 % | 30 % |

Land is state owned in Ethiopia and this is subjected to controversy. Advocates of a liberal land policy state that insecure land tenure fosters unsustainable and inefficient land use because it doesn’t provide incentives for the farmers to invest labour and money in the land. On the other hand, advocates of state ownership argue that privatised land could become concentrated in the hands of a few persons, increasing the inequality and the amount of landless persons. This could increase the population pressure on marginal land and therefore decrease overall sustainability (FAO, 2003; FAO, 2007; Crewett and Korf, 2008).

In the Oromiya region, land tenure security is relatively high because lifelong usufruct rights are accorded to the residents. Though land remains state owned, the perception of tenure security is increased among farmers. By this means, the government of Oromiya tries to increase investments and sustainable management practices among farmers without increasing the risk of inequity. The government can, however, still expropriate land in certain conditions. As farmers are often unaware of this possibility, tensions are likely to arise when expropriation occurs (Kidanu, 2004; Crewett and Korf, 2008).

## *3.2. Qualitative assessment of land use dynamics*

### *3.2.1. Objectives and methodology*

The objective of this thesis is not to reveal the spatio-temporal patterns of land use changes on the Planosols in the catchment, as this would require the comparison of high-resolution satellite imagery of at least two different moments in time, combined with ground truthing (e.g. Reid *et al*., 2000). On the contrary, land use changes are assessed in a mere qualitative way in order to acquire a more comprehensive insight in the land use dynamics of the region. It is believed that a better understanding of these dynamics will increase the quality and reliability of the evaluation of different (potential) land uses in a region.

Qualitative information regarding current land uses on the Planosols and recent changes has been obtained using three complementary approaches. First, field observations and transect walks allowed to identify the different land uses and management techniques. Subsequently, interviews of farmers and of experts provided extra information regarding previous land uses, drivers for adopting the current uses and management techniques. Finally, recent land use changes have been visualized with Google Earth satellite images of 2012 and 2003. The use of three different sources of information makes it possible to obtain a reliable overview of the recent land use changes at the sites under investigation. Though not the entire catchment is covered by this means, it allows the identification of at least some patterns in the land use dynamics on the Planosols in that region.

Assumptions on the potential driving forces have been formulated after inspection of different sources of information. It has been taken into account that the importance of different driving forces varies depending on the scale of assessment (Verburg *et al*., 2004). The interviews of farmers have allowed to identify potential driving forces at local level, while data from the Central Statistical Agency have been used to find potential driving forces at catchment level. A distinction has been made between, on the one hand, the effects of policies and development projects that do not directly drive changes, but create an environment suitable for changes, and on the other hand, socio-economic drivers that provide a more direct incentive for land use change (Kamara *et al*., 2004). The driving forces are mere hypotheses that should be further investigated before formulating valid conclusions.

### *3.2.2. Transect walks*

The transect walks have been carried out across several valleys with Planosols in Serbo, Borè, Beda Buna, Dimtu and Ketim Bile (figure 3.1). Up to 103 different points around the catchment have been described and recorded. Special attention has been given to the position in the landscape and the slope, the soil type, the land use and possible problems like overgrazing or erosion. The soil type was identified visually using an auger, while the slope was measured with a clinometer and the location recorded with a GPS (UTM 37N coordinates). A visual characterisation of the soil type by augering the upper horizon was possible because of the clear difference in colour between the Planosols, Vertisols and Nitisols in the catchment (Dumon, 2010). When necessary, farmers in the fields have been asked additional information about specific observations. Some vegetation samples and pictures of the land use have been taken as well.

### *3.2.3. Interviews*

Based on the findings of the transect walks, farmers have been interviewed in the vicinity of three of the five inspected sites, namely Serbo, Borè and Beda Buna. In order to cover the variability in geographical location and management practices, farmers were approached at random on their fields or in the villages. Only those farmers who said they cultivated or exploited the Planosols (defined as 'white soils') were retained for further interview. As such, 22 farmers have been interviewed in a systematic way, as described in the next paragraph. Though not purposely, only men have been interviewed, which makes gender comparison impossible.

The interviews have been conducted by means of the questionnaire given in appendix 1a. The questionnaire comprises three different parts. The first part inquires about general information regarding the household, area cultivated, crops grown and animals owned. The second part focuses on specific questions regarding the land uses mentioned in the first part. Only the questions relevant for these land uses were asked. This part covers questions about the management techniques and micro-economic factors like the costs of the inputs and prices of the outputs. Some questions also inquire whether the farmers discern specific problems or trends. The last part of the questionnaire gives special attention to the working schedule in order to gather monthly information about the management practices. The questionnaire has been designed in such a way that similar information is asked in different ways and at different times. This technique is called triangulation and makes it possible to discern doubtful answers and directly confront the farmers with contradictions. When possible, farmers were asked to show their fields and describe the management of those specific fields. Though this sometimes caused the interviews to take a long time, it significantly increased the accuracy of the information obtained.

Two experts in the Agricultural Office of Kersa in Serbo have also been interviewed to know their opinion regarding the general trends in land use, the socio-economic situation of the farmers and the agricultural policy of the government. The questionnaire of these interviews is given in appendix 1b. The experts have also been asked to comment on some of the problems mentioned by the farmers in previous interviews. By this means some extra information was obtained on land use, livestock, land tenure policy, forest management and problems in the region.

### 3.2.4. Comparison of Google Earth images

Images obtained from Google Earth have been used to, on the one hand, validate the field observations, and on the other hand, compare current land uses with land uses in the recent past. Images of Borè, Beda Buna and Serbo have been inspected for the available years from 2002 till 2013 (Google Earth, 2013). Coordinates and descriptions obtained during the transect walks have allowed to identify different land uses.

## 3.3. Physico-chemical soil quality assessment

### 3.3.1. Soil sampling strategy

As the general physico-chemical characteristics of the Planosols in the Gilgel-Gibe catchment have been analysed in the past (Van Ranst *et al*., 2011), the purpose of current soil sampling was to reveal the impact of different soil uses and management techniques on the soil quality. In particular, sampling was conducted to investigate the chemical and physical properties of the soils subjected to guie and under eucalyptus. Therefore, mixed soil samples, core rings and Kubiëna boxes of soils under different land uses in the region have been taken. An overview of the sampling locations and corresponding land use and management is given in table 3.3.

Twenty composite samples have been taken of the upper 30 cm of the soil, comprising soils under grassland, agriculture and eucalyptus trees. The soil samples under eucalyptus comprise soils affected by guie this year and 1, 2, 3, 5, 8 and 10 years ago. In order to minimize the effect of microvariability, the composite soil samples consist of two separate samples taken at a distance of about one meter and mixed together in the same plastic bag. To preserve the natural condition of the aggregates, no soil samples have been taken when the soil was too wet (Le Bissonnais, 1996). Under eucalyptus plantations care was taken to always sample at a similar distance of the trees so that the distance from the stem could not influence the results. Each sampling location has been recorded with a GPS (UTM 37N coordinates) and the topography, vegetation and surroundings were described. Also a picture of the sampling location has been taken in the most cases.

Ten core rings have been taken of the upper soil horizon of 5 plots under different land uses to assess the physical characteristics of the undisturbed soil. Before sampling, grasses and litter layer was systematically removed with a knife in order to avoid excessive presence of roots. Care was taken not to close the pores or compact the soil while sampling (figure 3.4). The core rings were covered with plastic lids in order to prevent them from drying out. Each time, two core rings have been taken at the same location in order to obtain representative results, not affected by a potential microvariability.

Four Kubiëna boxes (front side is 6 by 9 cm) have been used to sample soils affected by the guie practice. Two boxes were taken of the upper and the lower part of a guie heap (figure 3.5 for the upper part). Another undisturbed and oriented sample was taken with a Kubiëna box in a field recently subjected to guie, while a last one was taken of a topsoil under eucalyptus that had been guied ten years ago. Before sampling, a small, vertical profile was made and a picture of that profile was taken. Next, the Kubiëna box was inserted in the profile and carefully removed with a knife.

**Figure 3.4: Sampling an eucalyptus seedbed after guie in Serbo**

**Figure 3.5: Kubiëna box in the top of a guie heap in Serbo**

**Table 3.3: Geographical location, altitude and land use of the sampled sites, together with the type of samples taken. Four groups are defined, based on the soil use: (1) 'GY: the soils that have recently been under guie'; (2) 'GO: the soils that have under guie a longer time ago'; (3) 'PL*: the Planosols that have not been affected by guie'; and (4) 'VE: the Vertisols'. One outlier in the group of unaffected Planosols (12/812) has not been included in the group PL***

| Sample number | Location | Coordinates (UTM 37N) | Alt (m) | Samples | Description soil use | Group |
|---|---|---|---|---|---|---|
| **12/795** | Serbo | E 02 75 880<br>N 08 52 324 | 1787 | Bulk sample<br>Kubiena box (2) | Recent guie hill | GY |
| **12/796** | Serbo | E 02 75 880<br>N 08 52 324 | 1787 | Bulk sample<br>Core rings (2) | Recently spread out guie (eucalyptus tree seedbed) | GY |
| **12/797** | Borè | E 02 611 05<br>N 08 430 03 | 1732 | Bulk sample<br>Kubiena box | Guie (1 year ago) on field for teff | GY |
| **12/798** | Ketim Bile | E 02 823 67<br>N 08 525 53 | 1773 | Bulk sample<br>Core rings (2) | Recently spread out guie (eucalyptus tree seedbed) | GY |
| **12/799** | Borè | E 026 17 16<br>N 084 16 85 | 1724 | Bulk samlpe | Guie (1-2 years ago) for eucalyptus | GY |
| **12/800** | Serbo | E 02 75 975<br>N 08 52 054 | 1792 | Bulk sample | Guie (1-2 years ago) for eucalyptus | GY |
| **12/801** | Ketim Bile | E 02 823 65<br>N 08 525 50 | 1775 | Bulk sample | Guie (1-2 years ago) for taro | GY |
| **12/802** | Ketim Bile | E 02 829 18<br>N 08 526 73 | 1745 | Bulk sample | Guie (3 years ago) for teff | GO |
| **12/803** | Serbo | E 02 760 65<br>N 08 521 04 | 1792 | Bulk sample<br>Core rings (2) | Guie (around 5 years ago) for eucalyptus. Old hill discernable. | GO |
| **12/804(A)** | Borè | E 02 610 22<br>N 08 431 10 | 1733 | Bulk sample<br>Core ring<br>Kubiena box | Guie (10 years ago) for eucalyptus | GO |
| **12/804(B)** | Borè | E 02 610 22<br>N 08 431 10<br>(same as previous) | 1733 | Bulk sample | Guie (10 years ago) for eucalyptus | GO |
| **12/804(C)** | Dimtu | E 03 07 561<br>N 08 70 998 | 1752 | Bulk sample | Guie (8 years ago) for eucalyptus | GO |
| **12/805** | Serbo | E 02 75 929<br>N 08 52 437 | 1787 | Bulk sample | Soil excavated for walls | VE |
| **12/806** | Serbo | E 02 75 881<br>N 08 52 335 | 1788 | Bulk sample | Planosol under grazing | PL* |
| **12/807** | Borè | E 02 611 02<br>N 08 430 01 | 1732 | Bulk sample | Planosol under grazing | PL* |
| **12/808** | Borè | E 02 612 26<br>N 08 427 60 | 1724 | Bulk sample | Soil excavated for brick making | VE |
| **12/809** | Borè | E 02 612 14<br>N 08 417 86 | 1725 | Bulk sample | Eucalyptus (around 10 years old), no signs of | PL* |
| **12/810** | Beda Buna | E 02 673 70<br>N 08 486 76 | 1818 | Bulk sample | Planosol under grass between sites with brick making | PL* |
| **12/811** | Beda Buna | E 02 673 72<br>N 08 486 76 | 1818 | Bulk sample<br>Core rings (2) | Soil excavated for brick making | VE |
| **12/812** | Beda Buna | E 02 680 80<br>N 08 492 89 | 1809 | Bulk sample<br>Core ring | Ploughed field for teff on Planosol | PL |

### 3.3.2. *Soil chemical analyses*

Routine analyses have been performed on the fine earth fraction (< 2 mm) of all the mixed soil samples to determine the acidity, organic carbon (OC) content, total nitrogen (N) content, CEC, exchangeable basic cations, exchangeable acidity and aluminium. A charge fingerprint has also been determined for four selected samples. The analyses have been carried out in the Laboratory of Soil Science, Ghent University. The analytical methods used are described in the 'Manual for the Soil Chemistry and Fertility Laboratory' (Van Ranst *et al.,* 1999) and in 'Procedures for soil analysis' (Van Reeuwijk, 2002).

**Acidity**

The pH was measured both in $H_2O$ and 1M KCl. Mixtures with a ratio of 1:2.5 were allowed to equilibrate for more than two hours, after which pH was measured with a pH meter.

**Organic carbon**

The soil organic carbon was determined with the method of Walkley and Black (Walkley and Black, 1934). The organic carbon was first totally oxidized with 1N $K_2Cr_2O_7$ in the presence of sulfuric acid (96%). Then automatic back titration with ferrous sulphate was used to measure the amount of excessive chromate. A comparison with blanks allowed calculating how much chromate had reacted with organic matter and thus, how much organic matter was present in the samples.

**Total nitrogen**

Total nitrogen was determined by first mineralizing the nitrogen with sulphuric acid ($H_2SO_4$) in bloc digesters, followed by steam distillation and titration. Catalysers, like copper sulphate and selenium, were added to accelerate the mineralization. Next, NaOH was added to react with ammonium sulphate that had formed, yielding ammonia. This ammonia was then titrated with hydrochloric acid in an automatic titrator. Also in this case a comparison with blanks was used to calculate the amount of nitrogen in the samples.

**CEC and exchangeable basic cations**

The CEC was determined by first leaching the soil with a 1M ammonium-acetate solution (pH 7). The solution was sucked through the soil by means of a mechanical vacuum extractor (Centurion) during 16h. The leachate was then used to measure the exchangeable cations ($Na^+$, $K^+$, $Ca^{2+}$ and $Mg^{2+}$) in an Inductive Coupled Plasma Atomic Emission Spectrometry (ICP-AES). The leached soil was washed with ethylalcohol to remove the ammonium that was not on the soil complex and then NaCl was added so that $Na^+$ could replace the ammonium. This ammonium was then titrated in a boric acid solution (2%) with 0.05N HCl.

**Exchangeable acidity, exchangeable aluminium and ECEC**

Because pH measurements revealed a low pH, the exchangeable acidity and the exchangeable Al have been determined. The samples were first slowly percolated with a 1M KCl solution. The exchangeable acidity was then determined by titration with 0.025 M NaOH. This exchangeable acidity comprises exchangeable protons and aluminium ions. Because they can be toxic for plants, the exchangeable aluminium ions have been measured separately. The percolate was diluted with a 1:1 ratio and then placed in an ICP-AES and compared with a 0-50 mg/l standard series. Effective CEC is the sum of the exchangeable bases and the exchangeable acidity.

**Charge fingerprint determination**

A charge fingerprint was constructed for the mixed soil samples 12/796, 12/800, 12/803, 12/806 (all from Serbo) in order to look at the long-term changes of guied soil under eucalyptus. From each sample six subsamples of 2 g have first been saturated with $Ca^{2+}$ by adding 20 ml of 0,1 M $CaCl_2$. In order to better reflect field conditions, the ionic strength was then lowered by adding 20 ml of 0,002 M $CaCl_2$ two times. A pH range between 3 and 6,8 was established using a 0,1 M HCl or a saturated $Ca(OH)_2$ solution. After equilibration, first the $pH_0$ was determined as the soil pH at which the pH did not vary with changing ionic strength.  Then the ionic strength was lowered again and adsorbed Ca, Al and Cl have been determined (Gillman, 2007).

### *3.3.3. Soil physical analyses*

Particle size distribution has been determined for all disturbed soil samples, while aggregate stability has been determined for all samples except 12/795, 12/796 and 12/806. These three samples had been grinded by a lab technician at Jimma University before aggregate stability could be analysed. Bulk density, water content in the field and soil moisture characteristics have been determined on the undisturbed samples. One core ring (12/812) could not be used for pF measurements because the soil shrank too much upon drying during determination of the moisture content in the field. Except for the particle size distribution, which was determined at the Laboratory of Soil Science, Ghent University, all physical analyses have been carried out at the Department of Soil Management, Ghent University.

**Particle size distribution**

The particle size distribution has been analysed by means of the method of sieving and sedimentation (ISO 11277). The sand fraction was determined by wet sieving on a 63 μm sieve after organic matter was removed with $H_2O_2$. The clay and silt fraction was determined with the pipette method of Robinson-Köhn after dispersion of the colloidal fraction with sodiumpolyphosphate.

**Aggregate stability**

The aggregate stability of the soil has been determined in order to investigate the risks for crust formation and erosion. Soil sample aggregates with a diameter between 3 and 5 mm have been subjected to the three tests proposed by Le Bissonnais and Le Souder (Le Bissonnais and Le Souder, 1995). These tests have been designed to reflect the stability of aggregates under natural conditions. The first test investigates the effect of rapid wetting by emerging aggregates in deionized water for 10 minutes. The second test investigates the effect of slow wetting by putting aggregates on a filter paper at a matric potential of -0.3 kPa for 30 minutes. The third test looks at the mechanical breakdown of the aggregates by shaking after pre-wetting. To prevent slaking upon wetting during the third test, aggregates are first emerged in ethanol before they are emerged in water. After wetting the aggregates are collected in an Erlenmeyer flask and agitated 20 times. After each test aggregate size distribution and the mean weighted diameter was calculated (Le Bissonnais, 1996).

**Water content in the field and bulk density**

The undisturbed samples that had been taken in the field with core rings have been weighted immediately the day of sampling. They have then been dried in an oven at a temperature of 105°C for 24h and weighted a second time. Later, after determination of the Soil Water Retention Curve (SWRC) in Belgium, the weight and volume of the core rings has been measured and bulk density of the soil samples was determined.

