Growth, Morphology and Biomass of *Arundinaria alpina (Highland Bamboo) (Poaceae)* as Affected by Landrace, Environment and Silvicultural Management in the Choke Mountain, Northwestern Ethiopia

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This is to certify that the thesis prepared by Yigardu Mulatu, entitled "Growth, Morphology and Biomass of *Arundinaria alpina* (*Highland Bamboo*) as Affected by Landrace, Environment and Silvicultural Management in the Choke Mountain, Northwestern Ethiopia" and submitted in partial fulfillment of the requirements for the Degree of Doctor of Philosophy (Biology/Botanical Sciences) complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

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ABSTRACT

Growth, Morphology and Biomass of Arundinaria alpina K. Schum (Highland Bamboo) (Poaceae) as Affected by Landrace, Environment and Silvicultural Management in the Choke Mountain, Northwestern Ethiopia

Yigardu Mulatu, Addis Ababa University, 2012

Arundinaria alpina K. Schum. (highland bamboo) (Poaceae) is the characteristic and definitive dominant species of Afromontane bamboo vegetation. It is found covering about 148,626 ha of land in Ethiopia. The current and potential advantage of this species is enormous. However, among others, lack of research information on the basic structure (morphology), its relation with environmental factors and silvicultural management has become impdement for enhancing productivity and yield of the resource. The objectives of this study, therefore, were to determine the variation in morphology, stand structure, growth and biomass among landraces and investigate the effects of environmental gradients and silvicultural management on stand structure, growth and yield of A. alpina. The result indicated that the rhizome proper of all landraces was nearly vertically positioned, exhibiting sympodial branching pattern and significant variation in rhizome neck length among landraces. Besides, stand structure, growth and biomass of A. alpina varied significantly along environmental gradient. DBH, height, growth rate and biomass (117 t ha^{-1}) of plants was foud to be superior for 40-60% concave slope landform as compared to 5-15% level-slopping. Therefore, superior performance of bamboo on this landform can be an *excellent opportunity for the area and the community. Moreover, it was observed that culm yield can be improved to 158-589% through the combined application of soil loosening, selective thinning and removal pof old stumps and protection from encroachment. Evaluation of propagation techniques indicated that culm cutting and branch cutting performed poorly; whereas, three rhizome-based techniques and the whole culm method demonstrated reasonably good performance. The whole culm method can be used to establish a plantation under similar environmental conditions and to produce starting materials for mass production of rooted plants. Rhizome and stump techniques can be directly used at field condition, but improved management than applied in this experiment may produce better survival rate. Finally, it is hoped that the information generated in this research will be used in the future resource development endeavors.*

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LIST OF ACRONYMS

AGTDW	Above Ground Total Dry Weight
AGTFW	Above Ground Total Fresh Weight
CEC	Cation Exchange Capacity
DBH	Diameter at Breast Height
C:N ratio	Carbon to Nitrogen Ratio
EC	Electric Conductivity
INBAR	International Network for Bamboo and Rattan
MAP	Months After Planting
SNNPRS	Southern Nations and Nationalities and Peoples Regional State
TDW	Total Dry Weight
TFW	Total Fresh Weight

CHAPTER ONE

1 INTRODUCTION

1.1 Overview of the Problem

There is nearly one million hectares of bamboo forest in Ethiopia having a huge potential for economic development and environmental benefits. If this resource is managed and utilized effectively, over 12 billion Birr can be generated every year (Melaku Tadesse, 2008). This output accounts for almost three times the gross value of production on handicrafts, urban informal sector industrial bamboo production operators and small scale manufacturing establishments in Ethiopia which is 3.6 billion Birr (CSA, 1997). Besides, bamboo can play a significant role in offsetting the tremendous deforestation, which is 150,000-200,000 ha $year^{-1}$, in the country (EFAP, 1994).

However, lack of awareness about the multiple uses of bamboo and scientific knowledge about their production and main properties have become impediments for utilization and conservation of the resource (Kassahun Embaye, 2000). Starting from the 1950's, donor-driven projects and other studies indicated the urgent need of sustainable utilization of the bamboo resource for different applications (Kassahun Embaye, 2000; Anonymous, 2008). But, activities at ground level towards sustainable utilization were almost abscent for long time, except some trainings particularly in 1970's on bamboo weaving (BWEGC, 1975). It is very recently that the potential of bamboo for economic development and its environmental benefits started to be acknowledged at public and higher officials levels.

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Despite its current and potential advantages for economic development and environmental benefits, bamboo resource of the country has been deprived of research attention so far. Up to now, only very few research activities have been done: vegetative propagation of highland bamboo (Tesfaye Hunde *et al.*, 2005); utilization of lowland bamboo stems as reinforcement steel (Melaku Abegaz *et al.*, 2005); suitability of highland bamboo for oriented particle board (Seyoum Kelemework, 2005; Seyoum Kelemework *et al.*, 2007) and ecological and resource management aspects of highland bamboo (Kassahun Embaye, 2000; Kassahun Embaye, 2001; Kassahun Embaye *et al.*, 2003; Kassahun Embaye *et al.*, 2005). However, information about the within and between species genetic diversity, growth dynamics, ecological interaction, physiological and morphological characteristics, large scale regeneration/propagation techniques, and knowledge on feasible rehabilitation and optimum silvicultural management techniques of bamboo is virtually absent in the country (FAO and INBAR, 2005). This PhD thesis research project is therefore stemed from the recognition of the aforementioned research problems.

Accordingly, basic premises, objectives and corresponding research components of this thesis that focus on the biology, ecology and silvicultural management aspects of *Arundinaria alpina* (highland bamboo) are presented in the following section. Then, an overview of Ethiopian Forestry and information on state of knowledge about the species (Chapter Two), materials and methods followed (Chapter Three) and research results and dicussion (Chapters Four and Five) are provided sequentially.

1.2 Research Premises and Objectives of the Study

The research addressed under this study had defined premises and objectives as described below.

1.2.1 Research premises

A) That landraces could vary in stand structure, morphology, growth and biomass

B) That topographic and altitudinal gradients (landforms) could influence stand structure, growth and biomass

C) That soil and plant management practices could enhance shoot recruitment in mismanaged bamboo forests

D) That different vegetative propagation techniques could influence shooting and rooting of vegetative buds under field condition hence could give rise to propagation material for further plantation

1.2.2 Objectives

The general objective of this thesis was to determine the effects of landraces, environment and silvicultural management on morphology, stand structure, growth and biomass of *A. alpina*. Specific objective include (1) determine morphology, growth and biomass of *A. alpina* landraces; (2) investigate the effects of topographic and altitudinal gradients (landforms) on stand structure, growth and biomass; (3) determine the effects of silvicultural management tehniques on shoot recruitment and culm yield of a mismanaged stand and (4) examine the performance of different propagation techniques in producing new shoots under field condition.

1.3 Description of Research Components

This thesis consists of four research components (two field studies and two field experiments) conducted from April 2009 to September 2010. The first study dealt with variation of *A. alpina* landrace in growth, morphology and biomass. The study was made on church bamboo forests of age greater than 60 years that by tradition have been harvested every 3-4 years.The second study dealt with the effects of topographic and altitudinal gradient on stand structure, growth and biomass of one *A. alpina* landrace, locally called TIFRO. This was conducted on farmers' bamboo plots of more than 30 years of age. The third research was a field experiment that aimed at investigating the effects of soil management practices and plant management techniques on shoot recruitment and culm yield. It was conducted on a communally owned bamboo stand that had been used for timber production and at the same time for livestock browsing. The last part of the research dealt with the response of different propagation techniques to shooting and rooting of vegetative buds under field condition. This experiment was conducted by establishing a propagation site adjacent to a bamboo forest that had been used for the first study (growth, biomass and morphology of landraces) in this thesis. Field investigations of the first and second studies were accomplished within six months (one growing season) while the third and last took 18 and 15 months (two growing seasons), respectively.

CHAPTER TWO

2. LITERATURE REVIEW

2.1 Overview of Forestry in Ethiopia

There is no accurate or reliable information about the extent and location of the present natural forest and woody vegetation cover in Ethiopia. However, the forest and woody vegetation resources of Ethiopia had been estimated to cover more than 27.5 million ha (out of the 113 million ha area of the country) or 24% in 1992 (EFAP, 1994). These resources comprised natural high forests, slightly and heavily disturbed high forests, woodlands, bush lands, plantations and on-farm trees. Nonetheless, in the recent past, natural forests of the country weredestroyed at alarming rate (EFAP, 1994) leaving the undulating landscapes bare. In view of that, the Ministry of Agriculture and Rural Development had already identified the current low degree of forest cover, estimated to be 3.5 percent of the land area (Bane *et al.*, 2008) as a major concern and that the recent forest policy has set out to increase this area to nine percent within five years.

Bamboo cover, as an integral part of Ethiopian forests, is not explicitly indicated in EFAP (1994) report. However, later, from more recent reports, bamboo cover of the country is stated to be about one million ha (LUSO, 1997; Kassahun Embaye, 2003), i.e. 67% of the bamboo in Africa and 7% of the world. The two indigenous bamboo species in the country are *Arundinaria* *alpina* (African alpine bamboo /Mountain bamboo /Highland bamboo) and *Oxytenanthera abyssinica* (Azene Bekele, 2007; Kassahun Embaye, 2003). LUSO (1997) and Kasahun Embaye (2003) estimated the total area coverage of *Oxytenanthera abyssinica* to be more than 800,000 ha, out of which only 481,000 ha was mapped and partially surveyed. Similarly, the total area of mapped naturally grown *Arundinaria alpina* is 129,626 ha and the area planted by farmers is estimated to be about 19,000 ha, together, summing up to 148,626 ha (FAO and INBAR, 2005).

Despite its vast coverage, bamboo resource of Ethiopia has been deprived of research and extension interventions so far. The research organization that is intended to handle forestry research (Forestry Research Center) that has also been expected to comprise bamboo, like many other countries in the world, has been undergoing restructuring being placed under different institutional setups. Currently, it is operating under the Ethiopian Institute of Agricultural Research (EIAR). However, since its inception in 1975, the Forestry Research Center (FRC) has been running different research programs and projects (Alemu Gezahegn, 2008). But bamboo, the high potential species and also good forest resource of the country has been hardly considered. There is only a pilot research on the utilization aspects of lowland bamboo as reinforcement steel, bamboo timber and composite materials and a trial on vegetative propagation of *Arundinaria alpina*. Surprisingly, forest extension packages both at federal and regional levels were not cognizant of bamboo.