**Soil moisture characteristics**

The same core rings have been used to construct a SWRC, which gives the relation between the soil water content ($\theta$) and the matric potential ($\psi$). As the samples had been dried in Ethiopia they had to be saturated with water again. They were therefore first covered with a nylon cloth and placed in a sandbox. Water level was raised up to half of the height of the core rings and water was allowed to enter by capillary rise. Once saturated, samples were subjected to suction by lowering the water level of the sandboxes. Water content was measured by weighting the samples after stabilization at 5 different suction pressures in the sandboxes, ranging between -1 and -10 kPa. Higher suction pressures were applied in a pressure chamber. Undisturbed subsamples were taken to determine the water content at suctions of -33 and -100 kPa. A disturbed subsample was taken to measure the water content at a suction of -1500 kPa (Cornelis *et al*., 2005).

### *3.3.4. Soil micromorphological analysis*

The undisturbed and oriented samples taken with the Kubiëna boxes have been used to make thin sections. Pictures of these sections have been taken and enlarged to allow a better interpretation. The description and interpretation was based on the concepts proposed by Stoops (2003). Special attention was given to signs of biological activity and the interpretation of the voids in the soil space.

### 3.3.5. Soil quality assessment

The results obtained from the soil analyses have been used to investigate the impact of the guie management practice for eucalyptus seedbed preparation and soil excavation for brick making on the physico-chemical soil characteristics.

In order to facilitate the interpretation, the different soils have been grouped based on information collected during the transect walks and interviews (table 3.3). Four different groups have been formed: (1) 'the soils that have recently been under guie (GY)'; (2) 'the soils that have been burned a longer time ago (GO)'; (3) 'the Planosols that have not been burned (PL*)'; and (4) 'the Vertisols (VE)'. Means and standard deviations of the chemical and physical analyses have been compared for different groups of soils and related to the conditions in the field. The significance of the difference between the means of the four groups has been checked with two-sample t-tests (Rstudio, 2013)

To increase the understanding of the impact of the guie practice for eucalyptus seedbed preparation on the physico-chemical characteristics of the Planosols, an in depth analysis has been performed with a selected number of samples. The short-term effects of the guie practice have been discussed by comparing the physico-chemical soil characteristics of an unguied soil (12/806), a guie heap (12/796) and recently spread out guied soil for eucalyptus seedbed preparation (12/796). In the field these soils are located at less than 10 m distance from each other and are therefore likely to show similar characteristics in unmanaged condition. The long-term effects of the guie practice have been discussed by investigating the evolution of the physico-chemical soil characteristics with time after guie. Charge fingerprints and thin sections have been used to increase the understanding of the processes in the field.

## 3.4. Suitability assessment of land uses and management practices

### 3.4.1. Analysis of climatic data

Daily climatic data from the Jimma meteorological station (1981 – 2005) have been analysed to find trends, year-to-year and within-year variability and to calculate the reference evapotranspiration (ETo).

The daily data have been merged to decadal sums or averages (depending on the variable) and the amount of days per decade with a precipitation > 0 have been counted. These decadal data were then compared across the years to find trends. Averages and standard deviations have been calculated. As the variability of the precipitation was high, also the dependable rainfall (with 80% chance of exceeding) has been calculated with the decadal values.

The ETo has been calculated with the decadal maximum and minimum temperatures, wind speed, hours of sunshine and precipitation. Because no data were available on relative humidity or vapour pressure deficit, the dewpoint temperature was assumed to be close to the daily minimum temperature during the rainy season. This assumption will probably not be valid during the dry season. ETo (average over 25 years) and dependable rainfall (calculated from 25 years) have been used to define the growing period. This growing period was then compared with the growing period according to the farmers (FAO, 1979; Allen *et al*., 1998; FAO, 2009).

### 3.4.2. *The guie practice for eucalyptus seedbed preparation*

As the guie practice only affects the upper cm of topsoil and as its effects on chemical soil fertility are reported to last for maximum two years, only its effects on the establishment of eucalyptus seedlings has been evaluated.

The suitability for eucalyptus seedlings has been compared for guied Planosols, unguied Planosols and Vertisols with the maximum limitation method. More precise evaluation methods exist, but the maximum limitation method is not sensitive to interactions between land qualities, which is an advantage when comparing land qualities derived from the same parameters (Sys *et al*., 1991a).

The different land qualities under investigation, the land characteristics related to these qualities and the land use requirements (LUR) of eucalyptus are given in table 3.4. As no full requirement table for *Eucalyptus globulus* spp. has been found, several separate sources were used. Except for precipitation, climatological parameters have not been incorporated into the analysis because they are not affected by the management practice applied. Though the different requirements of eucalyptus obtained by this way have never been validated for the site under study, they can be used to qualitatively compare different management practices in the region.

**Table 3.4: Measured land characteristics and related land use requirements of eucalyptus seedlings**

| Land quality | Measured land characteristics | LUR of eucalyptus | Source |
|---|---|---|---|
| **Moisture availability** | Precipitation, flooding, texture, soil moisture characteristics | Length of effective growing period increases with longer availability of water. First year after planting is most important for establishment. | Pohjonen and Pukkala (1990); Pohjonen and Pukkala (1991) |
| **Oxygen availability/ drainage** | Texture, soil moisture characteristics, porosity | Productivity increases for increasing drainage | Castro *et al*. (2010); Laffan (1994); Laffan (2000) |
| **Availability of foothold for roots** | Depth of bleached layer | Optimal rooting depth is > 0.80 m, heavy clays or stones in subsoil decrease productivity | Laffan (1994) |
| **Nutrient availability** | ECEC, OC, Total N, Basic cations, pH | Nutrients important for good growth, fertilization of seedlings recommended soon after planting | Laffan (2000) |
| **Resistance to structural degradation** | OC, aggregate stability, topography | Structural stability of the soil important for roots and to avoid slaking and erosion | Le Bissonnais and Le Souder (1995) |

### *3.4.3. The potential for rice cultivation after soil excavation*

The potential for upland rice cultivation in the catchment has been evaluated in a qualitative way because this crop is gaining importance in Ethiopia and because a field experiment has been conducted for upland rice in the catchment.

A parametric evaluation has been performed with the land characteristics obtained for the Planosols in the catchment. It was assumed that rice was planted in the first decade of the growing period (based on rainfall with 80 % chance of exceeding) and harvested after 120 days, which is the length of the growth cycle of rice according to Sys (1991b). The averages of the Planosols not affected by Guie (group PL*) and of the Vertisols (group VE) have been used for the evaluation of the soil characteristics. ACEC of the clays was calculated with a correction for the contribution of organic matter (Klamt and Sombroek, 1988; Batjes, 2002).

The tables given in appendix 2a were used to rate the suitability of different land characteristics for upland rice production (Sys, 1993). The table given in appendix 2b has been used to give a better interpretation of the results obtained with the tables from appendix 2a (Sys, 1991b). The overall rating was calculated according to the square root method (Sys, 1991a).

As no climatic data were available for the year of the crop growth experiment, the land evaluation could not be performed for that specific year. However, the land evaluation performed in this thesis is useful to give a general evaluation of the potential for upland rice cultivation in the catchment. Together with average retail prices obtained from the Central Statistical Authority, the results from the land evaluation are used to discuss the relevance of research on rice production in the catchment.

## *3.5. Overview of the land use dynamics with the DPSIR framework*

As explained in the previous chapters, this thesis describes the land use changes and driving forces on the Planosols, the state of the soil after application of the guie practice for eucalyptus growth and the potential for rice cultivation after soil excavation. In the discussion this information is categorized with the DPSIR framework to give a good overview of some of the land use dynamics in the catchment. The objective is not to define cause-effect relations or to propose a model for further research, but to structure the information obtained in the previous chapters.

The DPSIR framework was originally designed by the European Environmental Agency (EEA) as a method for integrated environmental assessment, but will be used here to structure the information concerning the land use changes on the Planosols in the catchment. The ‘Drivers’ are the human or natural determinants that induce changes on the Planosols, while the ‘Pressures’ describe the pressures on the current land use. The ‘State’ describes the properties and characteristics of the land and the ‘Impact’ relates the state of the land to the socio-economic environment and sustainability. The ‘Responses’ are the potential and actual responses to the changes of both the farmers as the local authorities.

The structure of the DPSIR framework, describing responses of the society to cope with changes in the environment, can sometimes promote a conservationist approach to the changes, because it implicitly suggests that the changes are undesirable (Svarstad *et al*., 2008). As the land use changes described in this thesis are, however, not perceived as undesirable per se, this conservationist point of view is avoided by suggesting responses that do not aim to prevent the changes. The suggested responses rather aim to decrease the costs and increase the benefits of those changes.

# 4. Results

## 4.1. Current land uses

Land use on Planosols in the catchment can be categorized into four broad classes: communal grazing land, cropland, eucalyptus plantations and soil excavation. Though these four land uses are found at all the study sites, their relative areal extent differs from site to site. This is illustrated in table 4.1, together with a description of the topography (slope gradient classes according to FAO (2006)). Grazing land is important at all the sites except in Ketim Bile, where cropland is most important. Cropland is important in both Dimtu and Ketim Bile, while eucalyptus cultivation is present at all sites, but seems most important in Serbo and Borè. Though soil excavation for plastering of walls can be seen everywhere, large-scale excavation for brick making is only present in Borè and Beda Buna.

**Table 4.1: Relative importance of land uses on the Planosols at the study sites (based on visual estimation of their areal extent during the transect walks)**

| Name | Slope gradient classes | Grazing land | Cropland | Eucalyptus | Excavation |
|---|---|---|---|---|---|
| **Serbo** | Nearly level | Very high | Low | High | Average |
| **Borè** | Very gentle slope | Very high | Low | High | High |
| **Beda Buna** | Nearly level | High | High | High | Very high |
| **Dimtu** | Gentle slope | Very high | High | Average | Low |
| **Ketim Bile** | Nearly level | Average | Very high | Low | Low |

An overview of the different land uses along a transect through the valley at Borè is given in figure 4.1. The crop in the alluvial plain is seriously waterlogged maize, while that on the colluvium at the upland border of Planosols with Nitisols is teff.

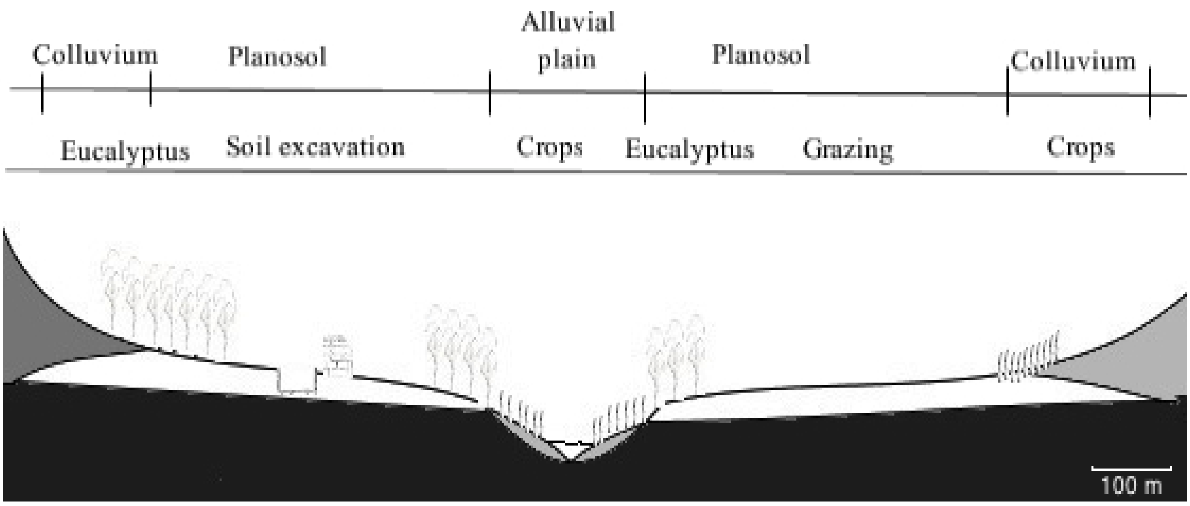


**Figure 4.1: Soils and land use along a North-South transect in Borè**

### 4.1.1. *Grazing and crop production*

A large part of the Planosols is under grazing land, of which the majority is communal. This implies that, during the rainy season, cattle of all households in the village graze on this land. During the rainy season, the grazing lands are commonly waterlogged and show signs of overgrazing or nutrient depletion (ground cover of grasses is low and grass is greener around cow dungs). At places with a lot of passage the grass also suffers from excessive trampling. Some smaller patches of grazing land are not under communal use, but are owned by families. This applies for only a marginal part of the grasslands and has therefore not been further investigated.

Most households own cattle because this has several important advantages (table 4.2). Bulls or oxen are important for traction, while cows produce milk and calves and can be sold when the household needs money. As cattle graze on communal land in the rainy season and survive on straw during the dry season, the major cost for owning cattle is their purchase.

**Table 4.2: Average stock of cattle per household and prices per animal, as reported by 18 farmers (exchange rate was 24 Birr/Euro)**

| | Average | St. Dev. |
|---|---|---|
| **Cows (amount/household)** | 4 | 2.5 |
| **Price when fat (Birr/animal)** | 1567 | 413 |
| **Bulls/oxen (amount/household)** | 2.5 | 1.5 |
| **Price when fat (Birr/animal)** | 4218 | 783 |

In Dimtu and Ketimbile large extents of the Planosols are under crop production. In Dimtu some fields are under shifting cultivation with a very short cycle of two years of fallow for every 4 years of cultivation. Yields are low, however, and gully erosion deep into the vertic horizon is common. Farmers in these villages state that, despite the low yields, cultivation is necessary because of a lack of agricultural land. Shortage of land is not a recent phenomenon in Dimtu, because it already started under the previous regime (more than 20 years ago) as a result of an increasing population pressure. Farmers attribute this increase to a high birth rate in the region, rather than to immigration. Most households have agricultural fields on both Planosols and Nitisols and are thus not solely dependent on the Planosols.

Crops grown on the Planosols are maize, teff, sorghum, taro or finger millet. When a field is brought into cultivation for the first time after several years of grazing, the guie technique is applied during the dry period. Farmers say that this is necessary to kill weeds and create a good soil condition. In the first years after guie, teff or taro is usually grown. When after two years of cultivation yields start to decline, another crop is sown.

Most farmers make use of di-ammonium phosphate (DAP) and urea to fertilise their soils. However, no urea is applied on teff plots because this causes lodging. Some farmers don’t use fertilisers on cultivated Planosols because fertilizers are considered too expensive for the low yields obtained. One farmer mentioned the use of glyphosate to kill weeds and grasses. The prices of fertilisers, as reported by five farmers, are given in table 4.3. Farmers have also been asked information about the amount of fertilizers applied and the yields obtained per ha, but answers were not reliable. Field size reported during the interviews often strongly differed from observations afterwards and farmers could not easily make a distinction between Planosols and Nitisols regarding the yields and amount of fertilizers applied. For teff, yields as low as 400 kg/ha are probably the rule on Planosols.

**Table 4.3: Average prices of fertilizers, as reported by five farmers**

| | Average price | St. Dev. |
|---|---|---|
| **DAP (Birr/kg)** | 16 | 0.4 |
| **Urea (Birr/kg)** | 12 | 3 |

### *4.1.2. Seedbed preparation and plot design for eucalyptus*

Eucalyptus is often planted on the better-drained Planosols, sometimes on red colluvium at the foot of the hills. Commonly the trees are planted on embankments along trenches that could function for drainage during rainy season and for water conservation during dry periods. In Serbo, trenches are up to 1 m large and 30 cm deep. By this means, plots with dimensions up to 900 $m^2$ are surrounded by trenches and embankments with eucalyptus (figure 4.2). The inner surface of these plots can be planted with eucalyptus as well or can be left as grazing land. Farmers report that planting rows of eucalyptus reduces the waterlogging of the soils.

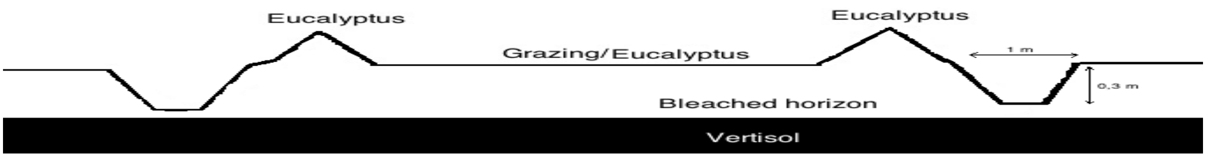


**Figure 4.2: Simplified representation of standard design of eucalyptus plots on Planosols (transect)**

Eucalyptus trees are not directly planted on these embankments, but are first raised on special seedbeds that are prepared with the guie technique. This is necessary for the establishment of the trees. The seedbeds are prepared on fallow land surrounded by trenches and sometimes bordered by older eucalyptus trees. The plot is first ploughed several times with a maresha plough and the upper cm of the soil are used to make heaps with a diameter and a height of 1 m and 0.3 m respectively. These heaps are set afire in the beginning of May. After one week, the heaps are spread out on a small part of the plot in a layer of less than 5 cm thick and eucalyptus seeds are sown. At the start of the rainy season of the next year, part of the eucalyptus trees are transplanted to the rest of the plot. The layout of such a plot for the nursery of eucalyptus in Serbo is illustrated in figure 4.3.