2.2 Management of *Arundinaria alpina* (Past Experience)

In Ethiopia, there is no management plan for government owned natural bamboo forests. No protection what so ever from illegal harvesting, wildfire, pests and disease; no protection from encroachment and clear felling; no practical arrangements exist to manage, protect and utilize the forests. The government owned bamboo forests are actually nobody's forests that have been suffering from the "tragedy of the commons" (UNIDO, 2006). According to the same author, however, there is visible effect to manage and harvest the private (planted) *A. alpina* bamboo forests as they are considered supplementary activities that produce useful commodities in perpetuity to complement the main stay of livelihoods, which is food crop production and animal husbandry. Yet, the quality of management and harvesting is limited by the relatively low level of knowledge and skills of farmers. Management practices are based on the knowledge transferred to them from their fathers and fore-fathers and common sense (Ensermu Kelbesa *et al*., 2000; UNIDO, 2006; Arsema Andargachew, 2008). Management is mainly limited to harvesting by selecting old or two and more year old culms, undertaken by area basis rather than by clump, because stems are usually well separated (PROTA, 1989; Kassa Oyicha, 1997; UNIDO, 2007).

2.3 *Arundinaria alpina* K.Schum (State of Knowledge)

2.3.1 Taxonomy

2.3.1.1 Taxonomic position and circumscription

The circumscription of *Arundinaria* has been altered and in strict sense now only includes bamboos with monopodial rhizomes (Phillips, 1995). As *Arundinaria* has a sympodial rhizome branching pattern, the Chinees genera Fargesia (syn. *Sinarundinaria*) and *Yushania* seem more appropriate. However, *A. alpina* is excluded from these genera in some bamboo treatments and most probably represents a different genus (PROTA, 1989; Phillips, 1995). The genus *Arundinaria* belongs to the family *Poaceae* (*Gramineae*), subfamily *Bambusoideae* and tribe *Bambusaceae* (woody bamboos). Other names (Synonyms) of *A. alpina are Sinarundinaria alpina* (K.Schum.)C.S.Chao & Renvoize and *Yushania alpina* (Chi-son and Renvoize, 1989; ABS, 2006). The vernacular names include African alpine /mountain /highland bamboo (English), Babou Creux (French), Mianzi /Mwanzi (Kiswahili). This species is known in different languages /local names in Ethiopia. The following are few of them (Woldemichael Kelecha, 1987; IBC and GTZ, 2003; Azene Bekele, 2007): *Anini (*Agew); *Kerkeha (*Amharic); *Kias (*Gamu); *Shineto /Shinato (*Kefigna); *Lemmen, Shimela (*Afan Oromo); *Shenbek'wa* (Welayita); *lema* (Konso*,* Kembata, Sodo Gurage and Sidamo); *werye /shikaro /Shinato* (Kefa); *lewu* (Nuwer)*.*

Different authors including Breitenbach (1963), Mooney (1963) and Woldemichael Kelecha (1987) noted the names of Ethiopian highland bamboo. The specimen collected from southern Ethiopia (Hagere-Selam) by Dr Mooney (the first collection of the species) and identified as *Arundinaria alpina* K. Schum in 1954 is found preserved in the National Herbarium (ETH) Addis Ababa University, to date. However, how and where the name *A. alpina* was known for Ethiopian highland bamboo is not documented. But from species identification history of the National Herbarium (ETH), the following can be speculated. The pre-herbarium establishment botanical collection i.e. the first botanical exploration by Dr Mooney, dates back to 1953 to the southern parts of the country in which he collected as many as a thousand specimens. The National Herbarium was established in 1959 (Ensermu Kelbessa, 1986) but determination had been done by dispatching specimens to the Royal Botanical Garden (Kew) through the British Embassy (Mesfin Tadesse, 1991). It should be during this time (1954 as indicated in the herbarium collection of Dr Mooney) that the name *Arundinaria alpina* was assigned to Ethiopian highland bamboo by relating it with the then bamboo species collected from Asia and America at the Royal Botanic Gardens, Kew. Here, it is important to note that still today the Royal Botanic Gardens, Kew, is responsible for the world's largest collection of living plants (Wikipedia, the free encyclopedia).

2.3.1.2 Taxonomic problems

According to PROTA (1989) and Watanabe *et al.* (1994), *Arundinaria* has been included in several genera, but in recent molecular phylogenetic analysis its exact position is within the so called *Thamnocalamus* subtribe. But still nomenclature remains less than clear as allies in the phylogenic analysis remained unclear, hence more research is needed.

According to Chi-son and Renvoize (1989), the bamboo species in South Asia and Africa had been taxonomically studied by Munro (1866), Gamble (1896) and A. Camus (in several publications), whose work received much acclaim in their time. The same author stated that there were 29 species of *Arundinaria* in the world in Munro's monograph, 28 species in the Himalayan region in Gamble's monograph and 14 species collected from Indo-China and Madagascar named by *A. Camus* and *P. Balansa*. In the course of their study, Chi-son and Renvoize (1989) examined most of the type specimens of these species and came to the conclusion that only two species are true *Arundinaria* and transferred the others to seven other genera. They grouped the bamboos that have (1) sympodial rhizome with short or long necks lacking buds and roots, (2) culms erect, branch complement without a conspicuous dominant branch, (3) inflorescence exserted, an open panicle or raceme, supported by small narrow sheaths under *Sinarundinaria* or *Yushania* Keng. *Sinarundinaria* occurring in Asia, America, Africa and Madagascar, are very important bamboos in the mountains, especially at high altitudes (Chi-son and Renvoize, 1989). In the Himalayan region, the species are usually the dominant plants under the coniferous or broad-leaved forests of high mountains, forming their own extensive understory bamboo forests.*Yushania* is a genus comprising approximately 50 species, 2 in Central America, three in Africa and Madagascar, the rest in Asia.

Cooper (2011) stated that isolated botanists in China, Japan and India used widely differing systems for the same bamboos come up with different names. According to the same author, geographic remoteness of many bamboo rich areas such as the Himalayas and China has been exacerbated by political problems between countries such as China, India, and Japan over the last century. Because of such problems in naming the species, the Flora of Ethiopia and Eritrea preferred to maintain the old name *Arundinaria alpina* until it becomes clear (Phillips, 1995). Owing tothe same reason, the name *Arundinaria alpina* is used in this thesis

2.3.1.3 Botanical description of *A. alpina*

Arundinaria alpina (highland bamboo) is a very large and perennial woody grass; woody culms up to 12 cm in diameter at the base and rising to 15 m from a stout branching rhizome, thick walled but clearly hollow (Azene Bekele, 2007; Phillips, 1995). These two authors described *A. alpina* as follow:

Stems: Smooth, woody and hollow, growing from swollen underground stems (rhizomes). Whorls of thin branches grow at the upper nodes between stem sections. In good conditions, stems may be 7-10 cm in diameter.

Leaves: Grow from the branchlet nodes, pale green, 20 x 1 cm, the tip long and thin and feel rough due to short hairs.

Culm sheath: Densely pubescent with reddish-brown bristles, tipped with a linear blade 0.6 cm long and fimbrate auricles. Leaf blade linear-lanceolate, 13-20 cm long and 8-16 mm wide, conspicuously cross-veined, the tip extended into a fine flexuous bristle up to 2 cm long; blades and the prominent fimbriate auricles tardily disarticulating from the sheath.

Inflorescence: Paniculate, panicles 10-15 cm long, loose to fairly compact; spikeletes 4-11 flowered, linear-elliptic, 1.5-4.8 cm long; glumes ovate; lemmas lanceolate-oblong, 0-12 mm long, pubscent, acute, acuminate or awn-pointed.

2.3.2 Biology

2.3.2.1 Plant growth and stand development

The mature *A. alpina* plants, mainly from 1 to 2 years old, produce shoots every year throughout the rainy season. The shoots attain full height in 2-4 months and branch in the following year. New culms are softer and less woody than older culms. Rhizome networks producing new stems annually may survive for at least 40 years, but individual stems survive only for 8-14 years. New stem production is a seasonal process, allowing cohorts of stems in different age classes to be recognized. By the fourth year of growth the stems are glabrous and sufficiently rigid for use as poles (Were, 1988). Similarly, Seyoum Kelemework (2005) reported that culms of *A. alpina* in

Ethiopia need about three years for complete maturation of tissues and to be used for industrial application.

It is commonly known that the production of new culms can be very prolific one year and quite sparse in another year, i.e. the growth rate may vary widely between the individual growing seasons (Were, 1988). LUSO (1997) indicated that there might be some years when no new culms appear at all. Production of new culms is influenced by two major factors: ample soil moisture and good rainfall (Were, 1988) but from experience of other bamboo species, production of new culms is highly linked with the leaf growth cycle but not principally by climatic conditions (Quantai *et al.*, 1993). Sparse production of new culms happens particularly in years following an abnormal drought. These seasonal fluctuations are quite pronounced in undisturbed stands, but less marked in areas where the crops are regularly managed (LUSO, 1997). If the older culms are not removed from the clump, they restrict the development of the rhizome system and subsequent emergence of new shoots (Were, 1988).

2.3.2.2 Rhizome Morphology

The term ‘rhizome’ is used generally to describe the subterranean system of bamboos (McClure, 1966). According to McClure (1925; cited in Liese, 1998) the terms “monopodial” and “sympodial” were introduced by McClure to characterize parts of the rhizome system for the first time. These terms were used to describe only the branching pattern of the rhizome, but not the clumping habit of bamboos (Meredith, 2001). In sympodial branching, each succeeding branch or axis becomes dominant, turning upward and becoming a culm. In monopodial branching, a single dominant stem or axis gives rise to secondary branches or axes. According to Liese, (1998), it was Takenochi who adopted McClure's terminology of rhizome branching pattern, but he later (in 1932) developed the concept of "leptomorph" and "pachymorph" to describe the rhizome system. This view was subsequently accepted by McClure (1966). Ding *et al*. (1996) reviewed the terminology and suggested that only "running bamboos" have a genuine rhizome; the subteranean part of "clumping bamboos" is a part of the culm axis.