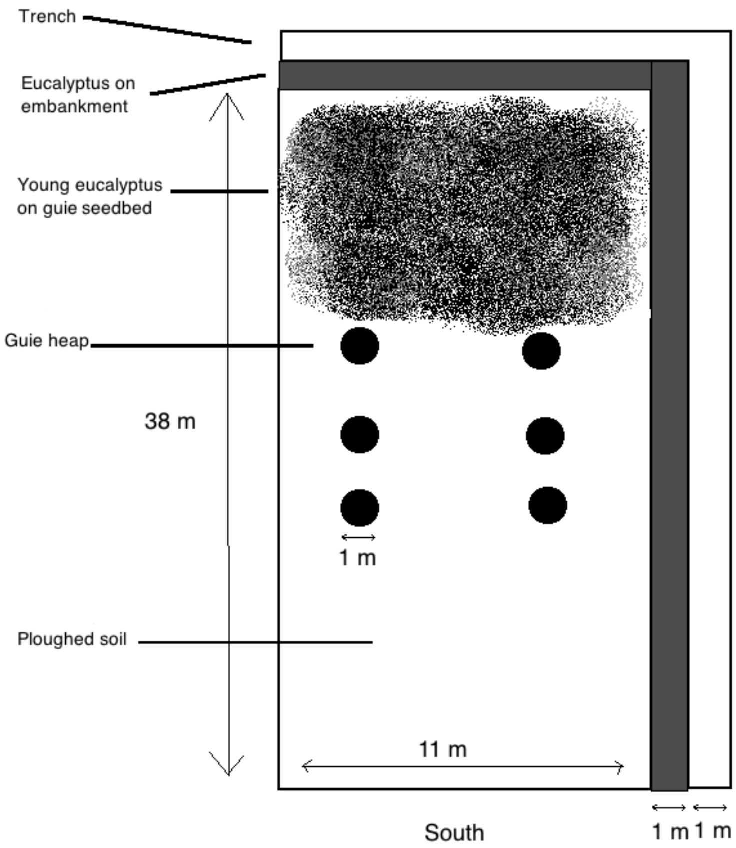


**Figure 4.3: Layout of a plot with eucalyptus nursery in Serbo (top view)**

Figure 4.4 shows a photograph of a section through the centre of a guie hill. A clear zonation of a burnt, carbonized, heated and cover layer, as described in Pulschen and Koch (1990), is not present. Figure 4.5 shows a seedbed with young eucalyptus plants on soil that was spread out after guie.

**Figure 4.5: Vertical section of a guie hill**

**Figure 4.4: Seedbed with young eucalyptus trees**

Tree density in these seedbeds is originally high, but most trees are transplanted after one year. In young stands of a few years tree density varies, but is about 2.5 trees/$m^2$. Older stands have a lower tree density, about 1 tree/$m^2$. Farmers harvest the trees a first time after 5 years, after which coppicing makes harvesting possible every 3 years. They believe coppicing can go on forever without replanting young trees. Selling prices for small and large trees have been obtained from six farmers (table 4.4). These prices are indicative, as they depend on the effective size of the trees and the bargaining at the moment of selling. Agricultural experts at the office in Serbo reported a tree density of 1.2 trees/$m^2$ and prices of 25 birr for trees with a diameter of 20 cm. However, not many trees with such diameter have been seen in the field.

**Table 4.4: Average selling price for eucalyptus trees, as reported by 6 farmers**

| | Average price | St. Dev |
|---|---|---|
| **Small tree, around 3 years old (Birr/tree)** | 6 | 4.7 |
| **Large tree, around 5 years old or more if first harvest (Birr/tree)** | 12 | 8.6 |

Eucalyptus nurseries and plantations have recently been significantly expanding into the communal grazing land. According to experts in the agricultural office in Serbo, an unwritten rule says that whoever drains and tiles a plot on the Planosols has the right to harvest and sell the yields. They say that the high demand for wood for burning and construction works fosters the conversion of communal grazing land into woodlots. Though the authorities allow this conversion because it implies an intensification of soil use, they promote the planting of cypress instead of eucalyptus, because it yields better wood quality and doesn't degrade the soil. One plot with cypresses has been found on colluvium on the border of the Planosols. The owner of this plot said one cypress with a diameter of 25 cm valued more than 400 birr.

### *4.1.3. Brick making: impact on the soil and crop yields*

While informal excavation of the Planosols for the plastering of walls has been going on for a long time already, intensive excavation for brick making is a relatively recent phenomenon, which is now regulated by the authorities. Groups of ten persons have to apply for permissions at the district office for micro-enterprises before a piece of land ranging from 400 $m^2$ to 1 ha is attributed to them. As long as the excavation is ongoing, this land is owned by the micro-enterprise. In theory, after excavation, pits have to be refilled and the land returns to the community, but in practice, pits are partially refilled with broken bricks and are then left as such.

The bleached layer is excavated up to a few cm above the vertic horizon. Farmers avoid using the last cm, which are mottled and sometimes have nodular concretions. Pits formed have a depth of approximately 30 cm and diameters ranging from 3 to 15 m. These pits are filled with stagnating water during the rainy season. Farmers complain about a bad smell and say that only donkeys can graze on the vegetation growing in the pits. If the pits are located on a slope allowing water to flow, the remaining bleached layer is removed by sheet wash and gully erosion occurs.

Workers report that the production of bricks is a high yielding activity. One farmer (which is also teacher in a nearby school) said that a plot of land could give a similar return whether used for brick making or for eucalyptus. The difference, he said, is that brick making directly yields an extra income, while eucalyptus only starts to yield an income after several years. An overview of the costs and benefits of brick making, based on 4 different interviews, is given in table 4.5. One micro-enterprise can bake about 3 mounds of 33,000 bricks each year. If an average volume of 1,650 $cm^3$ of excavated soil is assumed to be required for every brick (Vandemeulebroeke, 2012) and an average excavation depth of 30 cm is taken, the amount of bricks per ha can be calculated. As around 70% of the bricks do not break, up to 1.3 million bricks can be made from one ha, yielding 0.9 million Birr for ten persons in 18 years. This results in 5,000 Birr per person per year (without taking into account taxes and other extra costs).

**Table 4.5: Costs and gains of brick making and yearly gains for micro-enterprise of ten persons, as reported by 4 different workers (exchange rate is 24 Birr/Euro)**

| | **Average** | **St. Dev.** |
|---|---|---|
| **Cost of wood for baking (Birr/brick)** | 0.3 | 0.04 |
| **Selling price (Birr/brick)** | 0.7 | 0.3 |
| **Amount before baking (bricks/year)** | 100,000 | 8,660 |
| **Amount not broken during baking (bricks/year)** | 70,000 | 7,500 |
| **Total yield for micro-enterprise (Birr/year)** | 28,000 | |

### *4.1.4. The farmers' calendar of activities*

Timing of the alternative farmers' activities on the Planosols has been summarized in a calendar of activities in figure 4.6. This calendar doesn't represent the different activities of one household, but gives an overview of the distribution of different possible activities throughout the year. The variability among farmers regarding the precise start and end dates for the different activities is illustrated with the brackets in the figure.

The difference in sowing dates between teff on Planosols and maize on Nitisols is striking. Farmers start sowing their crops much earlier on the Nitisols than on the Planosols. This is related to the waterlogging of the Planosols during the rainy season and the tendency of teff to lodge when soils are waterlogged during maturation phase. On the contrary, eucalyptus seeds are sown on the Planosols, around the same period as the sowing of crops on the Nitisols.

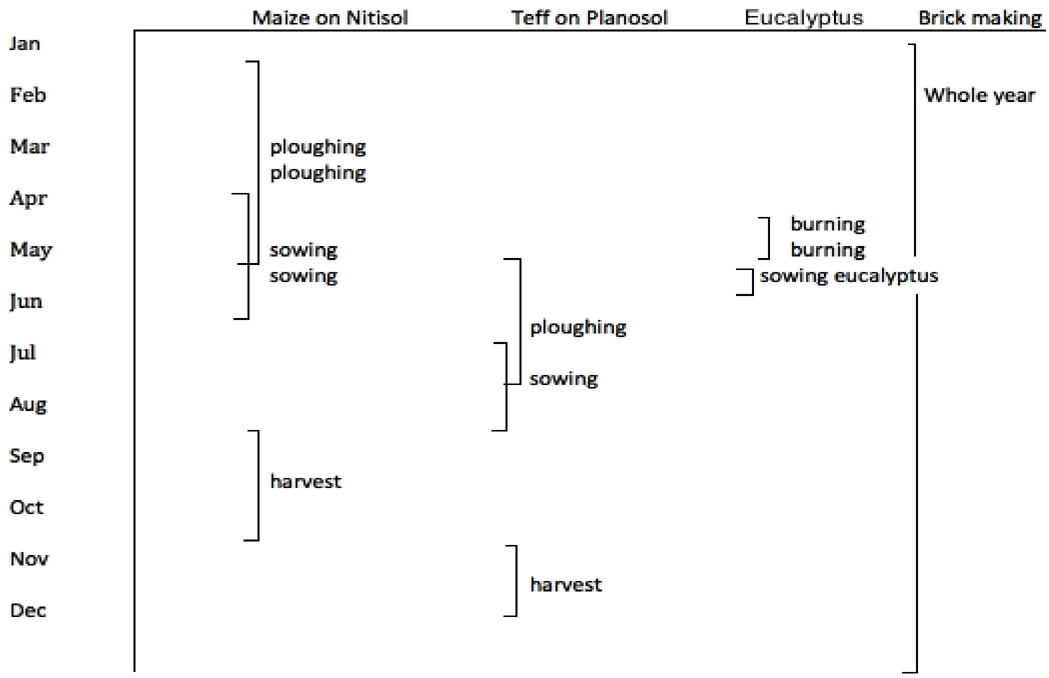


**Figure 4.6: Timing of different land use activities in the Gilgel Gibe catchment, obtained from the interview of 22 farmers**

## *4.2. Recent land use changes*

When comparing satellite images from 2003 with images from 2011 or 2012 it becomes clear that some land uses on the Planosols are recent. Satellite images from 2003 and 2012 are compared for the southern and the northern side of the valley in Borè in figures 4.7 and 4.8 respectively. Both figures visualise the very recent development of settlements along the road. In the southern part of the valley (figure 4.7), the development of Eucalyptus plots is visible, whereas the most recent image of the northern part of the valley (figure 4.8) reveals the excavation of Planosols for brick making and some new fields for crop production.


**Figure 4.7: Google Earth images of the southern part of the valley in Borè (2003 left and 2012 right), showing recent development of settlements and eucalyptus plots (Google Earth, 2013a)**

**Figure 4.8: Google Earth images of the northern part of the valley in Borè (2003 left and 2012 right), showing recent development of settlements and soil excavation for brick making (Google Earth, 2013b)**

Satellite images of Beda Buna for 2002 and 2013 are given in figure 4.9. While brick making activities are barely visible in 2002, they have taken large amplitude in 2013. This brick making has increased the trampling in some places and new mud roads have been formed. Also some new fields for crop cultivation are visible in the lower part of the picture for 2013.

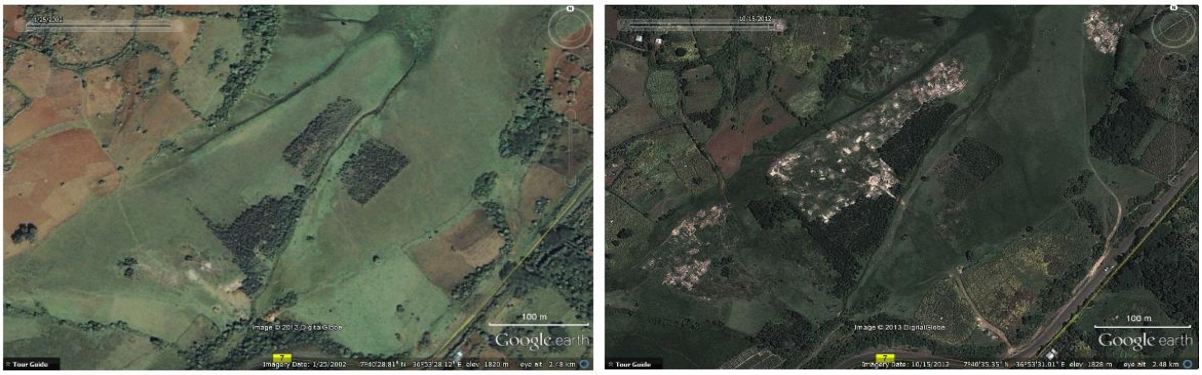

**Figure 4.9: Google Earth images of Beda Buna (2002 left and 2013 right), showing recent development of soil excavation for brick making (Google Earth, 2013c)**

For Serbo only satellite images from 2011 are available on Google Earth (figure 4.10), so no comparison with older images is possible. It is, however, possible to recognize the pattern of plots surrounded by eucalyptus trees as previously described. Recent field observations confirm that the number of plots has increased even more during the past year.


**Figure 4.10: Pattern of eucalyptus plots in Serbo (2011): eucalyptus trees on embankments along trenches surround plots of grazing land (Google Earth, 2013d)**

## *4.3. Physico-chemical quality of Planosols and Vertisols*

An overview of all analytical data is given in appendix 3. The chemical and physical soil characteristics are summarized for the different soil groups in table 4.6 and 4.7 respectively. Some physico-chemical soil characteristics of recently guied soils in Serbo are given in table 4.8.

### *4.3.1. Particle size distribution*

The texture of the different soils is represented in the textural triangle in figure 4.11. The sand content (2 mm - 63 µm) is very low in all soils. The major differences between the soils relate to the silt (63 - 2 µm) and clay (< 2 µm) content. The recently guied soils have higher silt content (on average 78 %) than the Planosols that have never been under guie (on average 69 %). These differences are significant (p-value < 0.05), but disappear for soils that have been guied a longer time ago (p-value > 0.05). The Vertisols have a clay content (on average 60 %) that is significantly higher than that of the Planosols.

One Planosol (12/812) has a very high clay content (64 %) as compared to the other Planosols, similar to the clay content of the Vertisols. As this soil is from a ploughed field, its clay content is probably resulting from admixure of the vertic material with the bleached layer. As other characteristics of soil 12/812 (e.g. CEC) also differ from the other Planosols, this soil has been left out of the further analysis. The group of the Planosols without this soil is referred to as PL*.

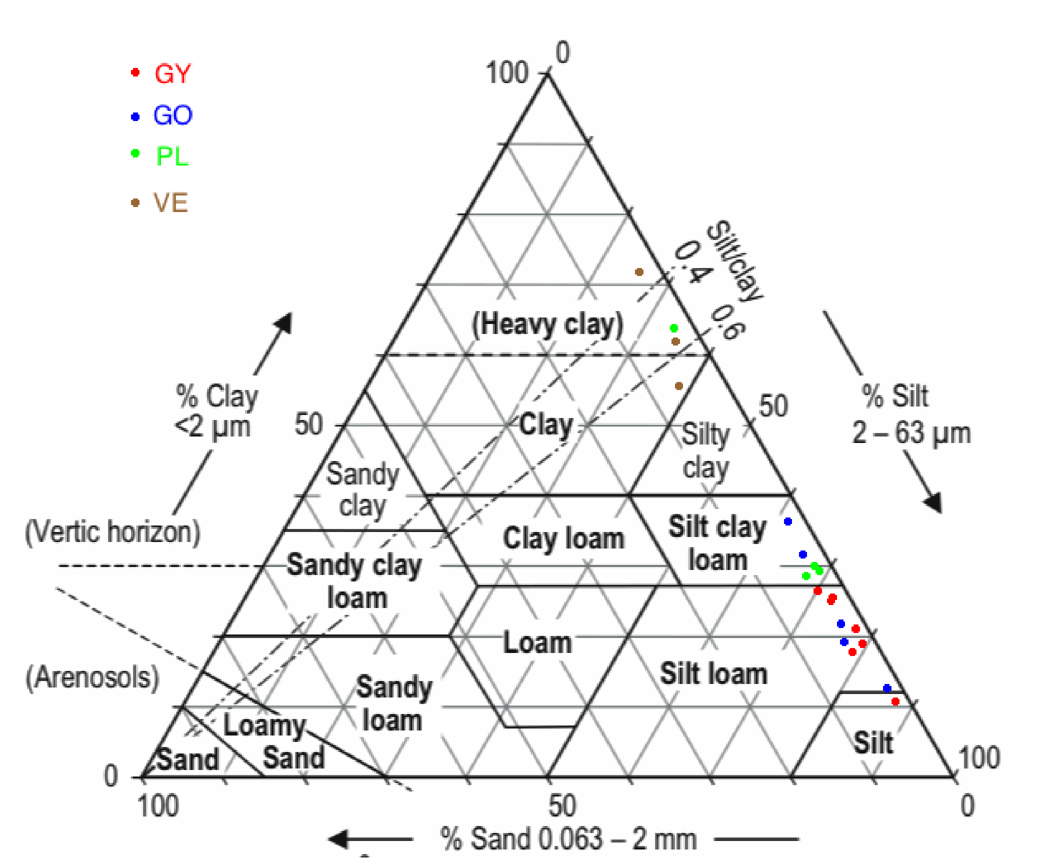


**Figure 4.11: Textural classes of the samples in the FAO textural triangle. Four different colours are used for the different groups: (1) 'GY: the soils that have recently been under guie'; (2) 'GO: the soils that have been burned a longer time ago'; (3) 'PL: the Planosols that have not been burned'; and (4) 'VE: the Vertisols' (adapted from FAO, 2006)**