Most authorities have generally adopted the terms pachymorph and leptomorph to describe rhizome types. Separating branching habit (sympodial, monopodial, amphipodial) from rhizome morphology (pachymorph, leptomorph) is a step forward in clarity. Culm and clump spacing refers to whether the spacing of culms is caespitose (closely spaced), diffuse (widely spaced) or pluricaespitose (culms arise in dispersed clumps). Informally culm and clump spacing is expressed as clumping and running (Meredith, 2001).
Arundinaria alpina was reported to be a (robust) clumping /sympodial /pachymorphic species that under cultivation maintains very strong clumping characteristic (Breitenbach, 1963; Phillips, 1995; Kigomo, 2007) whereas non-clumping /monopodial /leptomorphic species by Were (1988), Kassahun Embaye (2005), Seyoum Kelemework (2005), Kigomo (1988a, b). Wimbush

(1945) described that *A. alpina* occurs gregariously (not in clumps) within mountain forests in tropical Africa.

How far apart do culms need to be for sympodial and monopodial bamboos is not quantitatively defined. A rhizome neck length is also subjected to differences in site conditions and the growing season (Kawai *et al.*, 2008; Kawai *et al*., 2010). For instance, *Olmeca reflexa* is a pachymorph bamboo, its culms can be spaced as far as 8 m apart. *Fargesia nitida* and *Chusquea aff.culeau* have pachmorph rhizome system but the distance between culms is far greater (Meredith, 2001). In pachymorph species, the distance between the culms depends on length of the rhizome neck and position of the rhizome (McClure 1966). Vertically positioned rhizomes e.g. *Guadua angustifolia*, in Costa Rica, gives rise to densely caespitose clump whereas in horizontally positioned rhizomes with long rhizome necks, culms grow sparsely forming open clump. For instance, *Guadua angustifolia* that has horizontally positioned rhizome has minimum separation of 0.85 m and maximum separation of 1.7 m (Farrelly, 1984). Accordingly, the term “clumping” used in classifying bamboos is a relative term. Clumping species in Asia for instance *Giantochloa scortechinii, Dendrocalmus asper* and *Dendrocalmus gigantus* have pseudo rhizome neck that is part of the rhizome proper. That is why they have highly tufted culms within their clump. Separating each plant from the system is hardly possible because they have no space in between. One cannot pass through a clump unless it is opened because of harvesting or some disturbance. Commercial weight tables are predicted using clump diameter (Krishnankutty and Chundamannil, 2005) rather than in area basis.

The rhizome morphology of highland bamboo has been described as leptomorph having scientific name *Arundinaria alpina* since so long. But currently, *Arundinaria alpina* is given another ~~new~~ name (ABS, 2006) and the rhizome branching is described to be sympodial (Ohrnberger, 1999; Meredith, 2001). Different authors described the rhizome branching pattern of *A. alpina* as monopodial and simpodial. According to Meredith (2001), researchers had incorrectly grouped some bamboos with pachymorph rhizome system (and sympodial branching) including *Arundinaria* with bamboos that have leptomorph rhizome system (and monopodial branching). Although *Arundinaria* has pachymorph rhizome, the rhizome has very long necks and thus diffuse culm spacing.

The researchers had confused culm spacing and clump habit with rhizome type (and the rhizome type was also incorrectly characterized by terms that should have been used to describe branching habit rather than rhizome morphology). A system that separately describes culm and clump habit in conjunction with rhizome form is now in place at Britain's Royal Botanic Gardens, Kew (Meredith, 2001).

Clump forming bamboos have rhizomes that exhibit a sympodial branching pattern. Running bamboos, on the other hand, have rhizomes with a *monopodial* branching pattern (Meredith, 2001). Bamboos with pachymorph and leptomorph rhizomes can have the same clump habit. Conversely, bamboos with the same rhizome morphology can have different clump habits.

For example, both *Guadua angustifolia* (pachymorph rhizome) and *Phylostachys vivax* (leptomorph rhizome) have diffused (widely spaced) culms.

2.3.2.3 "Assumed" varieties of *A. alpina*

In Ethiopia, under field conditions, there are "assumed" varieties of highland bamboo mainly varying in their growth characteristics, morphological attributes and wood working properties (LUSO, 1997; Azene Bekele, 2000; SIM, 2002). Near Masha, one of the bamboo growing areas in Ethiopia, there are two types of natural highland bamboos showing different colors of the culm (LUSO, 1997). Near Kosober, major portion of the stands (about 60%) have green color culms while minor portion (about 40%) have yellow culms (personal observation and discussion with Awi Zone office of Agriculture and Rural Development). Still near Kosober, a few clumps of yellow stripped highland bamboo have been found (LUSO, 1997; SIM, 2002). The variation in wood working properties is also recognized by the local craftsmen who use culms to produce different bamboo products (SIM, 2002). In the Choke Mountain, four or even more "assumed" varieties differing in their morphological characteristics, utilization, regeneration and management need from one another are recognized by the community. Characterization of the landraces by the local community is presented in Appendix A. All these reports and field observations stressed that there should be scientific research to confirm the variations. Investigation conducted concerning landraces in this study is partly emanated from these recommendations.

Cultivating the various “assumed” varieties of *A. alpina* in the Choke Mountain has been going on for centuries (preliminary survey before the start of this reaserch). Hence, according to the definition by Cleveland *et al.* (1994), the “assumed” varieties can be called landraces. The term landrace refers to a local variety of a domesticated plant which has developed by adaptation to the natural and cultural environment in which it lives. For perennial crops and crops with vegetative reproduction like bamboos, the term landrace is used when the crop has been cultivated and reproduced in the area for more than 60 years (Calvet-Mir *et al*., 2011). Negri *et al*. (2009) defined landrace as a variable population, which is identifiable and usually has a local name but lacks ‘formal’ crop improvement, is characterized by a specific adaptation to the environmental conditions of the area of cultivation and is associated with the traditional uses, knowledge, habits, dialects, and celebrations of the people who developed and continue to grow it. This definition emphasizes the aspects of a longstanding, unbroken and active management of landraces in a specific human context (Negri *et al*., 2009). Landraces are also called falk varieties, traditional varieties, or primitive variety (Cleveland *et al.* 1994).

2.3.2.4 Regeneration and propagation

It is generally assumed that *Arundinaria alpina* plants die after flowering, although development of new shoots from parts of the rhizome network surviving after flowering has been noted in Kenya. Following mass-flowering, regeneration is usually from surviving rhizomes and only very seldom from seed (Agnew, 1985; Bussmann, 1994). Bussmann (1994) found evidence that rhizomes can persist for decades before making clumps. Bussmann (1994) and Agnew (1985) emphasized the vulnerability of young shoots to large mammal browsing in Kenya, although there is no proof that this ultimately causes the extinction of a regenerating bamboo-area. Farmers in north western Ethiopia (Choke Mountain) harvest culms immediately after flowering so as to get new shoots from the rhizome during the next rainy season (discussion with farmers and field visit of regenerated stands after flowering). Most seeds of *A. alpina* are empty, viability is low (LUSO, 1997). There is considerable evidence that *A. alpina* is a pioneer species that benefits from disturbance (Grimshaw, 1999). Estimates of the interval between flowering events vary from 15 years (Mount Elgon, Kenya) to 40 years at Aberdares Range, Kenya (PROTA, 1989). Flowering may be synchronous in patches several hectares in extent within a population. LUSO (1997) reported flowering in Ethiopia is scattered every year becoming more abundant every seven years.

Besides waiting for regeneration from seed and persisting rhizomes, establishment of stands from rooted plants employing vegetative techniques is a widespread technique in bamboos. Nowadays, vegetative propagation techniques are standardized and adopted to improve self-incompatible bamboos with poor seed set for Asian bamboo species (Lal *et al.*, 1998; Koshy and Gopakumar, 2005; Uchimura, 1980). Several methods of vegetative propagation techniques using offsets, rhizomes, culm and branch cuttings, layers and macroproliferation of rooted plants are being practiced for different species (Banik, 1995; Kleinhenz and Midmore, 2001; Pattanaik *et al.*, 2004; Othman, 2005). These methods also suit to the requirements of farmers and non-government organizations (NGOs) for their low cost and ease of management. Unlike tissue culture /micropropagation techniques, macropropagation techniques do not require laboratory facilities, expensive chemicals, etc. (Jiménez and Guevara, 2007). Rhizome-based propagules can be directly planted into the field. In the cutting methods, culm cuttings or branch cuttings of desirable sizes are planted in polybags or nursery beds to raise saplings (Koshy and Gopakumar, 2005).

Rhizome-based vegetative propagation technique is a time-tested and widely practiced method in Asia (Banik, 1995; NMoBA, 2004). A segment of the rhizome is severed or separated from the parent rhizome and nurtured to develop into an independent source of planting material. The detached portion of the rhizome carries all the elements needed for the growth of a new plant. It may be separated with other parts of the plant such as rhizome offsets, roots and culm. Common to all methods of rhizome-based propagation is the cutting away of a part of the rhizome from a healthy and mature clump.

Nevertheless, studies on propagating *A. alpina* are limited. From a research done in southern Ethiopia, the offset /traditional method and culm cutting were found to be superior propagation techniques (Tesfaye Hunde *et al.*, 2005). However, the offset method, i.e. the traditional method used by farmers has shortcomings as (i) the offsets are bulky, heavy and hence difficult to transport, (ii) the offsets that can be extracted from established clumps are limited and therefore large scale plantation is not possible, (iii) excavating out offsets and their transportation are labor intensive and expensive, (iv) continued extraction of offsets and cuttings often cause damage to the parent clumps (Koshy and Gopakumar, 2005). On the other hand, studies on culm cutting, collected from the same area, at laboratory level reported that the success of rooting and survival of sprouts from *A. alpina* culm cuttings was very poor (10% after seven weeks) hence may not be economically feasible (Kassa Oyicha, 1997).