**Table 4.6: Averages and standard deviations of chemical soil characteristics for the different groups ('GY, the soils that have recently been under guie'; 'GO, the soils that have under guie more than 2 years ago'; 'PL*, the Planosols that have not been affected by guie without outlier 12/812'; and 'VE, the Vertisols'). The second column (n) gives the number of samples in every group**

| | n | pH (H2O) | pH (KCl) | OC (%) | N (mg/kg) | CEC ($cmol_c$/kg) | Ca | Mg | Na | K | Al | Ac. | ECEC | BS (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **GY** | 7 | 6.02 (0.62) ac | 4.45 (0.48) ac | 1.98 (0.68) a | 2500 (797) a | 20.23 (4.59) a | 4.68 (1.06) a | 1.01 (0.12) a | 0.40 (0.27) a | 0.77 (0.31) ac | 0.54 (0.60) a | 0.67 (0.70) ac | 7.52 (0.76) a | 36 (13) a |
| **GO** | 5 | 5.40 (0.28) b | 3.84 (0.37) b | 2.19 (0.75) a | 2342 (792) ac | 27.27 (7.12) a | 3.18 (2.92) a | 1.27 (0.71) a | 0.48 (0.19) a | 0.54 (0.27) abc | 2.13 (1.30) b | 2.30 (1.50) ac | 7.38 (3.55) a | 20 (14) a |
| **PL*** | 4 | 5.51 (0.36) ab | 3.92 (0.11) b | 2.14 (1.14) ac | 1928 (1031) ac | 20.66 (5.89) a | 5.64 (0.82) a | 1.10 (0.29) a | 0.31 (0.08) a | 0.26 (0.08) b | 0.49 (0.27) a | 0.68 (0.24) a | 7.99 (1.36) a | 37 (0.05) a |
| **VE** | 3 | 6.28 (0.19) c | 4.32 (0.12) c | 0.74 (0.12) c | 1092 (786) c | 44.18 (13.66) a | 24.48 (5.68) c | 5.12 (1.79) a | 0.96 (0.24) c | 0.77 (0.09) c | 0.04 (0.02) c | 0.16 (0.02) c | 31.49 (7.73) c | 72 (6.1) c |

**The values followed by a different letter are significantly different (p-value < 0.05) according to the two-sample t-test**

**Table 4.7: Averages and standard deviations of physical soil characteristics for the different groups ('GY, the soils that have recently been under guie'; 'GO, the soils that have under guie more than 2 years ago'; 'PL*, the Planosols that have not been affected by guie without outlier 12/812'; and 'VE, the Vertisols'). The number of samples (n) used in every group is different for the different tests**

| Name | n | Sand (%) | Silt | Clay | n | BD (g/cm3) | Porosity (%) | Moisture (g water/g dry soil) at saturation | FC | WP | TAW (g/g) | Macropor. (%) | n | Mean weighted diameter (mm) after Fast wetting | Slow wetting | Mechanical disturbance |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Y** | 7 | 2 (1) | 78 (6) a | 19 (6) a | 2 | 0.81 (0.04) a | 70 (1.66) a | 0.71 (0.09) a | 0.45 (0.02) a | 0.16 (0.05) a | 0.30 (0.03) a | 32.96 (1.83) a | 5 | 1.59 (0.96) ac | 2.52 (0.84) a | 2.32 (0.74) a |
| **GO** | 5 | 3 (1) | 76 (10) ab | 21 (9) ab | 2 | 0.86 (0.01) a | 68 (0.48) a | 0.63 (0.05) a | 0.47 (0.02) a | 0.12 (0.05) a | 0.36 (0.02) a | 26.98 (3.08) a | 5 | 1.69 (0.77) a | 3.26 (0.23) a | 2.98 (0.37) a |
| **PL*** | 4 | 3 (1) | 69 (2) b | 28 (2) b | 0 | NA | NA | NA | NA | NA | NA | NA | 4 | 1.46 (1.04) ac | 3.36 (0.075) a | 3.20 (0.19) a |
| **VE** | 3 | 4 (3) | 36 (9) c | 60 (11) c | 1 | 1.01 | 62 | 0.5 | 0.41 | 0.28 | 0.13 | 21.18 | 3 | 0.67 (0.38) c | 2.40 (1.27) a | 0.66 (0.34) c |

**The values followed by a different letter are significantly different (p-value < 0.05) according to the two-sample t-test**

**Table 4.8: Physico-chemical soil characteristics of recently guied soils in Serbo**

| | Sand (%) | Silt | Clay | pH (H2O) | pH (KCl) | OC (%) | N (mg/kg) | CEC ($cmol_c$/kg) | Ca | Mg | Na | K | Al | Ac. | ECEC | BS (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Recent guie heap (12/796)** | 2 | 89 | 9 | 6.71 | 5.42 | 0.79 | 1945 | 15.69 | 5.23 | 1.19 | 0.99 | 1.2 | 0.03 | 0.08 | 8.69 | 55 |
| **Recent seedbed (12/797)** | 2 | 73 | 25 | 6.73 | 4.36 | 1.99 | 2179 | 17.63 | 5.42 | 0.93 | 0.47 | 0.44 | 0.21 | 0.27 | 7.53 | 41 |
| **Unaffected Planosol (12/806)** | 3 | 70 | 27 | 5.93 | 4.06 | 1.32 | 1061 | 16.79 | 4.94 | 0.87 | 0.43 | 0.22 | 0.24 | 0.42 | 6.88 | 38 |

### 4.3.2. Organic carbon and total nitrogen

The organic carbon (OC) and total nitrogen (N) content varies between the different Planosols. On average, the OC content in the Planosols is 2.1 % ($\sigma$ = 0.8) and the C/N ratio of the soil is 9. Differences in OC and N content between the different Planosol groups are not significant. As expected, the Vertisols have a lower content of OC (0.7 %) and N (1092 mg/kg) than the other soils. This difference is significant between guied Planosols and Vertisols (p-value < 0.05), but not between unaffected Planosols and Vertisols (p-value = 0.09). This is due to a higher standard deviation, rather than to a lower average content of OC and N in the unaffected Planosols. The average C/N ratio in the Vertisols is 8.

### 4.3.3. CEC and exchangeable base cations

The CEC of the Planosols is, on average, 23.6 $cmol_c$/kg, but variability among the different soils is large ($\sigma$ = 6.4). The average CEC of the GO group is higher than the CEC of the GY (not significantly, but p-value = 0.097). This could be related to the high exchangeable acidity and low soil pH of the soils in this group (see next section). Acid functional groups on organic matter in the soil contribute to the CEC measured at pH 7 because a lot of these groups are deprotonated and thus have a negative charge at that pH.

The base saturation of the Planosols is generally low (37 %), but has been calculated for a CEC that was determined at pH 7. As a part of the charge of the clays and the organic matter is variable, depending on the pH, this CEC is probably much lower in the field. The base saturation would probably be higher if it was calculated with the CEC measured at soil pH.

The Vertisols have both a high CEC and a high base saturation, which indicates that the proportion of variable charges in the CEC at pH 7 is smaller in the Vertisols than in the Planosols. The CEC of the Vertisol is, however, not significantly higher than the CEC of the Planosols, because standard deviation inside the soil groups is high. The majority of the CEC in the Vertisols is occupied by Ca and Mg, while K and Na have only a minor importance.

### 4.3.4. Acidity, exchangeable aluminium and ECEC

The Planosols are generally acid, but some significant differences exist between the different soil groups. The pH of the recently guied Planosols (GY) is, on average, 0.6 units higher than the pH of the other Planosols (p-value < 0.05 for pH in KCl). The average difference between the pH in water and in KCl is similar for the different groups of Planosols.

Both the pH (H2O) and pH (KCl) in the Vertisols are significantly higher than in the Planosols that have not been recently guied. The difference between the pH in water and in KCl is large in the

Vertisols because these soils consist of dominantly open 2:1 clay minerals. This large difference between the two measurements is, however, not reflected by a high exchangeable acidity.

The exchangeable aluminium in the GO soils is significantly higher than in the GY and PL soils. The aluminium saturation (defined as the percentage of ECEC that comes from Al) in the former group is 29 %. The high standard deviation for exchangeable aluminium and exchangeable acidity in the GO group is caused by the presence of one soil with a low exchangeable acidity. This soil (12/802) is the only soil in that group that is not under eucalyptus. The impact of the guie practice followed by the cultivation of eucalyptus on soil acidity and exchangeable aluminium will be further discussed in section 4.4.

The ECEC of the Planosols (on average 7.7 $cmol_c$/kg) is much lower than the CEC measured at pH 7 and doesn't vary between the different groups. The ECEC is significantly larger in the Vertisols (on average 31.5 $cmol_c$/kg) than in the Planosols.

### *4.3.5. Soil moisture characteristics, porosity and aggregate stability*

The bulk density of the Planosols is lower than that of the Vertisols and the calculated porosity is thus higher. Differences in soil moisture characteristics between GY and GO are not significant. Macro-porosity (total porosity - water content at field capacity) is highest in the recently guied soils and lowest in the Vertisols. The total available water for plants, which is the amount of water between field capacity ($\psi$ = -30 kPa) and wilting point ($\psi$ = - 1500 kPa), is higher in the Planosols than in the Vertisols. The pF curve (figure 4.12) of the Vertisols is steeper than that of the Planosols because the water content at nearly saturation ($\psi$ = -1 kPa) is less, while the water content at wilting point is higher. The higher water content near saturation in the GY soils as compared to the GO soils indicates a higher macro-porosity in the former soils.

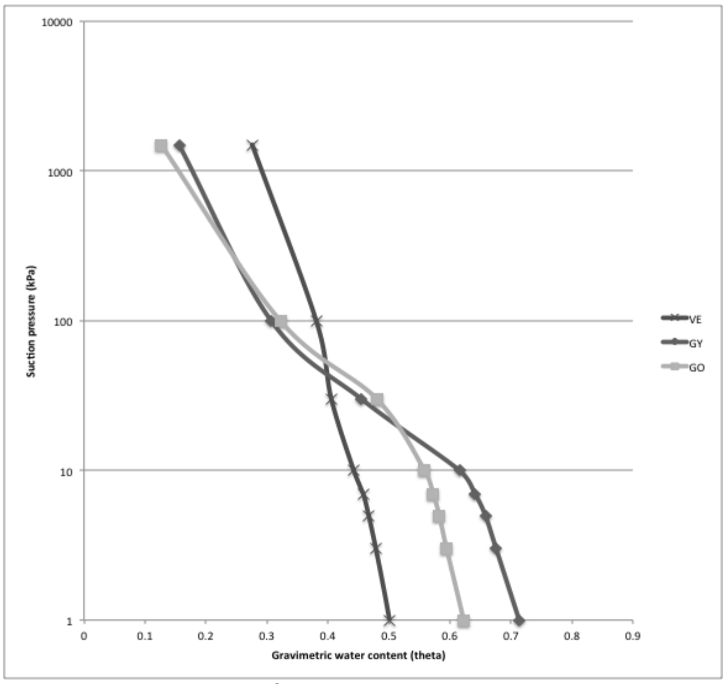


**Figure 4.12: pF curves of recently guied Planosols (GY), Planosols guied a longer time ago (GO) and Vertisols (VE)**

The aggregate stability of the different Planosols is generally high and doesn't significantly differ between the different groups. As expected, aggregates of the Planosols are more sensitive to fast wetting than to slow wetting or mechanical disturbance. This suggests that if aggregates break down in the field, this is due to slaking of dry aggregates upon sudden rains rather than to physico-chemical dispersion or the impact of raindrops. However, as the mean weighted diameter of the aggregates after the treatments is larger than 1.3 mm, slaking is not likely to occur in a way that can negatively affect soil quality (Le Bissonnais, 1996).

The Vertisols are significantly more sensitive to fast wetting and mechanical disturbance than the Planosols, but not significantly more sensitive to slow wetting. The aggregates in the field can be expected to break into smaller fractions upon sudden and heavy rains. Without mulching or other soil cover the Vertisols are therefore expected to be prone to crusting and sensitive to erosion.

## *4.4. Effects of guie practice on physico-chemical soil characteristics*

### *4.4.1. Short-term effects of guie*

The physico-chemical soil characteristics are given in table 4.8 for an unaffected soil (12/806), a recent guie heap (12/795) and a recently spread out guie for eucalyptus seedbed preparation (12/796) in Serbo.

The silt content is higher in the guie heap (89 %) than in the unaffected soil (70 %), which indicates that the guie practice induces an aggregation of the clay particles. The silt content of the guied seedbed (73 %) is, however, only slightly higher than in the unaffected soil. This is a result of the sampling technique, in which the 30 upper cm have been sampled. This sampling technique reflects the situation in the field: as the thickness of the seedbed is less than 5 cm, its impact on the overall texture of the upper 30 cm is minimal. This observation applies for all guied soils because the guie practice always affects only a small part of the overall soil volume in the upper 30 cm and will therefore not have a large impact on the overall particle size distribution.

The OC content in the guie heap (0.79 %) has strongly decreased as compared to the unaffected soil (1.32 %), while nitrogen content has increased (1945 mg/kg in the former and 1061 mg/kg in the latter). Contrarily to what would be expected, the OC content in the recently spread out guied soil (1.99 %) is higher than in the unaffected soil. This might be due to local variability.

The CEC measured at pH 7 is slightly lower in the guie heap (15.7 $cmol_c$/kg) than in the unaffected soil (16.8 $cmol_c$/kg). This difference is small when compared to the high variability in CEC among the Planosols. The Ca and Mg content in the guie heap (respectively 5.23 and 1.19 $cmol_c$/kg) are slightly higher than in the unaffected soil (4.94 and 0.87 $cmol_c$/kg). The Na content is twice as high in the guie heap and the K content is five times higher than in the unaffected soil (respectively 0.99 and 1.2 $cmol_c$/kg in the guie heap and 0.43 and 0.2 $cmol_c$/kg in the unaffected soil). As a consequence, the base saturation is also higher in the guie heap (55 %) than in the unaffected soil (38 %). The CEC and base saturation in the seedbed lay between the values in the guie heap and in the unaffected soil.

Both the pH measured in water and in KCl are highest for the guie heap (table 4.13). The pH (KCl) in the guie heap is 1.4 units higher than in the unaffected soil. The ECEC is also higher in the guie heap, while the exchangeable acidity is lower.

### *4.4.2. Long-term effects of guie*

**Soil pH and exchangeable Al**

The sole significant differences in chemical soil characteristics between the recently guied Planosols (GY) and the Planosols guied a longer time ago (GO) are the pH and the exchangeable aluminium. If the pH is set out in function of the time since guie was applied (figure 4.13), it is clear that both the pH ($H_2O$) and the pH (KCl) decrease with time.

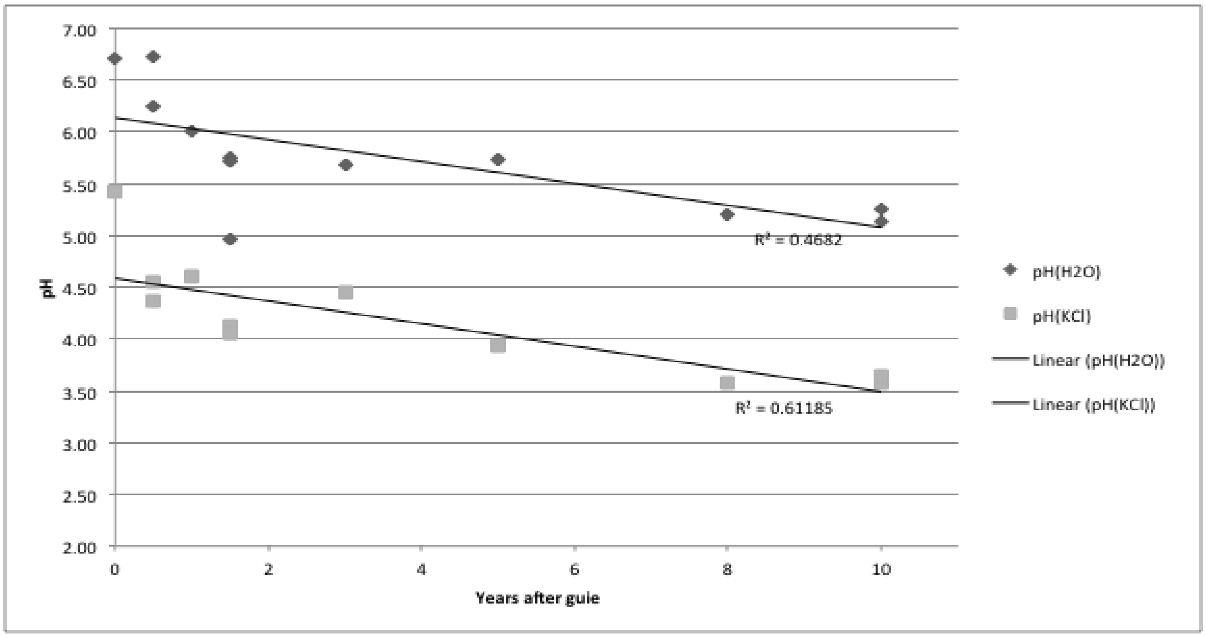


**Figure 4.13: Evolution of pH (H2O) and pH (KCl) with time since guie was applied. Linear trend lines have been fitted and $R^2$ values are given below**

The decrease in pH with time is reflected by an increase in exchangeable aluminium in the guied soils under eucalyptus, but not in the guied soil under teff (12/802). The evolution of the amount of exchangeable aluminium in the Planosols with time after planting eucalyptus is represented in figure 4.14. Surprisingly, the exchangeable aluminium in a soil that has never been guied and is under a 10 years old eucalyptus stand (12/809) is much lower than in soils that have been guied and that are under eucalyptus trees of the same age.

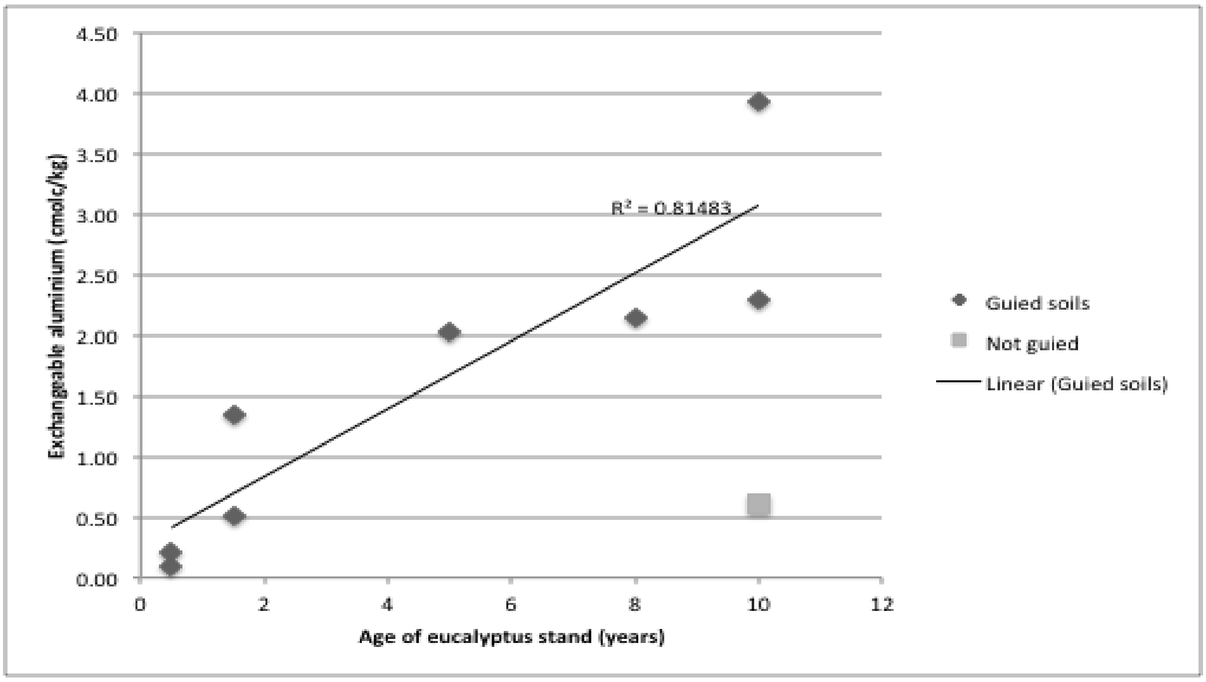


**Figure 4.14: Evolution of the exchangeable aluminium in the Planosols with time after planting eucalyptus for soils that have been guied before planting the trees and for an unguied soil. A linear trend lines was fitted and the $R^2$ value is given above**

### Charge fingerprints

An increased understanding of the long-term impact of the guie practice followed by eucalyptus cultivation is obtained by examining the charge fingerprints of a recently guied seedbed (12/796), a soil that has been guied 2 years ago (12/800) and one that has been guied 5 years ago (12/803), all under eucalyptus (figure 4.15).

The pHo is the pH at which variable positive and variable negative charges are equal. The difference between the total CEC (CEC T) and the sum of basic cations (CEC B) is the CEC occupied by aluminium. From these fingerprints it is clear that the soils have a low permanent negative charge (the total CEC at pHo) and nearly no permanent positive charge. The permanent charge doesn't differ much between the soils.

The recently guied soil under eucalyptus seedbed (12/796) has the highest soil pH, while the soil that has been guied the longest time ago (12/803) has the lowest. Soil 12/796 has nearly zero exchangeable aluminium at its soil pH, while soil 12/800 and 12/803 have. The CEC at soil pH is highest for 12/796 and decreases with time. The difference between the soil pH and the pHo also decreases as time since guie increases. The total permanent charge doesn't differ between the soils. The soils 12/800 and 12/803 have a more exponential increase in CEC for increasing pH than soil 12/796.

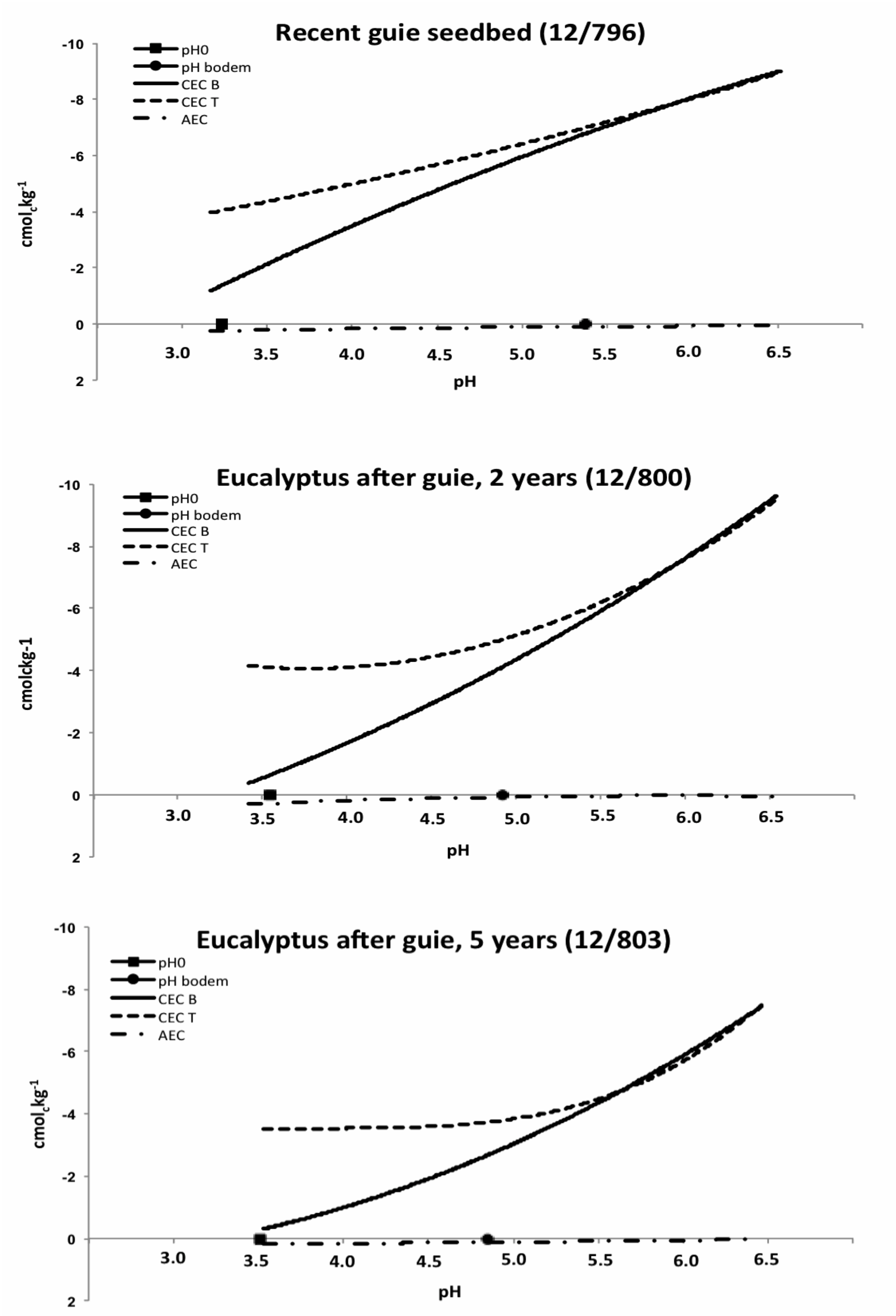


**Figure 4.15: Charge fingerprints of a recent guie seedbed (12796), a soil under eucalyptus that has been guied 2 years ago (12/800) and one that has been guied 5 years ago (12/803). Soil pH and pHo (measured in $CaCl_2$) are given, as well as the evolution of the AEC, the total CEC (CEC T) and the sum of basic cations (CEC B) in function of pH**

**Soil micromorphology**

From the pF curves (figure 4.10) it is clear that the macro-porosity of the guied soils is high. This is visualized with thin sections of undisturbed samples for a guie heap (12/796) and for a soil that has been guied 10 years ago and is under eucalyptus (12/804A) in respectively figures 4.16 and 4.17. The soil in the guie hill has a high porosity because of the recent ploughing and burning. Also the soil 12/804A still has a high porosity. Because eucalyptus is planted on this soil, its porosity is partially conserved because trampling is prevented. In both soils remnants of burned plant material are visible.. The rounded pellets in both soils indicate that biological activity is high.

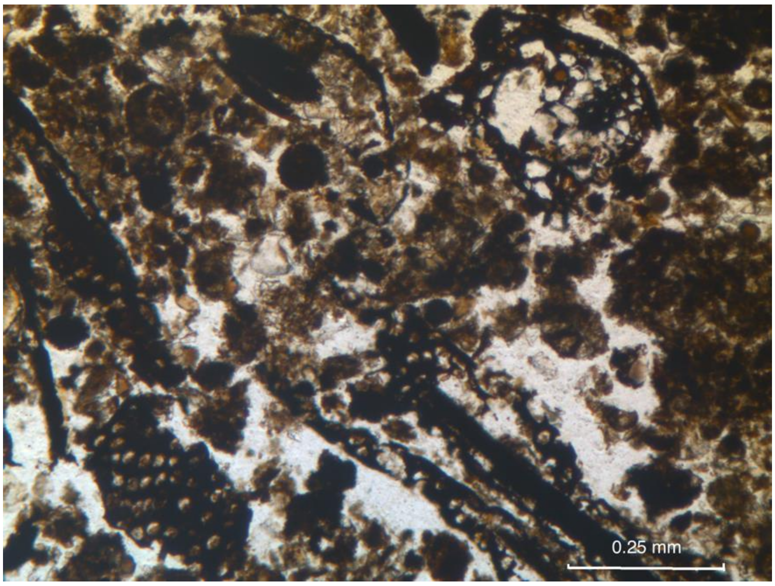


**Figure 4.16: Thin section of the upper part of a guie heap in Serbo (12/796). Macro-porosity is high and remnants of burned plant material are present**

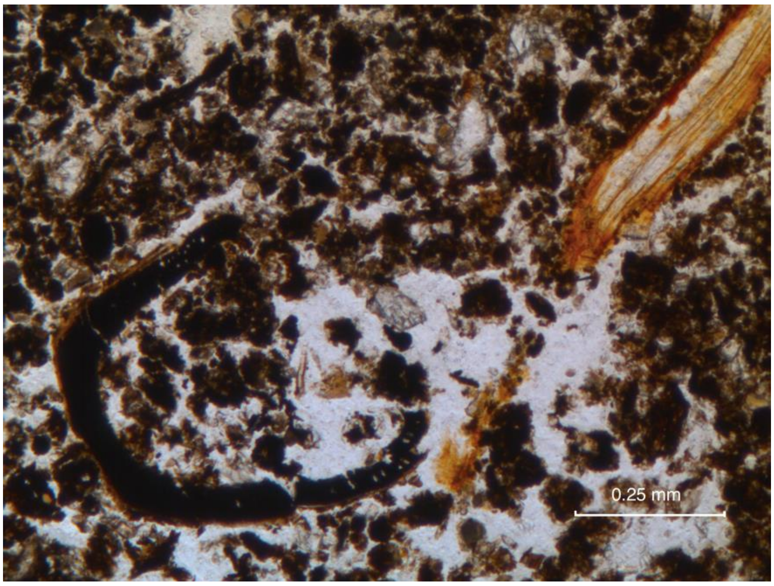


**Figure 4.17: Thin section of a soil that has been guied in the past and is currently under eucalyptus in Serbo (12/804A). The macro-porosity is still relatively high and still one remnant of probably burned plant material is visible**

## 4.5. Suitability of emerging land uses and management practices

### 4.5.1. Climatic data: variability and growing period

Among the different climatic parameters, only the precipitation shows a high decadal year-to-year variability (appendix 4). Standard deviations on decadal precipitation vary between 10 and 41 mm/decade. The precipitation also varies within the year, being highest from the end of April till the middle of October and lower in the rest of the year. The daily maximum temperature is highest during the dry season (29° C) and decreases during the rainy season (27° C), while the daily minimum temperature shows an opposite pattern (9° C and 13° C respectively). As a consequence, the average daily temperature doesn't vary a lot throughout the year. The hours of sunshine decrease during the rainy season, while the average wind speed is slightly higher during that season. No trends indicating climatic change have been discerned during the 25 years.

Because of the high rainfall variability, the growing period has been defined as that period in which dependable rainfall (80% chance of exceeding) is larger than half of the ETo (figure 4.18). This growing period lasts from the second decade of May till the end of September. The average number of days with rainfall during the growing period is 8 out of 10. This growing period corresponds with the dates of sowing and harvesting of maize on Nitisols, but not of teff on Planosols. Teff is sown later to prevent lodging during the maturation stage.

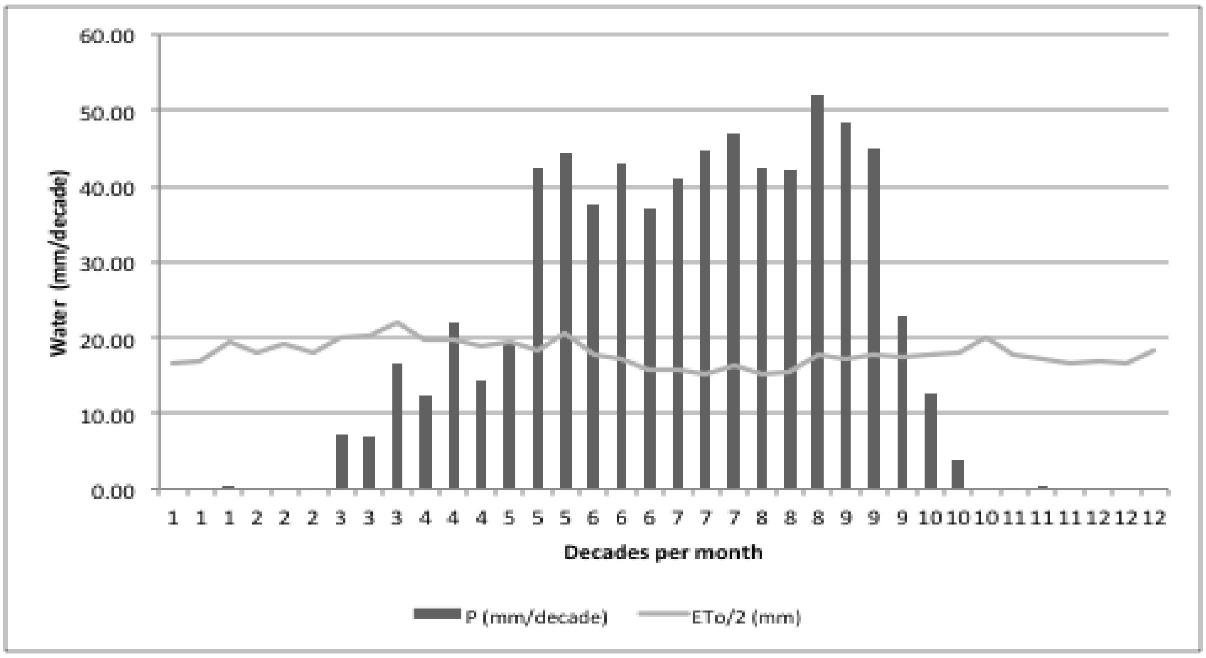


**Figure 4.18: Dependable rainfall (80 % chance of exceeding in 25 years) and calculated ETo/2 throughout the year at Jimma meteorological station**

### *4.5.2. Qualitative assessment of guie seedbeds for eucalyptus*

The land qualities of unmanaged soil are compared with the land qualities of a guie seedbed surrounded by trenches (as seen in Serbo) and with an unmanaged Vertisol after soil excavation (table 4.9). Limitation classes considered are ‘negligible’, ‘moderate’, ‘severe’ and ‘very severe’.

During the rainy season moisture availability is not limiting because of the high frequency of the rains and the presence of a perched water table on the Vertisols. During the dry season, the moisture availability depends on the total available water in the soil at the end of the rainy season, the extent of the roots and the presence of external water sources (water trenches or precipitation). The total available water in the Planosols is higher than in the Vertisol, but doesn’t differ much between managed and unmanaged Planosols. Yet, the trenches on the border of the managed plots might increase the water availability during the first months after the rainy season. However, as the water balance on the Planosols is complicated and should be further investigated, no distinction has been made between the managed and unmanaged Planosols for the rating of moisture availability. The Vertisols have lower moisture availability and eucalyptus trees might therefore suffer from a severe limitation of moisture during the dry season.

The oxygen availability on the Planosols is a problem during the rainy season. The managed Planosols have a slightly coarser texture and a higher macro-porosity in the topsoil. Together with the trenches along the plots, the management will increase oxygen availability for the roots of the seedlings. As the Vertisols do not drain well when moist and have a lower macro-porosity during the rainy season, oxygen availability will be a problem.

The nutrient content on the unmanaged Planosols is low. The guie practice, however, temporarily increases the availability of nitrogen and exchangeable basic cations, which can be decisive for the establishment of the seedlings. Therefore, the limitation for nutrients has been rated better for soils subjected to guie than for other Planosols. The Vertisols have a high CEC and a high content of basic cations. However, the content of OC is low and nitrogen will be a limiting factor.

The aggregate stability of the Planosols is high and is not significantly affected by the guie practice. Though the immediate decrease in OC content of the Planosols upon guie might temporarily decrease the stability of the topsoil, this effect does not significantly decrease the sensitivity of to soils to structural degradation. The aggregate stability of the Vertisols is much lower and this might become a severe limitation after time. The Vertisols are prone to crusting, and sheet wash and gully erosion are likely to occur. This is confirmed by the observations in Borè, where soils are excavated for brick making on a gently sloping land and gully erosion is frequent.

The availability of foothold for roots is not directly relevant for seedlings, but might become a limiting factor when the trees grow larger. The heavy clays at a depth of 30 cm will limit root penetration. It might be relevant to systematically plant trees on embankments, increasing the depth to the vertic horizon.

**Table 4.9: Qualitative comparison of limitations for the growth of eucalyptus seedlings**

| Land quality | No specific management | Guie seedbed and trench | Vertisol (after removal of the bleached layer) |
|---|---|---|---|
| **Moisture availability** | Moderate | Moderate | Severe |
| **Oxygen availability/ drainage** | Severe | Moderate | Severe |
| **Nutrient availability** | Moderate | Negligible | Moderate |
| **Resistance to structural degradation** | Negligible | Negligible | Severe |
| **Availability of foothold for roots** | Negligible | Negligible | Severe |

Based on the limitations given in table 4.16 and the maximum limitation method, the overall limitation for eucalyptus seedlings decreases from severe to moderate after the management techniques applied by the farmers. Of course, these results should be validated with experiments in the field before a strong conclusion can be made.