2.3.3 Ecology

2.3.3.1 Distribution

According to Phillips (1995) and Azene Bekele (2007), *Arundinaria alpina* is found in Gojam, Gamu Gofa, Kefa, Sidamo and Bale regions and Shewa Upland in Ethiopia. It covers a large area between Bale Mountain, Bonga and Metu in south west part of Ethiopia and up to Dangla in the North (Figure 1). These bamboo stands are situated in important agricultural zones with former (high) forests, where rainfall is adequate, with *Podocarpus* in upland and

Juniperus in drier forest. It is frequently planted along roads and villages. It is also recognized that many National Forest Priority Areas of Ethiopia have highland bamboo within: Belete-Gera, Jibat, Kolbu, Munesa, Sigmo, Tiro-Boter-Baecho, Bonga, and Wofwasha National Forest Priority areas are worth mentioning for their highland bamboo (IBC and GTZ, 2004). Northern highlands such as Denkoro (South Welo), Debre Tabor area (South Gonder), Qendach and Choke Mountain (East Gojjam), Enjibara (West Gojjam) are also bamboo growing areas (personal observation).

The species is also distributed inother East African Mountains, Cameroon, Mt. Zaire (Kivu), Rwanda, Burundi, Sudan (Imatong Mts.) and Malawi (Nyika Plateau) (Phillips, 1995). In Kenya, *Arundinaria alpina* is the only indigenous bamboo species and occurs in irregular patches in the central highlands, particularly in Timboroa plateau (31,000 ha), Aberdare range (65,000 ha) and in Mount Kenya, Elgon, and Maurange (51,000 ha) (Kigomo, 1988a). Its total cover in Kenya is about 150,000 hectares. In Uganda, this species grows in Rwenzori, western Elgon, and Mounts Virunga and Mgahinga (Clayton, 1970). In Tanzania, it grows in Mbulu, Arusha and Mbeya districts on the highlands of Iringa, Lukwangule and Ulugurus and Mount Meru. It is interesting that occurrence of this bamboo species on Africa’s highest mountain, Kilimanjaro, is rare (Grimshaw, 1999; Hemp, 2006) and yet is abundant on Mount Meru, only 48 km away. Generally, distribution in Africa comprises west-central tropical, northeast tropical, east tropical, and southern tropical parts (Clayton *et al.,* 2002).

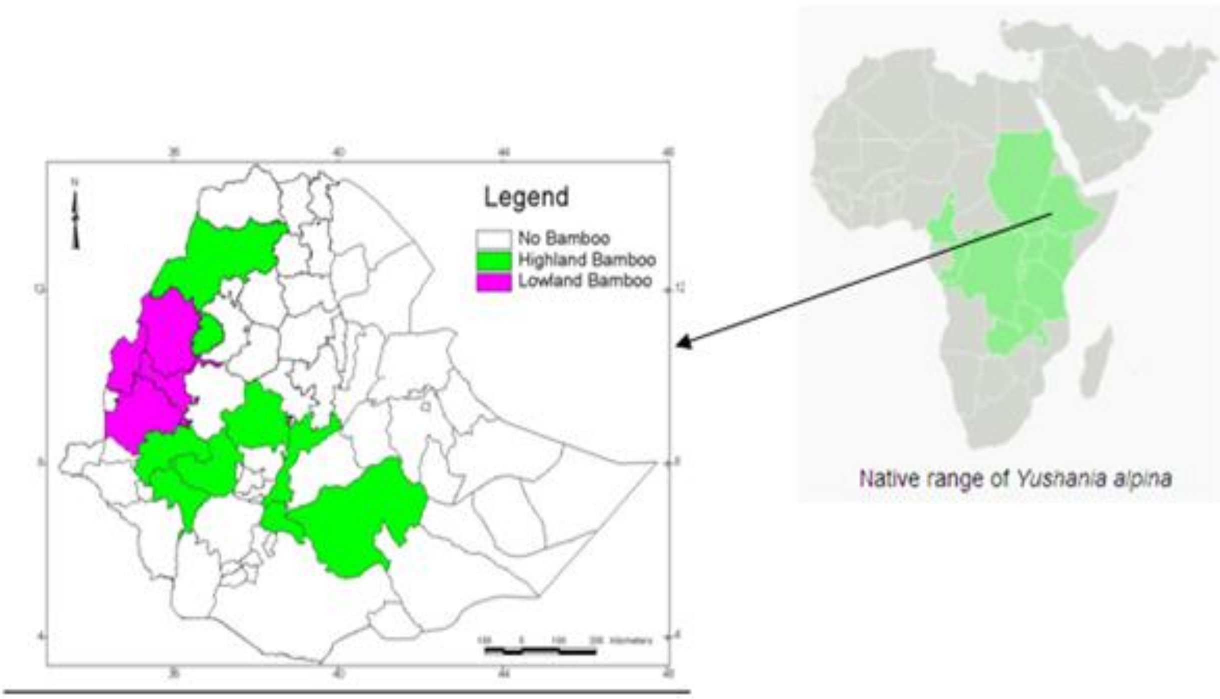

Figure 1. Distribution of *Arundinaria alpina* (syn: *Sinarundinaria alpina*) in Africa and Ethiopia. Sources (1) Wikipedia - the free encyclopedia (2008); *(2)* Forestry Research Center (2007).

2.3.3.2 Relationship with broad environmental factors

Arundinaria alpina is restricted to high elevations (2200-4000 m altitude) and is the characteristic and definitive dominant of Afromontane bamboo vegetation (PROTA, 1989; Philips, 1995). It also occurs in abandoned fields and it can form extensive pure stands. Afromontane bamboo vegetation occurs in cool growing conditions, with average annual temperatures of 14–17°C. Average monthly maximum temperatures are 13–32°C, and average monthly minimum temperatures range from –4°C to 11°C, implying that some populations tolerate frost. Rainfall is seasonal, with 3–6 dry months (mean rainfall less than 50 mm) in eastern Africa, but only 2 dry months in Cameroon. Annual totals vary from 800 mm in Tanzania to 1400-2000 mm in Ethiopia and 3000 mm in Cameroon (Phillips, 1995; PROTA, 1989). Climate requirements over-ride soil type requirements, with occurrences on impoverished ferralsols, moderately fertile cambisols, and richer andosols and nitisols. It is often found on volcanic soils and forming extensive pure stands in Ethiopia (Azene Bekele, 2007). Well-drained humus-rich soil on gentle slopes and in ravines, with space for vigorous rhizome development, allows luxuriant growth. On shallow soils and rocky ground individuals are stunted.

2.3.3.3 **Site factors**

Bamboo stand yield in a site is a function of locality /environment and stand structure. The locality class is determined by the soil and topography of the stand. The most important soil factors are the soil mineral and moisture (Chen, 2000; Chung and Ramm, 1990). The soil mineral and moisture of valleys and plain land, hillsides and ridges and soil texture created on these land features are different. The topography of the stand has significant but indirect effect on bamboo stand yield. The conditions of the topography such as the altitude, aspect, slope and physical properties such as texture and moisture holding capacity have considerable effect on bamboo growth (Kleinhenz and Midmore, 2001). Howevere, there is no well defined research on the topography, gradient, drainage and soil texture preferences of *A. alpina* in Ethiopia.

2.3.4 Management and silviculture

An important key in the implementation of sustainable forest is the implementation of silviculture as an objective guide in management of forest resources (Priyono, 2010). According to Smith *et al*. (1997), silviculture is the oldest conscious application of ecological science and the best known term before the term “ecology” was coined. Silviculture covers science, business, art and practice of deliberately creating and managing forest resources to provide sustainable benefit for the society (Guldin, 2006).

Productivity of bamboo stands can deteriorate because of different reasons. In ancient China, overharvesting of 1-year-old culms for paper making harmed bamboo populations (Fu and Banik, 1995), while harvesting of 2-year-old culms resulted in depleted bamboo stands in Indonesia (Sutiyono, 1987). Anthropogenic factors like intensive shoot harvesting and herbivory can also cause reduced timber yield (Wang *et al.*, 2007; Suzuki and Nakagoshi, 2008). Regeneration of *Bambusa bambos* was adversely affected in the inappropriately harvested clumps and resulted in the depletion of the resource (Krishnankutty, 2005). If plantations are left unmanaged, productivity declines after six years of age (Shanmughavel, 1997a), because of decline in photosynthesis, congestion and reduction in number of upcoming culms. Clump congestion in bamboos is one of the most series problems of management (Were, 1988; Shanmughavel, 1997b; Kleinhenz and Midmore, 2001). It may be due to (a) too much soil compaction mainly by animals, (b) insufficient soil depth for rhizomes and (c) development of too many rhizomes especially on river banks.

On the other hand, many studies indicated that application of different management practices including cultural operations and appropriate harvesting techniques help to rehabilitate /regenerate bamboo stands and sustainably increase growth (the number of shoots, culm diameter and height) and yield. Scientific management is one of the key factors for maximizing productivity of bamboo stands. Accordingly, different plant and soil management practices (intensive and extensive management) such as fertilization, weeding, soil loosening and deep tilling were applied for different Asian bamboo species such as *Dendrocalamus strictus, Bambusa cacharensis, B. vulgaris* and *B. balcooa* in India (Nath *et al.*, 2006); *Phylostachus pubescens*, *Bambusa oldhami* and *Dendrocalamus latiflorus* in China (Xu *et al.,* 2008; An *et al.*, 2009) and *Gigantochloa scortechinii* natural stand in Malaysia (Azmy *et al.,* 2004; Othman *et al.,* 2007). Selective thinning of natural bamboo forests, i.e. selectively removing old, malformed and congested culms accompanied by soil loosening was one important silvicultural measure that helped to improve bamboo productivity (Midmore, 2009). The application of large scale cultural operations such as removal of half cut, curved, malformed and dry bamboos and covering rhizome with soil applied on degraded *Dendrocalamus strictus* has given rise to overall production increased tremendously (30% in new sprouts) even by treatment of only a part of the area in India (Jain, 1995). Soil mounding to a depth of 10 cm has also showed significant increase in shoot recruitment of *Gigantochloa* *scortechinii* bamboo in Malaysia (Azmy and Hall, 2002). Removing old stumps (degenerated bamboo rhizomes) is applied in intensively managed high-yield model stand of moso bamboo for pulp-making in China to increase culm production (INBAR, 2005).