### 4.5.3. *Qualitative assessment of the potential for upland rice cultivation*

The results of the qualitative evaluation of the potential for upland rice cultivation according to the square root method are given in table 4.10. As the 'potential' suitability is rated, it is assumed that good management techniques (e.g. drainage trenches or broad beds) are applied so that flooding and drainage don't form a limitation. As drainage trenches are currently being used for the production of eucalyptus, assuming their use for crop production seems realistic. Without this assumption, wetness is a major limitation for the cultivation of upland rice.

The major limitation for rice cultivation is the climate and especially the mean temperature during the second month and the number of sunshine hours (n/N) during the growing period. Rice requires higher temperatures and higher amounts of sunshine than available during the growing period. Of course, these requirements can change for different varieties and varieties requiring lower temperatures and lower amounts of sunshine could be used. In that case, it might be necessary to use an adapted requirement table. It might also be necessary to modify the assumed length of the crop cycle, because at lower temperatures the crop cycle length will probably be longer than 120 days.

The evaluation of the climate (table 4.10) assumes rice is planted at the beginning of the growing period (the second decade of May, as calculated with 80 % dependable rainfall). As the precipitation is not the major limitation, it could be argued that choosing a different planting date might increase the suitability. Precipitation is, indeed, not a major limitation if crops are planted up to one month before or after the second decade of May (assuming a crop cycle of 120 days). This does, however, not increase the suitability of the climate, because mean temperature and sunshine duration during the crop cycle remain too low.

The low OC content in the Vertisols is the main reason for its lower rating for fertility status. However, as the CEC and base saturation in the Vertisols are both high, the rating for fertility might be too severe. The major limitation of the Vertisols is the availability of nitrogen (and probably phosphorous). An adequate use of (organic) fertilisers on both the Planosols and Vertisols should be able to solve the fertility problem of these soils. Differences in suitability for rice cultivation between the Planosols and the Vertisols would then be small, according to this evaluation method.

The physical soil characteristics get a lower rating for the Vertisols because vertic clay soils are rated less than silty clay loam. This is probably due to the low oxygen availability when the Vertisols are wet and due to the cracking when the soils are dry. It is not clear, however, if this rating does take into account the sensitivity of the soil to erosion. Soil erodibility of the Vertisol is high because of its low aggregate stability and its low permeability for water when wet. A more severe limitation for the physical soil characteristics of the Vertisols might therefore be appropriate.

**Table 4.10: Parametric land evaluation for the potential suitability of upland rice cultivation on Planosols and on Vertisols. Rating according to requirement tables of Sys (1993), assuming adequate drainage and prevention of flooding**

| | **Planosol** | **Vertisol** |
|---|---|---|
| **Climate (c)** | 52 | 52 |
| **Topography (t)** | 98 | 98 |
| **Flooding (w)** | 95 | 95 |
| **Drainage (w)** | 95 | 95 |
| **Physical soil characteristics (s)** | 97 | 95 |
| **ACEC (f)** | 100 | 100 |
| **pH (f)** | 100 | 98 |
| **OC content (f)** | 100 | 60 |
| **Overall rating** | 48 | 37 |
| **Class** | **S3c** | **N1c** |

According to this evaluation, the land characteristics for upland rice cultivation in the catchment are marginally suitable on Planosols and unsuitable on Vertisols. This is mainly due to climatic limitations and can therefore not be solved with adapted management practices. Yields on the Planosols will probably be low as compared to yields that are usually obtained for upland rice and it could therefore be argued that the cultivation of upland rice is not a viable option in the catchment.

However, if socio-economic information is taken into account, the cultivation of rice might become a relevant option. From the annual average retail prices at Jimma market (table 4.11), it is clear that the advantages of cultivating rice as a cash crop might be large compared to other crops. As the yields (e.g. teff) on Planosols in the catchment are generally low, even low yields of rice might increase the farmer’s income.

**Table 4.11: Annual average retail prices for some goods (July 2010 – June 2011) (Ashine, 2009; CSA, 2011)**

| Product birr | Jimma market | Country |
|---|---|---|
| **Teff (Birr/kg)** | 6.81 | 7.17 |
| **Maize (Birr/kg)** | 2.92 | 3.15 |
| **Rice (imported) (Birr/kg)** | 13.24 | 14.10 |
| **Rice (local) (Birr/kg)** | NA | 7.83 |

Care should be taken when interpreting this table because these prices might not reflect the prices in the villages. Several farmers living close to the field experiments reported not to know the crops. If demand for rice remains low in the villages, the prices might also be very low.

Even if the cultivation of rice is a relevant option on the Planosols in the catchment, one could wonder why upland rather than bunded rice is considered. The land evaluation in this research has been performed for upland rice because currently an experiment on this crop type is being conducted in the catchment. However, the relevance of investigating the potential for upland rice cultivation in the catchment is questioned. Bunded rice rather than upland rice seems more appropriate on the flooded Planosols. No drainage trenches are required and higher yields can be expected.

# 5. Discussion

In this thesis three research questions have been formulated to increase the understanding of the land use dynamics in the catchment. In order to answer these questions, the discussion of the results is structured according to the DPSIR framework. The first section in this chapter discusses the driving forces for land use change and the pressures on the Planosols, giving an answer to the first research question. The second section discusses the state of the soil and the impact on the land use (potential) of both the guie practice for eucalyptus seedbed preparation and soil excavation for brick making, giving an answer to the second and the third research question respectively. The third section discusses some potential responses.

An overview of the DPSIR framework applied to the Planosols in the Gilgel Gibe catchment is given in figure 5.1. Though this figure strongly simplifies reality, it can be useful to clarify the discussion.

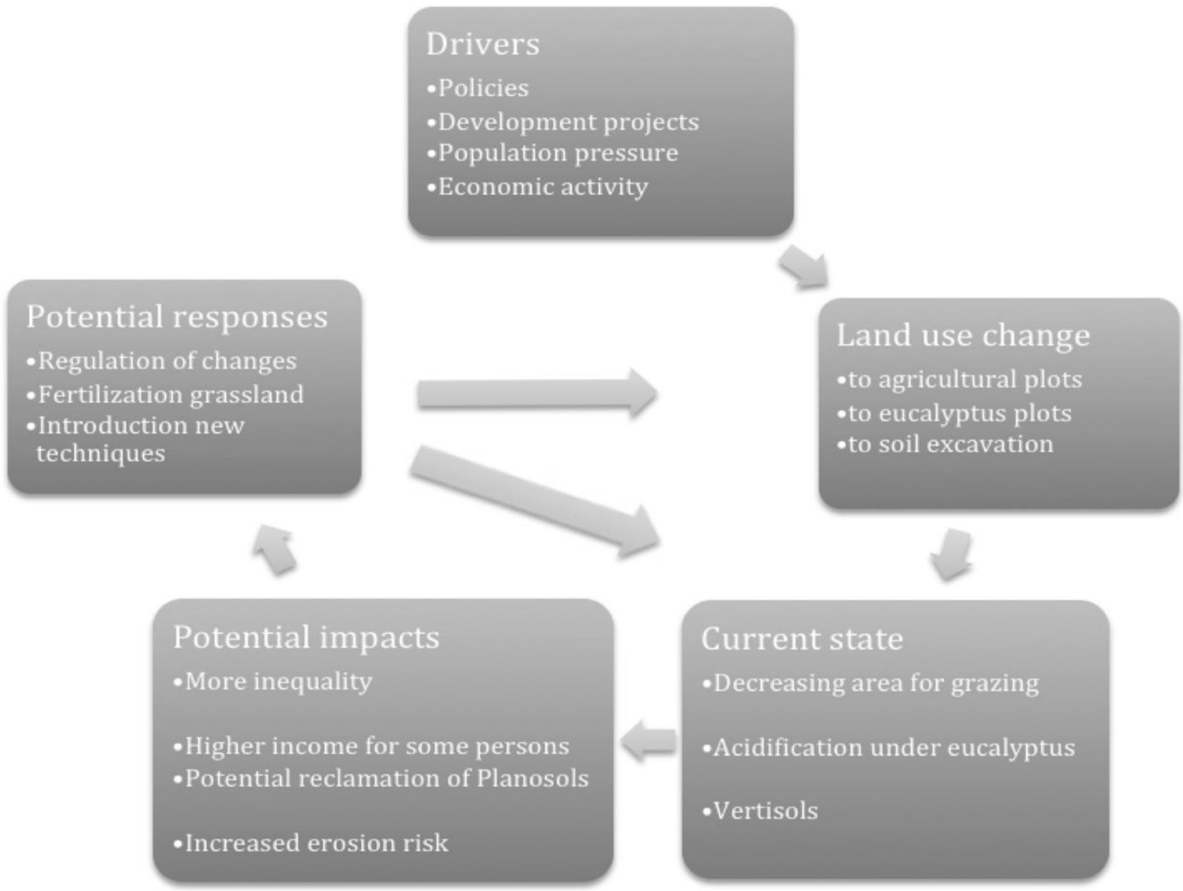


**Figure 5.1: An overview of the DPSIR framework, applied to the Planosols in the Gilgel Gibe catchment**

## *5.1. Driving forces and pressures*

Currently, the Planosols in the catchment are mainly used as communal grazing land for cattle. Cattle are important for the local communities because they are both a source of power for labouring the fields and a livelihood insurance for future needs of money.

The grazing land is under pressure because the area available for grazing decreases. At the sites under study, agricultural fields, eucalyptus plantations or pits after soil excavation are gradually replacing part of the grasslands. The benefits from these alternative uses of the Planosols are generally high, but contrarily to the benefits from the grasslands, they are not for the whole community.

A process in which communal land is gradually divided into privately owned plots, is called 'enclosure of the commons'. Though the process at hand is not a real enclosure of the commons because private property of land is not possible in Ethiopia, its result is similar. The area available for communal grazing decreases and some persons obtain more earnings from land that formerly belonged to the community.

The driving forces for these changes are related to, on the one hand, policies and development interventions, and on the other hand, socio-economic and demographic factors, in a probably similar way as described in Kamara *et al*. (2004). The policies and development interventions do usually not directly drive changes, but provide an environment suitable for them, while the socio-economic and demographic factors can provide more direct incentives for changes in land use.

The policies and development projects in the region have provided an environment that encourages farmers to get more from their land. First, tenure security has increased for private land use in the Oromya region. Secondly, local authorities in the catchment promote the production of bricks or eucalyptus on communal land because it implies an intensification of the land use. Thirdly, development projects, like the upgrade of the road between Jimma and Addis Ababa, have increased market accessibility. This makes it easier for farmers to sell their products and earn money from what they get from the land.

Demographic factors have been responsible for the conversion of Planosols into agricultural land in Dimtu and in Ketimbile in the past. Though yields on the Planosols are low, they are necessary for some farmers because of a lack of land. The population in the catchment is increasing and farmers obtain food and money by either intensifying the land use or bringing new land into use.

Socio-economic factors are probably driving the increasing demand for eucalyptus wood. The construction works in Jimma, new houses along the roads in the catchment and an increasing demand for firewood because of an increasing population pressure are responsible for this increasing demand. The evolution of prices in time should, however, be compared in order to confirm this hypothesis.

It is also an increased demand that is driving brick production on the Planosols. As local houses in the villages are not made from bricks, the demand for bricks probably comes from construction works in Jimma. The asphalted road between Jimma and Addis Ababa, whose upgrade was finished in 2007, might make it easier to transport bricks from Beda Buna to Jimma. However, this observation does not hold for brick making in Borè, as the road has not been upgraded there. Yet, also in Borè, bricks are produced for selling in Jimma rather than for local use.

## *5.2. State and impact*

The grazing land suffers from overgrazing and nutrient depletion, which results in a low ground cover by grasses at certain moments in the year. As the aggregates of the bleached layer are most sensitive to fast wetting, a low ground cover might increase sheet wash at the start of the rainy season. This can on its turn decrease the productivity of the grasslands and increase sediment load in the Gilgel Gibe dam.

This is, however, not further discussed here as the focus is on the state of the soil after the guie practice for eucalyptus seedbed preparation and after soil excavation for brick making.

### *5.2.1. The guie practice for eucalyptus seedbed preparation*

The guie practice increases the silt content in the soils due to an aggregation of clay particles, but the effect on the texture of the upper 30 cm of the soil disappears after a few years. In the guie heap organic carbon content of the soil is low and availability of nitrogen is high. However, the impact of guie on the OC and N content in the upper 30 cm of the soil isn't significant. Moreover, as the biological activity after guie is high, organic matter content in the burned soil is soon restored under eucalyptus.

The pH of the soil increases after guie. According to Nishita and Haug (1972) the increase in pH is due to the formation of oxides and carbonates of Ca and Mg and the destruction of organic matter at a temperature above 200 °C. Yet, contrarily to what would be expected, the exchangeable Ca and Mg content slightly increases in the guie heap as compared to the unaffected soil. This increase can be related to the techniques used to prepare the guie heap. Soil clods with a high content of organic matter and thus rich in nutrients are amassed and set afire. Though part of the amassed Ca and Mg forms oxides or carbonates and is therefore not directly exchangeable, this is not sufficient to balance the higher total amount of Ca and Mg in the heap. This hypothesis is confirmed by the fact that exchangeable Ca and Mg in the heap increase only slightly, while increase in exchangeable Na is more than twofold and exchangeable K content is 5 times higher.

Previous authors reported a decrease in CEC upon heating above 200°C due to an aggregation of the clay particles and a dehydration of the mineral crystal lattice (Nishita and Haug, 1972). This is, however, not observed in this study. The CEC measured at pH 7 is not significantly lower for recently guied soils than for unaffected soils. The lower CEC in the guie heap as compared to unaffected soils is probably mainly related to a lower organic carbon content in the heap. It is not clear why Nishita and Haug (1972) haven't attributed the decrease in CEC to the simultaneous decrease in organic matter at the same temperature.

In fact, the real CEC at soil pH in the field is higher for recently guied soils than for unaffected soils or soils that have been guied more than 2 years ago. As the pH is significantly higher in recently guied soils than in other Planosols, the fraction of variable charges that is protonated is lower and thus the CEC in the field is higher.

With time after guie, the pH of the guied soils decreases to its original value. From the charge fingerprints it appears that neither the amount of permanent charges in the Planosols nor the CEC measured at pH 7 significantly change with time after guie. Yet, none of these reflect the real CEC in the field. With the decreasing pH, also the CEC in the field decreases with time after guie.

Soils that have been guied in the past and are currently under eucalyptus have significantly more exchangeable aluminium than other soils. It is hypothesized that this is due to a combined effect of the guie practice and the presence of eucalyptus. This combination could result in different types of organic matter in the soils under eucalyptus after guie. As the guie practice initially burns the organic matter, also stable forms of organic matter, like stable Al-humus complexes with a low amount of variable charge groups, are destroyed. This initially doesn't increase the exchangeable Al in the soil because released Al directly precipitates due to the high pH after guie. With time, however, the pH decreases again due to deposition of fresh organic matter from eucalyptus and due to the dissolution of carbonates. It is hypothesized that fresh organic matter could have higher amounts of variable charge and might form less stable Al-humus complexes than older organic matter. This could explain why exchangeable Al is higher in the soils that have been guied in the past and are under eucalyptus as compared to unaffected soils. This could also explain why the exchangeable Al is lower in the soil that was never affected by guie, but is currently under eucalyptus (12/809) and has a low pH (3.82 in KCl). This hypothesis corresponds with observations in other studies, but should be further investigated before formulating strict conclusions (Hargrove and Thomas, 1982; Prosser *et al.*, 1993).

The macro-porosity in soils that have been subjected to the guie practice is high. This is due to ploughing followed by burning of the organic matter, leaving voids in the soil space. This macro-porosity is partly conserved under eucalyptus because of a high biological activity and fewer trampling as compared to the grasslands. The aggregate stability of the Planosols isn't significantly affected by guie.

Other publications that evaluate the guie practice for agriculture conclude that the practice increases the soil fertility for a few years, but has a negative impact in the long run. They attribute this to an initial increase in nutrient availability, followed by a decrease in soil quality due to a decreased CEC, low OC content and low aggregate stability. These publications therefore suggest that other practices than guie could increase yields in a similar way with less effort, no need for a period of fallow and no detrimental effects on the soil quality (Wolde-Yohannes and Wehrmann, 1975; Abebe, 1981).

In this research, on the contrary, the guie practice is evaluated for eucalyptus seedbed preparation. The sole significant negative long-term effect of the guie practice is an increase in exchangeable Al. It is argued that this negative effect on the soil quality might be outweighed by positive impacts on the land use. In fact, the guie practice for eucalyptus seedbed preparation could be a necessary step in the reclamation of the Planosols in the catchment.

The good soil conditions initially created by the guie practice are important for the establishment of the eucalyptus seedlings. One year after sowing the seedlings, a part of the young trees is transplanted to other plots or to embankments along trenches. The trees that remain on the guied soil have more space and are soon strong enough to grow on the acidifying and nutrient poor soil conditions that arise. The application of the guie practice on a small piece of land thus makes it possible to convert larger plots into eucalyptus stands.

As eucalyptus species are more tolerant to aluminium than other species (Silva *et al.,* 2004), they might be the best choice to increase productivity of these Planosols. Moreover, as eucalyptus trees grow fast and therefore consume a lot of water, in the long run they could contribute to the drainage of these soils. Once some plots are sufficiently drained, part of the eucalyptus can be cleared and agricultural crops can be grown. Though farmers might have to lime the soils to raise the pH after clearance of the trees, the application of the guie practice on a small piece of land could thus, in the long run, help to bring larger plots of land into agricultural use.

One could ask whether it is really necessary to guie the soil before planting eucalyptus. Probably, soil conditions that are similar to a guie seedbed can be created with the use of fertilizers (and liming) on a ploughed plot that is surrounded by trenches. However, this would require farmers to invest money in a piece of land which is not their own and which will only give a harvestable yield after three to five years. The guie practice is a labour-demanding, but cheap alternative to this rather risky investment.