There are only very limited research works on silviculture and management of *A. alpina* in Africa. Attempts to germinate seed of African alpine bamboo from the few seed crops in nursery beds and watered daily have germinated well in Kenya. Seedlings 2–3 cm tall transferred to soil boxes and planted out 8–12 months later, at 2 m spacing produced a stand with stems up to 12 m tall and 5 cm in diameter after 6 years (PROTA, 1989). In Ethiopia and Uganda, offsets are often planted. Offsets used for propagation by Ethiopian farmers are single stems pruned at 8-9 nodes above the base. In Kenya, experiments have been successful by using offsets (single stems shortened to 60 cm, with attached rhizome), clump division (groups of 5 stems shortened to 60 cm, with the parent rhizome) and 20 cm lengths of rhizome as propagules. Offsets from plants produced in the previous growing season are preferred. Stem cuttings have not produced shoots, not even after treatment with rooting compounds (PROTA, 1989; Kassa Oyicha, 1997). However, Tesfaye Hunde *et al.* (2005) indicated that culm cuttings and culm layering methods could be successfully used to propagate *A. alpina* vegetatively. Literature on production of rooted plants from culm cuttings of *A. alpina* are not in harmony to each other; further study is needed to fine-tune the discrepancies.

2.3.5 Pest and disease

Association of African alpine bamboo with the basidiomycete *Armillaria mellea* has been reported in Kenya and there is suspicion that the fungus spreads from a reservoir in the bamboo to planted pines and hardwood trees (PROTA, 1989).

2.3.6 Harvesting

There has not been research done in Ethiopia for harvesting of both natural and plantation bamboo stands. However, some survey reports have investigated the traditionally applied harvesting practices (Ensermu Kelbessa *et al.*, 2000; UNIDO, 2007; Arsema Andargachew, 2008). Harvesting from plantations is carried out all-year-round when required by resource-poor homestead bamboo cultivators for whom it is a supplementary source of income. Harvesting from natural stands is unregulated and is resulting in the severe depletion of the natural resources (Ensermu Kelbessa *et al.*, 2000). Bamboo is harvested at its 2-4 years of age. Culms harvested at 4 years old age fetch higher prices (UNIDO, 2007). Bamboo is harvested during January and February while there is no harvest during the months of Mayto August. While harvesting communal bamboo stands in northwest Ethiopia, the community assigns knowledgeable persons who can guide the selection of harvestable stems (more than two years old). Harvesting practice uses primitive tools, resulting in damage to the stands and increased wastage (Ensermu Kelbessa *et al.*, 2000; Arsema Andargachew, 2008).

According to PROTA (1989), natural stands of African alpine bamboo can be clear-felled but recovery is slow, development of full-sized stems taking 9–10 years. Stems must be full-sized and at least three years old before they can be exploited for structural use, and numbers must accumulate to levels making harvesting worthwhile, hence felling cycles of 14-21 years have been recommended. Felling cycle can be reduced to 5-6 years on good sites if modest yields are acceptable and 50% of the mature stems are retained. Harvesting of stems under two years old (suitable for weaving) and harvesting of edible shoots as vegetable are rainy season activities.

2.3.7 Yield

The dry weight of a standing crop of stems of well-stocked stands in Masha natural bamboo forest, Ethiopia has been estimated at 51 tha^{-1} by LUSO (1997) and 110 t ha^{-1} by Kassahun Embaye (2003) and in Kenya at 97 t ha^{-1} (PROTA, 1989). With a five-year cutting cycle exploiting only mature stems, representing 20% of the number of stems present, a potential yield of 10 t $ha^{-1}year^{-1}$ has been estimated for Ethiopia. Better management might raise this to 15 t ha^{-1} $year^{-1}$ (PROTA, 1989).

2.3.8 Post handling after harvest

Stems for construction are stripped off branches and trimmed to lengths of 7.5–9 m. Drying and protection against the powder-post beetle *Dinoderus minutus* attack are advisable. Protection of complete stems with preservative solutions is difficult but it is assumed that soaking in water for 2–3 months, widely used with other bamboos, may provide some protection. In Uganda, internodes of stems harvested for weaving material are cut into slivers which may be bundled and stored for several months before use. Edible shoots are sun-dried or smoked and can be stored for up to two years (PROTA, 1989). In Ethiopia, placing in drying sheds in a slanting position against a horizontally placed beam is the practice of drying bamboos by the Forestry Research Center.

2.3.9 Utilization

The strength and dimensional stability of particle boards manufactured from bamboo was determined by Seyoum Kelemework (2005). It is concluded that particle boards from *A. alpina* meets the ISO standards ISO/DIS 16978, ISO/DIS 16984 and ISO/DIS 16983 for high performance general purpose particle board. The species has all required properties for fiber board production as it has low density and hence requires less glue when fibers are processed into board. Besides, results of further wood testing (density, fiber length, cell wall thickness, wettability and buffering capacity) of *A. alpina* proved that the species fulfills the ISO standards for industrial products such as ply board, laminated bamboo lumber (LBL), oriented strand board (OSB), medium density fiber board (MDF) and floor boards (FRIM, 2008). Seyoum Kelemework (2008) and Seyoum Kelemework *et al.* (2008) also showed that a number of industrial bamboo products including pulp and paper, charcoal, furniture, edible shoots can be produced from highland and lowland bamboos. However, to date, production and consumption of the resource is traditional yet; processing of bamboo to bamboo products is not advanced, value addition is minimal due to poor processing technology (UNIDO, 2007). There is only one modern bamboo industry in Ethiopia that started functioning as of 2002 and others seem in preparation to come into being.

Communities in Ethiopia have history of customary utilization of *A. alpina*. It is used for diverse functions including construction of houses, mats, fencing, tool handles, umbrella, broom, wine storage barrels, musical instruments, crafts making and in animal and human bone setting in the traditional medicinal practice (Wassihun *et al*., 2003). From a study conducted at Hagereselam, SPNNR, and Enjibara (Awi Zone, Amhara) communities, bamboo is an important part of the farming system and serves as a major source of livelihood. Farmers use bamboo resources as their bank account; bamboo provides a ready source of livelihood (UNIDO, 2007).

Arundinaria alpina is also used for livestock and wildlife browse. The Bale Monkey (*Chlorocebus djamdjamensis*) that is endemic to the forests of the Bale Massif and Jamjam areas of Ethiopia feeds on bamboo (*A. alpina*) i.e.

responsible for a remarkable portion (76.7%) of their diet, with most (95.2%) of the bamboo consumption consisting of young leaves (Addisu Mekonnen *et al.,* 2010). The sustainable living of this wild endemic animal is strongly associated with the sustainable management of *A. alpina* bamboo forest in the area. Bamboo harvesting by local people for commercial purposes places Bale Monkey at risk of extinction. To ensure the long-term survival of Bale Monkey, appropriate management action should be taken to conserve the species and the bamboo forests upon which it depends. Addisu Mekonnen *et al.* (2010) also suggested that the Bale Monkey is more aware about the potential advantage of young leaves as they contain more protein, have lower fiber content, low cyanide and are more digestible than mature leaves.

2.3.10 Ownership of bamboo stands

According to the Forestry Conservation, Development and Utilization Proclamation No. 94/1994 (Negarit Gazette, 1994),two types of forest ownership are recognized in Ethiopia: forests that belong to the government (federal or regional) and private forests. "Private Forest" includes a private forest developed by any person and includes a forest development by peasant association or by an association organized by private individuals. Ownership of bamboo forests in northwestern Ethiopia is mainly private i.e. individually owned by farmers, communally owned by communities in peasant associations and institutionally owned by the Ethiopian Orthodox Church. Plantations at different microsites such as homesteads, valley areas, riversides, ridges, stream heads and farmlands are owned privately by farmers (LUSO, 1997; Kassahun Embaye, 2003; discussion with community and reconnaissance survey of the Choke Mountain).The Ethiopian Orthodox Church has relatively significant portion of the bamboo stands, in its church yard, in many highland areas in northwestern Ethiopia. Whereas *A. alpina* bamboo forests that are naturally occurring and mainly found in different parts of the country like the Masha bamboo forest are owned by the government. LUSO (1997) has categorized the *A. alpina* bamboo forests by type/ownership (Appendix B).

2.3.11 Conservation of bamboo forests in Ethiopia

In Ethiopia, the private bamboo forests which are all highland bamboo forests are not degrading much despite being harvested mainly for own use and for sale in local markets. However, the government bamboo forests (natural forests of highland and lowland bamboos) are degrading and eventually disappearing fast, although there are no statistically sound sets of data available to substantiate this point of view. The government lacked economic incentives to value and prioritize them as useful commodities that require attention and planned action, as a result did not budget adequate finance to protect, manage, and use them properly (UNIDO, 2006).

In Uganda, poor harvesting methods especially during the clear cutting of bamboo for bean-stakes and stakes for house wefts seems to be the remote cause of the bamboo forest decline (Bitariho and McNeilage, 2008). Other causes for the bamboo forest decline are damages caused by insect borers and climber loads on the bamboo stems. Seventy percent of the local people interviewed agree that over-harvesting of bamboo is the major reason for its decline in Uganda (Bitariho and McNeilage, 2008).

2.3.12 Prospect of *A. alpina* in Ethiopian economy

Currently there is better awareness about the potential advantages of the bamboo resource for economic development and environmental protection in Ethiopia. Research papers and reports by Kassahun Embaye that are also used to prepare technical reports to be presented at Government level by UNIDO (UNIDO, 2006) and works of the East African Bamboo Project /"Market-based development with bamboo in East Africa- Employment and Income generation for poverty alleviation" project under the Ministry of Agriculture and Rural Development seem to play important role in raising awareness at all levels. East African Bamboo Project, during its project period, had given much training for development agents, prepared manuals on bamboo weaving and management based on experience from China and Kenya, created forum for discussion under workshops at different levels, made experiences sharing trainings in China through the International Network for bamboo and Rattan (INBAR), introduced many bamboo species (UNIDO, 2008; 2009). Currently, there is only one modern bamboo industry (ADAL Industrial PLC.) started functioning as of 2006, utilizing only *A. alpina* culms as row material (EABP, 2008).

Forest-based investment in Ethiopia is better facilitated and conducive. Provisions have been made to encourage potential activities for private investors in commercial forestry (investments in large-scale plantations and establishment of integrated forest-based industries) are encouraged (UNIDO, 2007). Currently the wood supply from other forest sources is heavily dwindled, because of the deforestation carried out since so long time, resulting in wood famine (Demel Teketay, 2001). Combined with the created awareness about the potential of bamboo for economic development, this critical shortage of wood may create a good opportunity for the bamboo sector to develop. Important steps in scientific bamboo management like the initiation of this thesis and joint industrial development and marketing aspects seem the outcomes of the awareness about the potential of the resource. But still more efforts are required concerning the silvicultural management; industrial utilization and policy issues to further develop the bamboo sector and make it play a significant role in the country's development.

Though utilization of this species in the country todate has been limited to customary uses and cottage industries, currently its industrial application as superior wood substitute is also recognized making its demand escalating (EABP, 2008). On the contrary, the lack of modern management scheme or extremely traditional management system (UNIDO, 2006) and lack of research and extension packages (UNIDO, 2007) caused deterioration in productivity of bamboo stands. Thus, the issue of developing the resource base has become an important point of discussion by experts in the endeavor towards adequate and sustainable raw material supply for the customary uses and emerging industrial applications (Yigardu Mulatu and Mengistie Kindu, 2009). The giving of more emphasis on its economic value before adequate work is done on the production and management might further deplete the resource (UNIDO, 2007).

CHAPTER THREE

3 MATERIALS AND METHODS

3.1 Location and Topography

This work was conducted in East Gojam Administrative Zone of Amhara National Regional State ($10^{o}32'14.2''$ to $10^{o}34'40''$ N; 037^{o} 45' 30.7'' to 037^{o} 46' 06.2'' E.) which is located 330 km northwest of Addis Ababa and 30 km to the north of the zonal city, Debre Markos, within the Choke Mountain range (Figure 2). Both sites are found in Gedamawit Zuria Peasant Association in Sinan District that is adjoining the Arat Mekerakir hills along the Choke Montain range. The altitudes of the sites range from 2849 to 2954 m a.s.l. As the Choke Mountain is one of the highland complex mountains in Ethiopia, and also one of the sources of the Blue Nile River, it is known for its rising slopes at high elevations. Topographic features had been recorded during a site survey, which was carried out at the beginning of the research, and showed large variation across the gradient. At the upper slopes and valley areas the slope rises up to 70% while inbetween are the level to gently slopping sites of 5 to 15%.

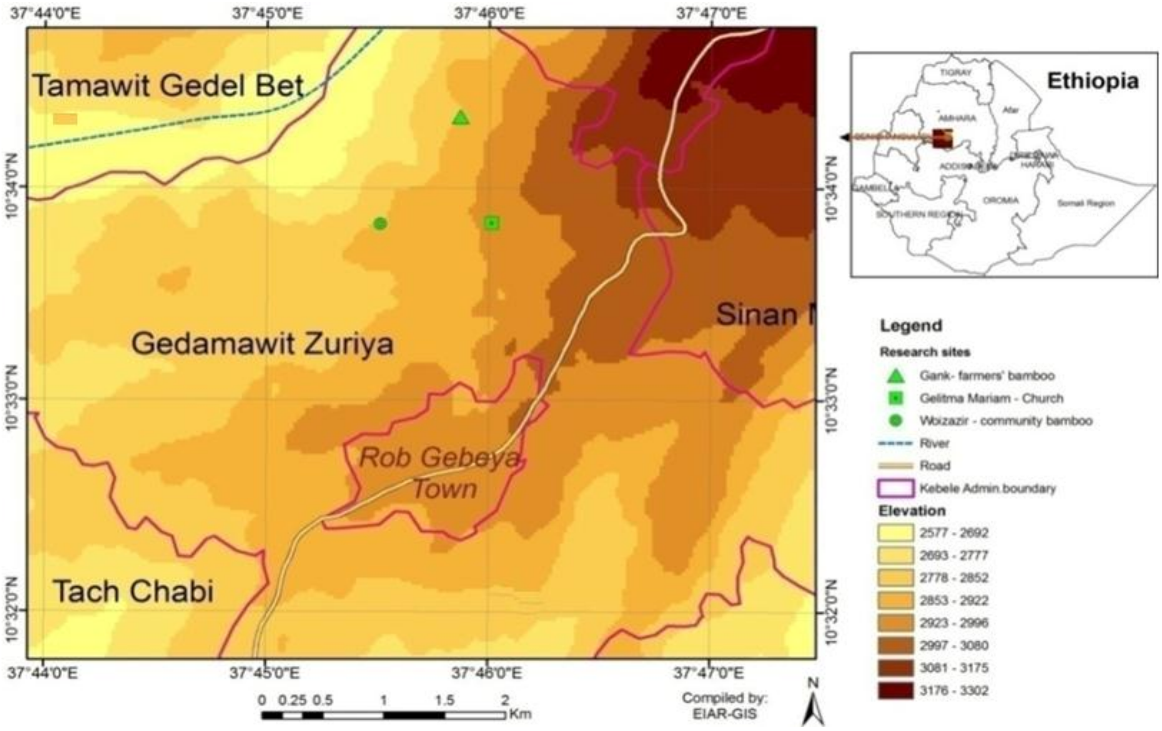

Figure 2: Map of Ethiopia and the study area.The locations are marked with a circle and polygons. (1) Geltima Mariam Church is site for the study on landraces and propagation; (2) Gank-farmers' bamboo and its surrounding are sites for the study on effects of Landform; (3) Woizazir-community bamboo is the site for study of effect of management.

3.2 Geology and Soils

The main geological unit in the area is the Tarmaber Gussa formation which represents Oligocene to Miocene basaltic shield volcanoes with minor trachyte and phonolite intrusions (Ermias Teferi *et al.,* 2010). The soil units covering the Choke Mountain are Haplic 20 Alisols (deep soils with predominant clay or silt-clay texture), Eutric Leptosols (shallow soils with loam or clay-loam texture) and Eutric Vertisols (deep soils with clayey texture and angular /sub-angular blocky structure). During this study selected physical and chemical properties of the soil in the research sites were analyzed. The soils generally have medium fertility, slightly acidic (pH 6.14) and clay to clay-loam texture (Table 1).

Table 1. Selected physical and chemical properties of soil of the study area (averageof the whole experimental area. Mean and SE)

Depth (cm)	pH_ H2O	EC	Sand	Silt	Clay	TN	OC	C:N ratio	Av.P (ppm)	Na	K	Ca	Mg	CEC	Base Sat. (%)
			%							Cmole/Kg					
0-20	6.13 (0.09)	0.18 (0.01)	35.8 (3.69)	33.6 (1.49)	30.6 (2.77)	0.56 (0.04)	5.7 (0.39)	10	45.7 (10.08)	0.26 (0.04)	1.7 (0.26)	24.1 (2.04)	5.0 (0.43)	44.4 (2.21)	68.8 (3.12)
20-40	6.14 (0.09)	0.12 (0.01)	33.3 (3.21)	33.4 (1.15)	33.2 (2.98)	0.42 (0.04)	4.1 (0.31)	10	33.4 (9.58)	0.27 (0.04)	1.3 (0.27)	21.7 (2.10)	4.7 (0.40)	43.2 (2.22)	63.9 (4.15)
40-60	6.09 (0.11)	0.08 (0.01)	23.3 (2.39)	37.8 (1.87)	38.9 (3.30)	0.30 (0.03)	2.9 (0.34)	9	19.4 (10.85)	0.31 (0.06)	1.5 (0.55)	20.6 (1.92)	5.7 (0.56)	41.3 (2.36)	66.3 (2.95)
Over all mean	6.14 (0.06)	0.14 (0.01)	33.7 (2.11)	33.9 (0.92)	32.4 (1.82)	0.47 (0.03)	4.6 (0.29)	10	38.9 (6.28)	0.26 (0.02)	1.47 (0.18)	22.7 (1.28)	4.9 (0.26)	43.57 (1.38)	66.3 (2.31)

TN= total nitrogen; OC=organic carbon; C:N- carbon to Nitrogen ratio; Av.P=Available phosphorus; Cmole/Kg= Centimole per Kilogram; Base Sat.= base saturation

3.3 Vegetation

There is no longer significant natural forest cover in the mountain range. The major remaining natural habitats are moist moorland, sparsely covered with giant lobelia (JIBARA/JIBBRA), lady's mantle (*Alchemilla* spp.), Guassa grass (*Festuca* spp.) and other grasses. There is very little natural woody plant cover; heather (*Erica* spp.; ASTA) and Hypericum (*Hypericum revolutum*; AMIJJA) are found in patches. The Afroalpine bamboo or *Arundinaria alpina* (*A. alpina* from now onwards) is found as homestead plantation as well as part of the natural vegetation cover in the area, albeit very sparsely. KORCH (*Erithrina brucei*) is commonly grown as border demarcation plant in the area. *Eucalyptus globulus is* extensively grown in plantation, and some of the residents have become dependent on it for their livelihoods (Ermias Teferi *et al.*, 2010).