### *5.2.2. Soil excavation for brick making*

Soil excavation changes the soil type from Planosol to Vertisol by removing the bleached horizon and uncovering the vertic horizon below. According to a parametric land evaluation, this excavation has a negative impact on the potential for rice cultivation in the catchment. Though it is argued that the excavation does indeed negatively affect the potential for rice cultivation, the usefulness of the application of this parametric land evaluation method in this situation can be questioned.

Chemically, excavation of the bleached horizon decreases the content of organic matter and nitrogen, but increases the CEC (though not significantly). The pH and base saturation are significantly increased and exchangeable aluminium is significantly decreased. Soil excavation therefore probably doesn't strongly decrease chemical soil fertility. Moreover, with the adequate use of organic fertilizers, chemical fertility of the Vertisols could be high.

The major impacts of soil excavation on the suitability for rice cultivation are related to the physical soil properties. The vertic horizon consists of heavy swelling clays, which are hard to plough, have low total available water and low macro-porosity when moist. Vertisols are known to form cracks when dry and to become impermeable when wet. The aggregates of the vertic horizon are also sensitive to fast wetting and mechanical disturbance. Soil excavation can therefore decrease the rootability for the crops, shorten the effective length of the growing period because of a lower moisture reserve after the rainy season and increase erosion.

These observations, regarding chemical and physical soil properties, are not reflected in the ratings in the applied parametric land evaluation method. The lower rating for the Vertisol is due to a lower rating of the chemical soil properties rather than the physical properties. Moreover, the parametric land evaluation is not able to explicitly take into account the most important feature of the Planosols, namely the presence of a bleached horizon above a vertic one. This feature slightly affects the rating in the calculation of the soil texture and of the ACEC, but is not rated as such. An adaptation of the method is therefore required before valid evaluations can be made.

The presence of a vertic horizon below a bleached one does strongly influence the suitability of the Planosols for crop production. On the one hand, the wetness problems caused by the presence of a perched water table negatively affect the suitability of the Planosols. This effect can be taken into account by decreasing the rating for wetness. On the other hand, the bleached and the vertic horizon might have complementary properties that, together, increase the suitability for crop production. The vertic horizon has a high CEC and base saturation, while the bleached horizon has a high macro-porosity, a high content of available water and a low erodibility. The bleached horizon might increase the replenishment of the water content in the subsoil by slowing down infiltration and subsequent closing of the cracks in the vertic horizon. The vertic Planosol could therefore be interpreted as a strongly mulched Vertisol, enjoying the high CEC of this soil, without its high erodibility and low workability. After establishment, crops have a root length of more than 30 cm and can therefore enjoy the advantages of both soil types. Yet, as the nutrient content of the bleached horizon is low, an initial fertilization of the soil is necessary for establishment of the crops.

From these observations, it might appear that the Planosols are suitable for crop production. This does, however, not correspond with the observations in the field. Why would the cultivation of the Planosols be so limited if they would be suitable for cultivation? And why do farmers apply the guie technique in the first year of cultivation? The Planosols are, in fact, not actually suitable for crop production because of the wetness problems during the rainy season and their low nutrient content. It is argued, however, that they might become suitable if the right management techniques, like broad bed furrows or drainage trenches, would be applied. Cultivation of the Planosols would also require higher inputs of fertilizers, which might be too expensive for the local farmers.

These observations might also suggest that the Vertisol after soil excavation is not suitable for crop production. This does, however, not correspond with what is reported in the literature on Vertisols in Ethiopia. Though the rice yields on the Vertisols are relatively low in the experiment, cereal cultivation on Vertisols is possible with the right management techniques. It has been demonstrated that broad bed furrows and conservation agricultural practices with the maresha plough can give high yields without increasing the risk of erosion or the need for traction by oxen (Nyssen *et al*., 2010; Araya *et al*., 2011).

One of the major limitations for the cultivation of rice in the catchment according to the applied parametric evaluation is the temperature regime during the growing period. This limitation is not affected by soil excavation or management techniques and can only be solved by using adapted varieties. With the right varieties, rice cultivation on the Planosols or on the Vertisols in the catchment might become an important activity because of the high prices currently offered in Jimma. As flooding is a recurrent problem on Planosols, the cultivation of bunded rice, rather than upland rice should be considered.

## *5.3. Responses*

It is clear that the availability of grazing land is decreasing and will continue to decrease if no measures are taken to prevent it. This decrease is, however, not negative per se, as the grazing land is replaced by more productive systems like eucalyptus or brick making.

However, cattle are currently very important as insurance and for ploughing. Therefore, a decrease in the area of grasslands could negatively affect the households in the catchment. Moreover, as the current enclosure of the communal grazing land is only profitable for a few and potentially detrimental for the rest, inequity among farmers might increase. Though it is not an option to prevent the changes on the Planosols, some regulation might therefore be necessary.

Part of the Planosols should be reserved as grazing land in order to provide in the needs of the cattle. Fertilization of these lands and sowing of specific grasses might be necessary to increase productivity.

At the same time, it might be good to decrease dependence on cattle for the cultivation of the land. The introduction of no tillage practices or other types of conservation agriculture, by means of a participatory approach, could be considered.

Eucalyptus trees on embankments along trenches can be used to drain the lands and generate new income for the community. Seedlings can continue to be raised on guied seedbeds without much cost. The potential for agriculture on plots surrounded by trenches and eucalyptus trees should be evaluated.

Soil excavation for brick making can generate a large and immediate amount of new income for the farmers and should therefore not be prevented. However, excavation should only be allowed on flat lands because of the sensitivity of the Vertisols to erosion. Potential uses of these Vertisols should be further investigated. Rice could be grown as a cash crop, but the potential for other crops, which are better adapted to the climatic conditions in the catchment, should also be considered.

# 6. General conclusions

From this research it is clear that adoption of complementary approaches is necessary for an appropriate evaluation of the land use dynamics on the Planosols in the Gilgel Gibe catchment. Though other frameworks exist, in this thesis the framework for land evaluation and DPSIR have been used.

The land evaluation framework allows comparing the suitability of different soils and different management techniques for specific crops. This framework makes it possible to relate physico-chemical properties of the land to land use requirements. However, as the framework has been designed to be easily applicable for a broad range of soils and crops, its direct usefulness for targeted scientific research is sometimes limited. Before the framework can be used to evaluate specific situations, it has to be adapted and these adaptations have to be validated. A good evaluation of the suitability of the Planosols for the cultivation of rice will therefore require some modifications to the framework in order to effectively take into account the presence of the two very different horizons.

The DPSIR framework is useful to structure and represent information obtained during an evaluation, giving special attention to the broader socio-economic and environmental context of the land uses in a region. However, one should be careful when using this framework, because it might force the information into a predefined structure, limiting the possibilities to nuance results and formulate different conclusions. The use of the DPSIR framework for structuring information concerning the land use changes in the Gilgel Gibe catchment can give the impression that these changes are something that has to be prevented. However, these changes are not negative per se and can be beneficial for the farmers if increased inequality is prevented.

A comprehensive evaluation of the land use dynamics in the catchment required the application of both frameworks in order to evaluate specific soil management techniques on the one hand and situate this evaluation in the socio-economic context of the catchment on the other hand.

By this means it has been demonstrated that land use changes in the catchment are driven by a combined effect of policies, development projects and socio-economic factors. These factors drive an intensification of the land use on the Planosols, resulting in a gradual decrease in area available for grazing.

It has also been demonstrated that the guie practice for eucalyptus seedbed preparation can be beneficial to intensify land use on the Planosols in a sustainable way, being a necessary step in the reclamation and drainage of the Planosols. This conclusion nuances the findings of previous researches regarding guie for agricultural purposes: though the guie practice might indeed negatively affect soil quality for crop production, it might be useful for the production of eucalyptus and the drainage of the Planosols in the catchment.

The negative impacts attributed to the guie practice in previous researches are also nuanced in this thesis. While other publications state that the guie practice negatively affects soil quality because it decreases the CEC, OC content and aggregate stability of the soil, current research has demonstrated that none of these effects are significant on the Planosols in the Gilgel Gibe catchment. The sole significant negative long-term impact of the guie practice followed by eucalyptus on soil quality is an increase in exchangeable Al due to a decrease in pH and a rejuvenation of the organic matter.

Finally, it has been shown that soil excavation probably negatively affects the potential for sustainable upland rice cultivation in the catchment. However, as brick making is a high yielding activity, further research should investigate options regarding potential land uses after excavation rather than searching potential measures to prevent excavation. Also cultivation of rice should be considered, because an economic evaluation of rice production might yield a higher suitability classification than a mere evaluation of the climatological and edaphic properties in the region.

# 7. Further research

In this research the land use dynamics have been evaluated in a qualitative way at selected locations in the catchment. It might, however, be interesting to quantitatively map the land use changes on the Planosols in the whole catchment by using satellite images. For this evaluation ground truthing and mapping of the Planosols is required. This could also contribute to a better understanding of the distribution of the Planosols in the catchment.

From this, the relation between land uses and land use changes can be further investigated. In current research a linear relation is assumed by using the DPSIR framework. This does, however, not correspond with the reality, as land use changes constantly feedback on the drivers, pressures and subsequent new changes in the catchment. An assessment of the changes during a longer period of time would allow discerning these relations and eventually modelling future evolutions in land use.

At farm scale, it might be interesting to compare potential land uses and management techniques on the Planosols from an economic and sustainability point of view. This would require precise information about yields of different crops and of eucalyptus. Crop growth experiments, like currently performed, are one of the elements necessary for this assessment. Also the rate of return from brick making and eucalyptus production should be evaluated. The effectiveness of the guie practice to increase eucalyptus production could be quantified by comparing the mean annual increment in the first years on guied and unguied plots.

It can also be useful to adapt the land evaluation framework to the specific situation in which a vertic horizon is covered by a different horizon. This would require a better understanding of the physical properties of the vertic horizon, and especially of the behaviour of the cracks under the bleached horizon. One possible question is whether the bleached horizon does effectively act as a kind of mulch or not. This could be investigated by looking at the distribution of the roots of the eucalyptus trees (or a crop, e.g. rice) in the vertic horizon. From these observations a water balance could be calculated and crop growth could be modelled in a quantitative way.

In this thesis no evaluation was performed of the potential ecosystem services of the grazing land or of the eucalyptus plots. Only the impact on erosion was discussed in a mere qualitative way. It might be interesting to investigate other potential ecosystem services of the different land uses. For example, it could be interesting to further investigate the nature of the organic matter in guied soils under eucalyptus. If this type of organic matter does indeed differ from the organic matter in unguied soils, the guie practice followed by eucalyptus cultivation could affect the species living in this soil and the potential of the soil for carbon sequestration.

Several of the above-mentioned researches, especially those related to agriculture on the Planosols or on the Vertisols, should be performed with a participatory approach. This would allow the farmers and potential other stakeholders to contribute to the research by sharing their knowledge. It would also increase the adoption of potential outcomes and recommendations of the research.

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# 9. Appendixes

## 9.1. Appendix 1: questionnaires for interviews

### 9.1.1. Appendix 1a, questionnaires for farmers

*I'm Kewan Mertens and I am a student at the university in Belgium. I come here to learn more about your land uses in the present and in the past. I would be gratefull if you would help me with my research by responding some questions.*

| **General Information** | |
|---|---|
| Date | |
| Location | |
| Name, gender | |
| Household<br>-How many, children…<br>-Persons with income + what is income (variations during year?)? | |

| **General questions on land** | |
|---|---|
| <u>Owned land</u><br>-type (planosols, vertisols, nitisols/acrisols)?<br>- Land uses (cultivation, brick making, herding, trees,…) for each type<br>- area (for each type/use) | |
| <u>Shared land</u><br>-type (planosols, vertisols, nitisols/acrisols)?<br>- Land uses (cultivation, brick making, herding, trees,…) for each type<br>- area (for each type/use) | |
| <u>Other (hired,…)</u><br>Same as above | |

**Land use: agriculture**

| | |
|---|---|
| Crops grown<br>- types + crop cycle | |
| Management<br>→ put categories in time table below<br><br>(1) land preaparation/burning/ guye method<br><br>(2) Seed bed preparation/ ploughing cost of seeds? Amount per ha?<br><br>(3) planting<br><br>(4) Weed control/ fertilisers + cost<br><br>(5) Harvesting<br><br>(6) Post harvest management soil (prevention of erosion, replenisching soil water/nutrients) | |
| Yield/uses<br>- Yield (total and on different plots/soil types): grain(human)/ straw(animal)<br><br>- Variability in yield? Remember past good/bad years? Why?<br><br>- Use: own use or selling? Price if sold? Amount sold? | |
| Sustainability<br>-Trends? (decreasing/increasing yield, pests,…)<br><br>- Other problems? | |

*Calendar of activities: different management practices*, *for planosols: waterlogging period ,…*

| **Calendar** | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Crop/activity | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sept | Oct | Nov | Dec |
| | | | | | | | | | | | | |
| | | | | | | | | | | | | |
| | | | | | | | | | | | | |
| | | | | | | | | | | | | |
| | | | | | | | | | | | | |
| | | | | | | | | | | | | |

**Land use: herding**

| | |
|---|---|
| Grazing total<br>- Total surface for grazing<br>- Duration grazing (begin+end)<br><br>- Total amount of animals on surface | |
| Animals owned<br>- types + amount<br><br>-Acquiring method (birth, buying,…) + cost<br><br>-growing time (years) | |
| Feeding (own animals)<br>*Will differ summer/winter*<br>*→calendar*<br>(1) Grazing<br>Different areas for different times of year?<br><br>(2) straw<br>Own production/ bought? Cost? Where grown? Amount?<br><br>(3) Other | |
| Yield/uses<br>- Uses animals (meat, milk, skin, renting for traction,..)<br><br>- Own use/sold? Prices of different things.<br><br>- Variability from year to year? | |
| Sustainability<br>-Trends? (decreasing/increasing cattle amount, pests,…)<br><br>- Other problems? | |

*Calendar of activities: different management practices, for planosols: waterlogging period ,…*

| **Calendar** | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Crop/activity | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sept | Oct | Nov | Dec |
| | | | | | | | | | | | | |
| | | | | | | | | | | | | |
| | | | | | | | | | | | | |
| | | | | | | | | | | | | |
| | | | | | | | | | | | | |
| | | | | | | | | | | | | |

**Land use: Brick making**

| | |
|---|---|
| Activity during year:<br>Is there a period of brick making? Who in family does it? Structure organisation.<br><br>How much time for making bricks? Amount of bricks/day.<br><br>Costs brick?<br>Price brick? | |
| Sustainability<br>-Awareness of changing soil type? | |

**Land use: Trees**

| | |
|---|---|
| Trees grown<br>- type of eucalyptus (or others)<br><br>-Growth cycle (how much time for certain diameter?, replanting after how much harvests?)<br><br>-How is choosen where to plant trees? Advantages of trees? | |
| Management<br>(1) land preaparation<br><br>(2) planting plants<br><br>(3) Weed control/fertilisers<br><br>(4) Harvesting after how many years?<br><br>(5) replanting of trees after harvest? Or different? | |
| Yield/uses<br>- diameters at harvest + selling prices for different diameters<br><br>- Years before harvest<br><br>- Use: own use or selling? Price if sold? | |
| Sustainability<br>-Trends? (amount of forest decreasing/increasing? Enough trees planted?)<br><br>- Other problems? | |

### *9.1.2. Appendix 1b, questionnaires for experts and officials*

| **General** |
|---|
| Date |
| Location |
| Name |

| **Population general** | |
|---|---|
| Amount | |
| Percentage<br>- directly living from the land<br>- living on the countryside | |
| Number of villages<br><br>Size of villages | |
| Level education | |
| Access to<br>- health facilities<br><br>- Clean water<br><br>- Roads/ transportation | |
| Percentage pop<br>- owning land<br>→amount of land usually owned by family (mean, median)<br><br>- owning animals<br>→ amount+type<br><br>- people needing food help? (e.g. the ones that had to move for dam | |
| Government policies<br><br>- Land tenure?<br><br>-Programs of sensibilisation regarding erosion/ use of fertilizers/ alternative land uses/... | |

| **Borè and Serbo** | |
|---|---|
| Size villages | |
| Population, ethnic groups, number of peasant associations,... | |
| Access water/sanitation | |
| Income source villages<br>Recent changes? | |
| Amount of grazing land<br><br>Amount of cattle on land<br><br>Feed for cattle during dry season<br><br>Value/ importance of cattle?<br><br>Problems with cattle? | |
| Amount of agricultural land<br><br>Crops grown<br><br>Value of land<br><br>Problems with agriculture? | |
| Brick making<br><br>Value of bricks?<br><br>Importance income?<br><br>Recent trends? | |
| Other problems? | |
| Recent evolutions? | |
| Difference between Borè and Serbo | |
| Anyhing more, your opinion… | |

## 9.2. *Appendix 2: crop requirement tables*

### *9.2.1. Appendix 2a, requirement tables rainfed upland rice (Sys, 1993)*

**CLIMATIC REQUIREMENTS - RAINFED UPLAND RICE** (growing cycle 90-150 days)

| Climatic Characteristics | Class, degree of limitation and rating scale | | | | | |
|---|---|---|---|---|---|---|
| | S1 0 | S1 1 | S2 2 | S3 3 | N1 4 | N2 |
| | 100-95 | 95-85 | 85-60 | 60-40 | 40-25 | 25-0 |
| Precipitation of the 1st month (mm) | 200-300 | 300-400 | 400-550 | 550-650 | - | > 650 |
| | 200-75 | 75-50 | - | - | - | < 50 |
| Precipitation of the 2nd month (mm) | 200-300 | 300-400 | 400-550 | 550-650 | - | > 650 |
| | 200-125 | 125-100 | 100-75 | 75-50 | - | < 50 |
| Precipitation of the 3rd month (mm) | 200-300 | 300-400 | 400-550 | 550-650 | - | > 650 |
| | 200-125 | 125-100 | 100-75 | 75-50 | - | < 50 |
| Precipitation of the 4th month (mm) | 200-300 | 300-400 | 400-550 | 550-650 | - | > 650 |
| | 200-75 | 75-50 | < 50 | - | - | - |
| Mean temp. of the growing cycle (°C) | 31-30 | 30-24 | 24-18 | 18-10 | - | < 10 |
| | 31-32 | 32-36 | > 36 | - | - | - |
| Mean max. temp. of warmest month G.C.(C°) | 35-36 | 36-40 | 40-45 | 45-50 | - | > 50 |
| | 35-33 | 33-30 | 30-26 | 26-21 | - | < 21 |
| Mean temp. crop development stage (2nd month) (°C) | 29-26 | 26-24 | 24-18 | 18-10 | - | < 10 |
| | 29-32 | 32-36 | 36-42 | 42-45 | - | > 45 |
| Mean min. temp. ripen. stage (4th month) (°C) | 20-18 | 18-14 | 14-10 | 10-7 | - | < 7 |
| | 20-22 | 22-25 | 25-28 | 28-30 | - | > 30 |
| Relative humidity (%) tillage+veg.stage (1st + 2nd month) | 65-60 | 60-50 | 50-40 | 40-30 | - | < 30 |
| | 65-75 | 75-90 | 90-100 | - | - | - |
| Relative humidity (%) at harvest stage | 50-37 | 37-33 | 33-30 | < 30 | - | - |
| | 50-65 | 65-80 | > 80 | - | - | - |
| n/N growing cycle | > 0.75 | 0.75-0.65 | 0.65-0.45 | < 0.45 | - | - |

**LANDSCAPE AND SOIL REQUIREMENTS - RAINFED UPLAND RICE**

| Land Characteristics | Class, degree of limitation and rating scale | | | | | |
|---|---|---|---|---|---|---|
| | S1 | | S2 | S3 | N1 | N2 |
| | 0 | 1 | 2 | 3 | 4 | |
| | 100 95 | 85 | 60 | 40 | 25 | 0 |
| **Topography (t)** | | | | | | |
| Slope (%) (1) | 0-2 | 2-4 | 4-8 | 8-16 | 16-25 | > 25 |
| (2) | 0-4 | 4-8 | 8-16 | 16-30 | - | > 30 |
| **Wetness (w)** | | | | | | |
| Flooding | no | - | F11 | F12-F13 | - | > F13 |
| Drainage (4) | good, | moder. | imperf. | poor, aeric | poor, drain. | poor, not drain. |
| (5) | imperf. | moder. | good | poor, aeric | poor drain. | poor, not drain. |
| **Physical soil characteristics (s)** | | | | | | |
| Texture/struct. | SiCs,Co, SiCL,Cl, Si,SiL | C-60s, C-60v, SC,L | C+60v, SCL,SL, LfS | LS,LcS, fS | - | S,cS |
| Coarse fragm(vol%) | < 3 | 3-15 | 15-35 | 35-55 | - | > 55 |
| Soil depth (cm) | > 120 | 120-90 | 90-50 | 50-20 | - | < 20 |
| **Soil fertility characteristics(f)** | | | | | | |
| Apparent CEC (cmol(+)/kg clay) | > 24 | 24-16 | < 16(-) | < 16(+) | - | - |
| Base saturation(%) | > 50 | 50-35 | 35-20 | < 20 | - | - |
| Sum of basic cations (cmol(+)/kg soil) | > 4 | 4-2.8 | 2.8-1.6 | < 1.6 | - | - |
| pH $H_2O$ | 6.5-6.0 | 6.0-5.5 | 5.5-5.0 | 5.0-4.5 | < 4.5 | - |
| | 6.5-7.0 | 7.0-7.5 | 7.5-7.9 | 7.9-8.2 | - | > 8.2 |
| Organic carbon(%) | > 2 | 2-1.5 | 1.5-0.8 | < 0.8 | - | - |

## 9.2.2. *Appendix 2b, land classes rainfed upland rice (Sys, 1991b)*

| SOIL AND TERRAIN CHARACTERISTICS | LAND CLASSES | | | | |
|---|---|---|---|---|---|
| | S1 | S2 | S3 | N1 | N2 |
| Climate (c) | According to separate evaluation | | | | |
| Topography (t) | | | | | |
| % slope (1) | < 4 | < 8 | < 16 | < 25 | > 25 |
| (2) | < 8 | < 16 | < 30 | < 30 | < 30 |
| Wetness (w) | | | | | |
| Flooding | no | no | no to slight | no to slight | any |
| Drainage (3) | good | moderate or better | imperfect or better | poor or better | very poor or better |
| (4) | imperfect | imperfect or moderate | good, moderate or imperfect | poor or better | very poor or better |
| Physical soil characteristics (s) | | | | | |
| Surface texture/structure (**) | C-60v to L | C+60v to LfS | C+60v to S | C+60v to S | Cm to Sc |
| Surface coarse fragments | < 15 | < 35 | < 55 | < 55 | > 55 |
| Subsurface texture (**) | C+60v to fLS | C+60v to Sc | C+60v to Sc | C+60v to Sc | Cm to Sc |
| Subsurface coarse fragments | < 35 | < 55 | < 55 | < 55 | > 55 |
| Depth to impermeable layer | > 90 | > 50 | > 20 | > 20 | < 20 |
| $CaCO_3$ (%) | < 6 | < 15 | < 25 | < 25 | > 25 |
| Fertility status (f) | | | | | |
| Apparent CEC at 50 cm (cmol(+)/kg clay) | > 16 | > 0 (-) | > 0 (+) | | |
| Sum of basic cations (0-25 cm) (cmol(+)/kg soil) | > 5 | > 2 | < 2 | | |
| pH $H_2O$ (0-25 cm) | 3.5-7.5 | 7.5-8.2<br>5.5-5.2 | 8.2<br>5.2 | > 8.2<br>< 5.2 | |
| Organic carbon (0-25 cm) (%) | | | | | |
| (5) | > 1.5 | > 0.8 | < 0.8 | | |
| (6) | > 0.8 | < 0.8 | | | |

(1) Intensive fully mechanized agriculture; (2) Primitive farming; (3) Fine loamy or clayey families; (4) Coarse loamy and sandy families; (5) Non-calcareous soils; (6) Calcareous soils.

(**) Textural sequence : **Cm** : massive clay; **SiCm** : massive silty clay; **C+60v** : very fine clayey, vertic; **C+60s** : very fine clayey, blocky; **C-60v** : clay, vertic; **C-60s** : clay, blocky; **SiCs** : silty clay, blocky; **Co** : clay, oxic; **SiCL** : silty clay loam; **CL** : clay loam; **Si** : silt; **SiL** : silt loam; **SC** : sandy clay; **L** : loam; **SCL** : sandy clay loam; **SL** : sandy loam; **LfS** : loamy fine sand; **LS** : loamy sand; **LcS** : loamy coarse sand; **fS** : fine sand; **S** : sand; **cS** : coarse sand

## 9.3. *Appendix 3: overview of sample analyses*

**Overview of the results of physico-chemical sample analyses**

| Number | pH | pH | OC | N | CEC | Ca | Mg | Na | K | Al | Exch. Acidity | Sand | Silt | Clay | Mean weighted diameter (mm) after | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | (H2O) | (KCl) | (%) | (mg/kg) | | | | (cmol+/kg) | | | | | (%) | | Fast wetting | Slow wetting | Mechanical Disturbance |
| 12/795 | 6.71 | 5.42 | 0.79 | 1945 | 15.69 | 5.23 | 1.19 | 0.99 | 1.20 | 0.03 | 0.08 | 2 | 89 | 9 | NA | NA | NA |
| 12/796 | 6.73 | 4.36 | 1.99 | 2179 | 17.63 | 5.42 | 0.93 | 0.47 | 0.44 | 0.21 | 0.27 | 2 | 73 | 25 | NA | NA | NA |
| 12/797 | 6.01 | 4.6 | 2.59 | 3967 | 23.38 | 5.50 | 0.96 | 0.27 | 0.87 | 0.15 | 0.22 | 2 | 81 | 17 | 3 | 3.3 | 3.3 |
| 12/798 | 6.25 | 4.56 | 1.60 | 1878 | 14.62 | 5.42 | 1.00 | 0.3 | 0.65 | 0.10 | 0.17 | 4 | 82 | 14 | 0.5 | 1.3 | 1.4 |
| 12/799 | 5.75 | 4.13 | 2.42 | 2482 | 19.25 | 4.58 | 1.15 | 0.22 | 0.46 | 0.51 | 0.64 | 2 | 78 | 20 | 1.7 | 3.2 | 2.7 |
| 12/800 | 5.71 | 4.05 | 1.74 | 1868 | 24.87 | 2.66 | 0.96 | 0.26 | 0.60 | 1.34 | 1.73 | 2 | 72 | 26 | 1 | 2.7 | 2.1 |
| 12/801 | 4.97 | 4.06 | 2.73 | 3179 | 26.16 | 3.93 | 0.85 | 0.31 | 1.16 | 1.44 | 1.58 | 2 | 73 | 25 | 1.7 | 2.1 | 2 |
| 12/802 | 5.69 | 4.45 | 2.32 | 2590 | 22.57 | 6.13 | 1.38 | 0.79 | 0.62 | 0.27 | 0.37 | 2 | 83 | 15 | 1 | 2.9 | 2.3 |
| 12/803 | 5.73 | 3.94 | 1.24 | 1590 | 21.06 | 0.59 | 0.94 | 0.53 | 0.54 | 2.03 | 2.39 | 2 | 87 | 11 | 2.3 | 3.3 | 3.1 |
| 12/804(A) | 5.25 | 3.58 | 1.67 | 1487 | 22.7 | 2.01 | 0.87 | 0.34 | 0.25 | 2.3 | 0.43 | 3 | 67 | 30 | 0.7 | 3.4 | 3.3 |
| 12/804(B) | 5.14 | 3.64 | 2.59 | 2682 | 35.74 | 0.68 | 0.70 | 0.38 | 0.33 | 3.93 | 4.04 | 2 | 78 | 20 | 2.1 | 3.3 | 3.1 |
| 12/804(C) | 5.20 | 3.58 | 3.13 | 3361 | 34.29 | 6.50 | 2.45 | 0.34 | 0.94 | 2.14 | 2.38 | 5 | 64 | 31 | 2.4 | 3.4 | 3.1 |
| 12/805 | 6.30 | 4.39 | 0.87 | 1793 | 57.82 | 30.42 | 7.07 | 1.16 | 0.77 | 0.03 | 0.15 | 1 | 27 | 72 | 0.3 | 1 | 0.4 |
| 12/806 | 5.93 | 4.06 | 1.32 | 1060 | 16.79 | 4.94 | 0.87 | 0.43 | 0.22 | 0.24 | 0.42 | 3 | 70 | 27 | NA | NA | NA |
| 12/807 | 5.64 | 3.93 | 1.26 | 1197 | 15.64 | 4.92 | 0.82 | 0.31 | 0.17 | 0.28 | 0.52 | 3 | 71 | 26 | 0.8 | 3.4 | 3.3 |
| 12/808 | 6.08 | 4.18 | 0.73 | 682 | 44.23 | 23.93 | 4.74 | 1.02 | 0.85 | 0.06 | 0.19 | 4 | 38 | 58 | 0.6 | 3.4 | 0.5 |
| 12/809 | 5.34 | 3.82 | 2.25 | 2171 | 21.62 | 6.42 | 1.35 | 0.27 | 0.36 | 0.62 | 0.88 | 2 | 71 | 27 | 1.1 | 3.3 | 3 |
| 12/810 | 5.11 | 3.85 | 3.71 | 3285 | 28.60 | 6.28 | 1.34 | 0.24 | 0.30 | 0.80 | 0.89 | 2 | 67 | 31 | 2.6 | 3.4 | 3.3 |
| 12/811 | 6.46 | 4.39 | 0.63 | 800 | 30.5 | 19.09 | 3.54 | 0.7 | 0.68 | 0.03 | 0.15 | 6 | 44 | 50 | 1.1 | 2.9 | 1 |
| 12/812 | 5.17 | 3.82 | 2.63 | 3125 | 40.31 | 9.89 | 3.43 | 0.22 | 0.47 | 1.01 | 1.20 | 0 | 36 | 64 | 2.2 | 1.4 | 3.2 |

**Overview of the results of the analyses of the soil water retention curve of the core rings, with number (n) of core rings taken at each location**

| Sample | n | Bulk density | Porosity | Moisture content (g water/g dry soil) at | | | TAW | Macroporosity |
|---|---|---|---|---|---|---|---|---|
| | | (g/cm$^3$) | (%) | saturation | FC | WP | (g/g) | (%) |
| **12/796** | 2 | 0.78 | 71 | 0.77 | 0.47 | 0.19 | 0.28 | 34 |
| **12/798** | 2 | 0.84 | 68 | 0.65 | 0.44 | 0.12 | 0.32 | 32 |
| **12/803** | 2 | 0.87 | 67 | 0.60 | 0.49 | 0.15 | 0.34 | 25 |
| **12/804(A)** | 1 | 0.85 | 68 | 0.67 | 0.46 | 0.08 | 0.38 | 29 |
| **12/811** | 2 | 1.01 | 62 | 0.50 | 0.41 | 0.28 | 0.13 | 21 |

## 9.4. Appendix 4: decadal climatological parameters

**Overview of the decadal climatological parameters at Jimma meteorological station (calculated for 1981-2005)**

| Month | Decade | Tmin | Tmax | P | Wind | Sunshine | ETo |
|---|---|---|---|---|---|---|---|
| | | Average (°C) | | Sum (mm/decade) | Average (m/s) | Average (h/day) | Sum (mm/decade) |
| Jan | 1 | 7.7 | 28.4 | 12.5 (19) | 0.4 | 7.8 | 33.5 |
| | 2 | 8.4 | 28.4 | 13.3 (17) | 0.4 | 7.4 | 33.6 |
| | 3 | 8.8 | 28.9 | 13.4 (14) | 0.5 | 7.7 | 39.0 |
| Feb | 1 | 8.8 | 29.2 | 10.6 (13) | 0.5 | 10.2* | 36.2 |
| | 2 | 9.3 | 29.7 | 8.5 (10) | 0.5 | 7.3 | 38.0 |
| | 3 | 10.3 | 30.1 | 14.1 (17) | 0.5 | 7.3 | 35.9 |
| Mar | 1 | 11.2 | 29.9 | 25.0 (22) | 0.6 | 7.1 | 40.1 |
| | 2 | 11.6 | 29.8 | 32.2 (34) | 0.6 | 7.1 | 40.7 |
| | 3 | 12.4 | 29.4 | 34.0 (21) | 0.6 | 6.7 | 44.1 |
| Apr | 1 | 12.7 | 29.1 | 32.4 (21) | 0.6 | 6.4 | 39.5 |
| | 2 | 13.0 | 28.9 | 50.4 (31) | 0.6 | 6.4 | 39.5 |
| | 3 | 13.2 | 28.2 | 50.4 (37) | 0.5 | 6.1 | 37.5 |
| May | 1 | 13.3 | 28.4 | 48.1 (26) | 0.6 | 6.7 | 38.9 |
| | 2 | 13.6 | 27.6 | 68.7 (32) | 0.5 | 6.2 | 36.8 |
| | 3 | 13.2 | 27.6 | 70.0 (41) | 0.5 | 6.9 | 41.4 |
| Jun | 1 | 13.3 | 26.6 | 66.2 (25) | 0.5 | 6.3 | 35.4 |
| | 2 | 13.6 | 26.3 | 70.8 (33) | 0.5 | 6.0 | 34.4 |
| | 3 | 13.6 | 25.5 | 72.9 (39) | 0.5 | 4.6 | 31.3 |
| Jul | 1 | 13.3 | 25.0 | 70.0 (34) | 0.4 | 4.4 | 31.3 |
| | 2 | 13.4 | 24.5 | 67.5 (24) | 0.5 | 4.8 | 30.2 |
| | 3 | 13.6 | 24.4 | 73.7 (32) | 0.5 | 3.4 | 32.9 |
| Aug | 1 | 13.6 | 24.6 | 69.2 (33) | 0.4 | 3.9 | 30.3 |
| | 2 | 13.6 | 25.0 | 67.1 (33) | 0.4 | 4.0 | 31.2 |
| | 3 | 13.6 | 25.3 | 73.9 (28) | 0.5 | 4.4 | 35.7 |
| Sep | 1 | 13.5 | 25.8 | 69.9 (25) | 0.4 | 5.3 | 34.5 |
| | 2 | 13.3 | 26.1 | 65.1 (26) | 0.5 | 5.8 | 35.3 |
| | 3 | 13.2 | 26.3 | 56.2 (35) | 0.5 | 5.8 | 35 |
| Oct | 1 | 12.7 | 26.5 | 44.1 (33) | 0.5 | 6.3 | 35.6 |
| | 2 | 11.5 | 27.2 | 41.7 (38) | 0.4 | 7.0 | 36.0 |
| | 3 | 10.1 | 27.3 | 28.2 (38) | 0.4 | 7.9 | 39.9 |
| Nov | 1 | 9.4 | 27.6 | 16.9 (27) | 0.4 | 10.4* | 35.3 |
| | 2 | 9.0 | 27.7 | 16.3 (21) | 0.4 | 7.9 | 34.3 |
| | 3 | 8.3 | 27.7 | 28.1 (41) | 0.4 | 7.9 | 33.2 |
| Dec | 1 | 8.2 | 27.9 | 15.8 (21) | 0.4 | 8.2 | 33.8 |
| | 2 | 7.3 | 28.0 | 13.8 (24) | 0.4 | 8.1 | 33.1 |
| | 3 | 7.0 | 28.3 | 9.7 (17) | 0.4 | 8.0 | 36.7 |

**Standard deviations for precipitation from 1981 till 2005 are given between brackets. Hours of sunshine with a * are outliers, but as they are outside the rainy season, they don’t affect the calculated ETo during the growing period**