3.4 Climate

Mean annual rainfall of the area is 1445 mm (20 years average data collected from Rebu Gebeya Meteorological Station of the Ethiopian Meteorology Agency). Average temperature is 20.9^{O}C (extrapolated from nearby stations using LocClime 2.0). The absolute monthly minimum temperature has positive value (Figure 3) indicating that the probability of having frosts in the coldest months is low. The humid months (blue vertical pattern in Figure 3) extends from March to November while aridity (the dotted red one) prevails from

November to February. The months of May to September are high rainfall months

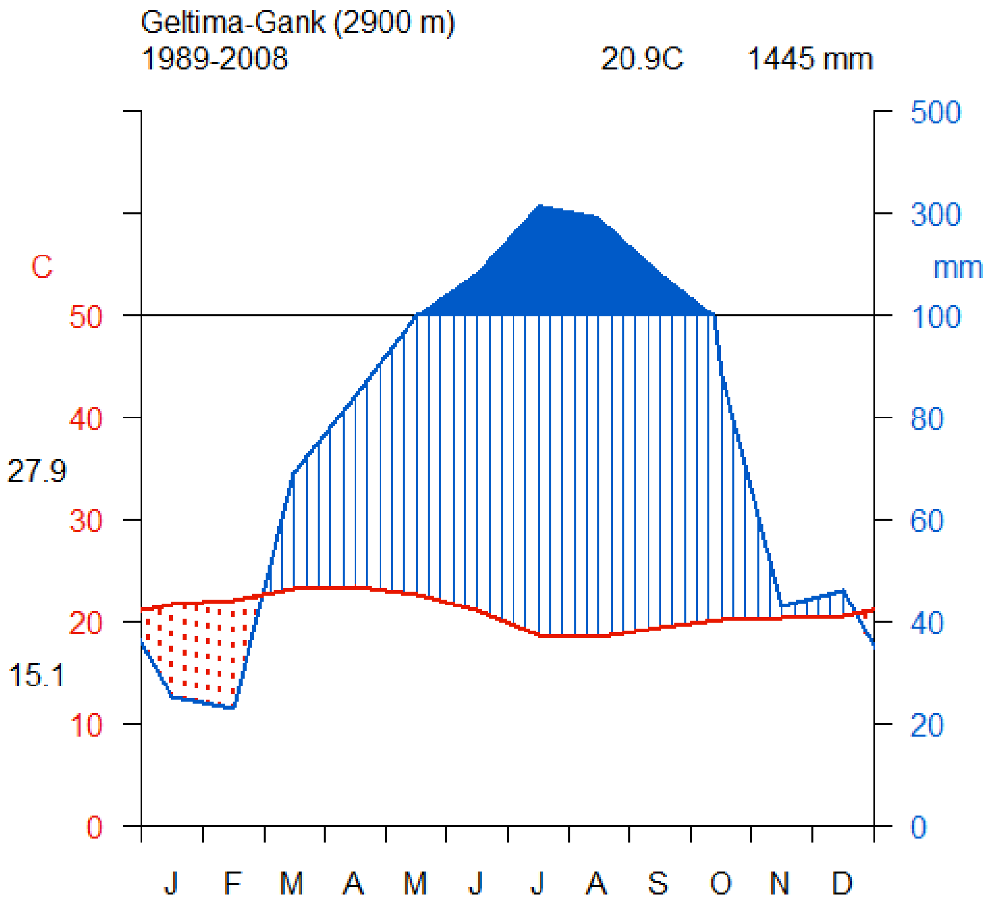

Figure 3: Clima-diagram showing total monthly precipitation and mean monthly temperature of the study site. Temperature data used to develop this figure was extrapolated from many similar nearby meteorological stations using the software LocClim 2.0 while rainfall data was what is actually collected from Rebu Gebeya Meteorological Station of the Ethioppian Meteorology Agency.

3.5 Working with the Community

Before the actual field work, reconnaissance survey of the area was made. The different peasant associations of Sinan District were visited in search of an area that accommodates all the research components stated in the research proposal. After determining the Geltima-Gank area as research site, continual discussion was made with the community so as to get license for research plots. The community has a tradition of passing decision on communal matters on every Sundays after the Sunday prayer at Geltima Mariam Church. Consequently, consecutive Sundays were used to discuss and sign Memorandum of Understanding on the utilization of the community, church and individual bamboo stands for research data generation (Figure 4). Discussion on the bamboo resource, management and utilization in the area was also held with knowledgeable farmers and bamboo processors.

Figure 4. Discussion with Geltima-Gank community representatives to sign memorandum of understanding on the use of research plots

3.6 Flow Chart of the Study

Under this study, four research components were investigated. Plots were established starting from April 2009 and data collection continued for 18 months depending on the experiments or investigations. The detail methodology of each component is presented under sections 3.7, 3.8, 3.9 and 3.10 of this thesis. Hereunder the generalized methodology is presented as flow chart so as to see the whole flow of activities at a glance. Starting with literature review and reconnaissance survey as a preparatory step, the flow chart shows selection of research plots, application of treatments, data collection and analysis and finally how conclusion and recommendations were made (Figure 5).

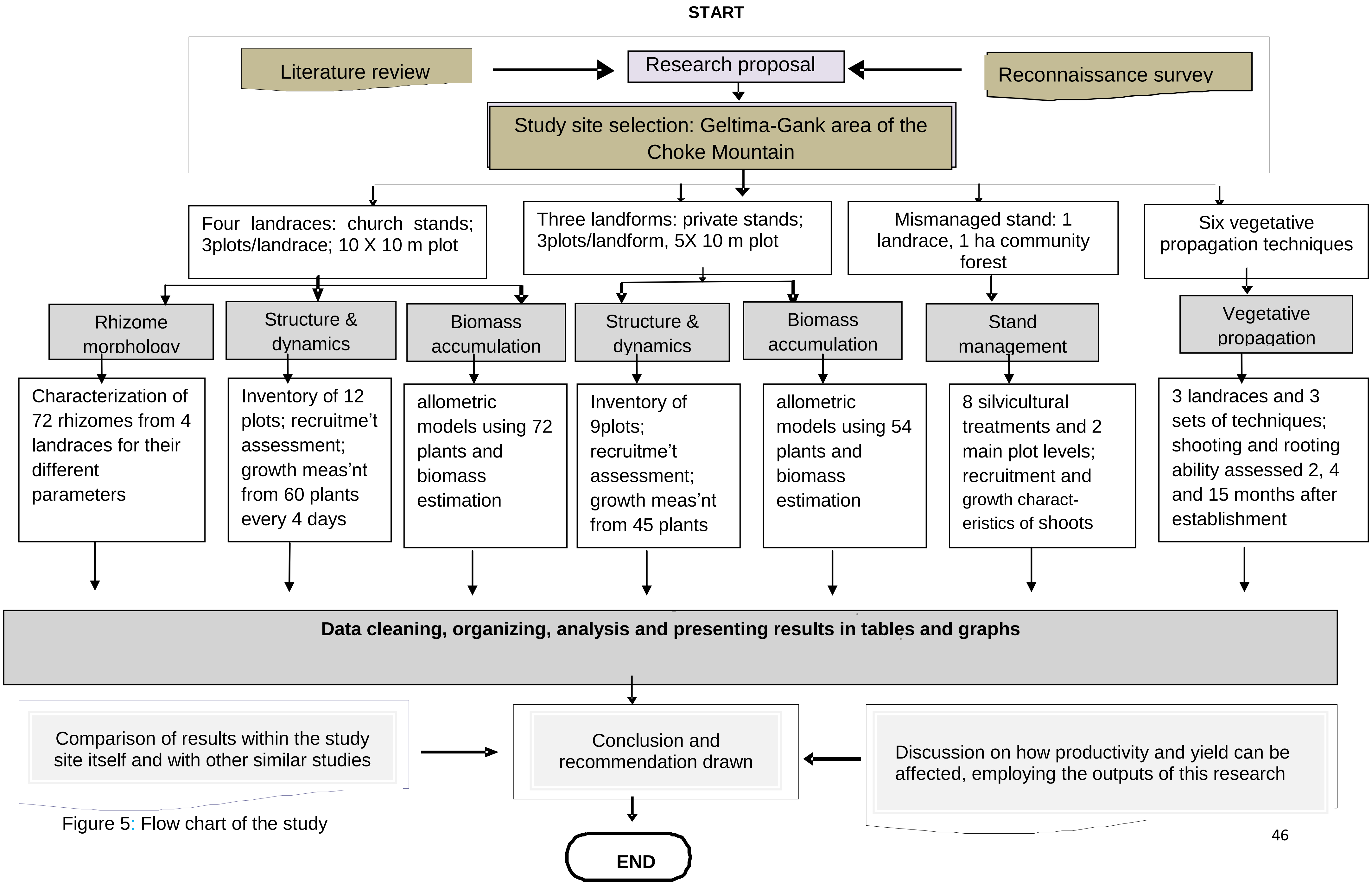

Figure 5: Flow chart of the study

3.7 Morphology, Growth and Biomass Variation of *A. alpina* Landraces

3.7.1 Selection of landraces and sample plots

Reconnaissance surveys of the area and group discussion with communities were made ahead of selecting the landraces. Though there are variations in naming the landraces and also variation of the landraces themselves, only three dominantly growing and one landrace having high preference by handicrafts for its bamboo products were selected for this study. The four landraces (local varieties) selected are locally called TIFRO, WELELE, WONDEand ENKOTEKOT (Figure 6).

Based on prior agreement and memorandum of understanding with the community and church leaders, three 10 m X 10 m sample plots were randomly selected from each landrace from a church forest of age more than 60 years. The first plots of each landrace were laid 10 m away from two sides of the stands and the consecutive plots at each 40 m distance within the forest.

3.7.2 Age determination and diameter measurement

After the plots were demarcated, age determination of each plant was done. Permanent markers were used to write age of the plants on culms. Age was determined following manuals (Ronald, 2005) and local experience. The highly appreciable indigenous knowledge on age identification within bamboo farmers was used. According to the manuals and local experience, the main criteria for age determination were internode color, internode cover, internode epiphytes, culm sheaths, sheath ring at node and branches (Table 2).

Figure 6. Mature stands of bamboo landraces in the Choke Mountain (A) TIFRO, (B) WELELE, (C) WONDE and (D) ENKOTEKOT landraces. Note the spacing between plants, culm color and shape of the nodal region

Table 2. Criteria used for age determination

Diagnostic feature	Age of plant < 1 year	1-3 years	> 3 years
Internode color	light green	gets yellowish or darker	yellow, dusty or dark depending on landrace
Internode cover	covered with white flour	flour is falling off	no flour left
Internode epiphytes	No. of internode epiphytes	has lichen and epiphytes	has lichen and epiphytes
Culm sheaths	all or part of the culm sheath kept	begin to fall off until none are left	no culm sheath remaining
Sheath ring	whole sheath ring or part of it kept	remaining sheath ring gets harder	no culm sheath ring , it falls off
Branches	light colored, not tough; no second - ary branches	branches feel soft, turning into yellow-green or dark	has secondary branches

Diameter at breast height (DBH) i.e. diameter at 1.3 m above ground, of each plant whose age determined in advance was then measured with Vernier Caliper. The minimum diameter of plants that were considered to be at their full grown stage was ≥2.5 cm, hence diameter of all plants having ≥2.5 cm was measured and data summarized.

3.7.3 Rhizome morphology characterization

Two plants were randomly selected from each age-group and plot (a total of 72 plants) and excavated out. The different plant parts were measured and counted. Quantified parameters include length of rhizome neck, number of internodes of the rhizome neck, thickness of the rhizome neck, length of rhizome proper, number of internodes of the rhizome proper, thickness of rhizome proper, thickness of the attached culm and number of elongated rhizome necks attached to rhizome. Description of the rhizome before and after excavating out from the soil was made in the field. Description of parts of the rhizome is following McClure (1966).

3.7.4 Height growth measurement and assessment of shoot mortality

After the emergence of more than 50% of the expected shoots at the end of July, five newly emerging shoots of height 5-50 cm were selected from each of the three plots under each landrace. Height growth was measured at every four days interval using graduated dry bamboo culms of different lengths up to 8 m and wooden ladder when necessary. Because of obstruction problems from branches of the neighboring plants, height measurement of the last two days was made using clinometer and for some plants with graduated culm supported by ocular estimation. The measurement was continued throughout the active growing period, starting from shoot emergence (30 July 2009) till the starting of sheathing-off of WELELE*,* TIFRO *and* ENKOTEKOT landraces (28 September 2009). The growth of WONDE landrace was slower than the others, it took extra two weeks to start sheathing-off, however the duration of data collection was kept same to other landraces.

Average daily height growth rate of plants from each landrace was then calculated by taking the height growth differences of consecutive measurements and dividing the difference by the number of days elapsed between the two measurements. Assessment on the total number of emerged and dead shoots from each plot was also conducted simultaneously with height growth measurement. Thus, the number of shoots emerged and the number of shoots died (aborted) was determined after confirming the accomplishment of shoot emergence and death of aborted shoots in August, 2009.

3.7.5 Biomass data collection

The 72 plants that were randomly selected from the DBH data list for rhizome characterization were also used for biomass data collection. Height of the excavated out plants was measured after felling, then sorted into four components as rhizome, aerial stem, branch and leaf. Total component fresh weight of each part was measured immediately with suspention and sensitive balance. Sensitive balance (precision 0.01) was used for leaf samples as leaf from <1 year old plants was very small to be measured with suspension balance. Accordingly, total fresh weight (TFW) of plants was determined by aggregating component fresh weights. Subsamples were then taken from each component for dry to fresh weight ratio determination. Subsamples from stems were taken from the second internode of the bottom, middle and top parts, after dividing the culm into three equal parts. The subsamples were then dried in an oven till constant weight at 103^{o}C was reached. Component dry weight and total dry weight (TDW) were determined using the dry/fresh weight ratios of subsamples.

3.7.6 Biomass estimation functions

Biomass models were developed using the regression curve-fit facility of PASW Statstics 18. Many possibilities were tried using landrace and plant age as factors and DBH, height and their transformations as predictor variable. Exponential functions gave the higher R^2 and smaller SE and DBH was found to be best predictor variable for plant total dry weight (TDW) and above ground total dry weight (AGTDW). Grouping plants into age-groups gave rise to more precice models hence one model was selected for each age-group for the landraces considered and used in estimating its corresponidng biomass. The following are the selected models for the three age-groups.

$$\mathrm{TDW}(< 1\ year) = \exp(0.185 * \mathrm{DBH}) \qquad \mathrm{R}^2 = 0.835, \mathrm{SE} = 0.444$$

$$\mathrm{TDW}(1 - 3\ \mathrm{years}) = \exp(0.3004 * \mathrm{DBH}) \quad \mathrm{R}^2 = 0.965, \mathrm{SE} = 0.324$$

$$\mathrm{TDW}(> 3\ years) = \exp(0.323 * \mathrm{DBH}) \qquad \mathrm{R}^2 = 0.950, \mathrm{SE} = 0.366$$

Where, TDW represents total dry weight; DBH represents Diameter at Breast Height

Similarly, the exponential functions selected for estimating above ground total dry weight of plants of the different age-groups in each plot had the following formula:

$$\mathrm{AGTDW}(< 1\ \mathrm{year}) = \exp(0.147 * \mathrm{DBH}) \quad R^2 = 0.749, \mathrm{SE} = 0.461$$

$$\mathrm{AGTDW}(1 - 3\ \mathrm{years}) = \exp(0.267 * \mathrm{DBH}) \quad R^2 = 0.9430, \mathrm{SE} =$$

$$\mathrm{AGTDW}(> 3\ years) = \exp(0.278 * \mathrm{DBH}) \quad R^2 = 0.930, \mathrm{SE} = 0.377$$

Where, AGTDW represents above ground total dry weight; DBH represents Diameter at Breast Height

3.7.7 Biomass estimation

Biomass estimation was made employing the functions developed for the three age-groups of plants from the three landraces. The general formula for biomass of each age-group in each plot was:

$$TDWj = \sum_{i=1}^{n} (\exp(Bi * DBHi))$$

$$AGTDWj = \sum_{i=1}^{n} (\exp(Bi * DBHi))$$

Where TDW=total dry weight, AGTDW=above ground total dry weight, j=the j^{th} age-group, i= the i^{th} plant in age-group j, B_i=coefficient of the predictor variable DBH, DBH=Diameter at Breast Height.

The estimates of the different age-groups in each plot were then aggregated to plot value and then to values at landrace level.

3.8 Stand Structure, Growth and Biomass of *A. alpina* along Environmental Gradient

3.8.1 Study site and plot selection

The landscape that extends from up the ridge down to the valley bottom of the water shade was stratified into three landforms based on slope gradient and shape and its position along the gradient. The landforms were categorized as 1) 5-15% level to slopping land, 2) 40-60% straight slope (ridge) and 3) 40-60% concave slope (valley). Altitudes range from 2,849 to 2,938ma.s.l. (Table 3). A soil description guideline (FAO, 2006) was used in stratifying the landforms. SuuntoClinometer was used for determining slope of the plots and eTrex GPS (Geographical Positioning System) for recording elevation and geographical coordinates.

Then after, three plots were selected from each landform based on their representativeness to bamboo forests found on each landform. Stands were considered provided that they had wider area (at least 100 m^2 so as to get buffer zones while delineating plots) and sufficiently even and undisturbed stocking, except selective harvesting by landowners. The minimum age of the selected stands was 30 years. Size of the actual sample plots was 5 m X 10 m. Though bamboo forests in the area are plantation forests, stand management is mainly limited to harvesting of mature culms. Except protection of young shoots from free grazing at the time of shooting (May-

October), any other bamboo management practices are hardly exercised. All the selected plots were private holdings of the farmers.

3.8.2 TIFRO landrace of *A. alpina*

The *A. alpina* bamboo forest investigated under this study was of TIFRO landrace. TIFRO is one of the dominantly growing and important landrace in the study area. This landrace grows in wider topographic and soil conditions and performs well. The name TIFRO is given because it has adventitious roots throughoutall the culm nodes. It has light green stem the first year and gets darker afterwards. As compared to other landrace, rhizome neck of this landrace is significantly longer hence number of stems per unit area is smaller but growth and biomass are higher.

Table 3: Characteristics of sample plots under three landforms

S.N.	**Landform**	**Plot**	**Slope (%)**	**Elevation (masl)**
1.1	steep land (straight slope)	1	40	2909
1.2	steep land (straight slope)	2	67	2937
1.3	steep land (straight slope)	3	55	2938
2.1	level–slopping land	1	5	2900
2.2	level–slopping land	2	10	2906
2.3	level–slopping land	3	14	2923
3.1	Steep land (concave slope)	1	62	2857
3.2	Steep land (concave slope)	2	40	2849
3.3	Steep land (concave slope)	3	62	2869

3.8.3 Age determination and diameter measurement

After the plots were demarcated, age determination of each plant was done. Permanent markers were used to write age of the plants on culms. Age was determined following manuals (Ronald, 2005) and local experience. The highly appreciable indigenous knowledge on age identification within bamboo farmers was used. According to the manuals and local experience, the main criteria for age determination were internode color, internode cover, internode epiphytes, culm sheaths, sheath ring at node and branches. The criteria used for age-determination are the same as what is presented in Table 2 (section 3.7.2). Diameter at breast height (DBH) i.e. diameter at 1.3 m above ground, of each plant whose age was determined in advance was then measured with Vernier Caliper. The minimum diameter of plants that were considered to be at their full grown stage was ≥2.5 cm, hence diameter of all plants having ≥2.5 cm was measured and data summarized.

3.8.4 Height growth measurement and assessment of shoot mortality

After the emergence of more than 50% of the expected shoots at the end of July, five newly emerging shoots were selected from each of the three plots under each landform. Height growth and assessment of shoot mortality continued starting from shoot emergence (30 July 2009) till the starting of sheathing off (28 September 2009) following the same procedure as section 3.7.4.

3.8.5 Biomass data collection

Plants were grouped into three age classes as <1, 1-3, >3 years of age. Then two plants were randomly selected from the DBH data list prepared for population structure determination, from each age-group and plot. Selected plants were extracted out, their height measured after felling, then sorted into four components as rhizome, aerial stem, branch and leaf. Total component fresh weight of each part was measured immediately with suspention and sensitive balance. Sensitive balance was used for leaf samples as weight of leaf from <1 year old plants was very small to be measured with suspension balance. Subsamples (15-50 gm for leaf and branch and 100-300 g for stem and rhizome) were then taken from each component for dry to fresh weight ratio determination. Subsamples from stems were taken from three positions along culm height so as to get representative subsamples along the density gradient of the culm. The subsamples were taken from the second internode of the bottom, middle and top parts, after dividing the culm into three equal parts. The subsamples were then dried in an oven till constant weight at $85^{o}C$ was reached. Component dry weight and total dry weight were determined using the dry/fresh weight ratios of subsamples.

3.8.6 Biomass estimation functions

Biomass models were developed employing data generated under section 3.8.5 and in a similar way to models developed under section 3.7.6. The following are the selected models under each group.

$$TDW(< 1year) = \exp(0.202 * DBH) \qquad R^2 = 0.914, SE=0.431$$
$$TDW(1 - 3\ year) = \exp(0.310 * DBH) \qquad R^2 = 0.984, SE=279$$
$$TDW(> 3\ year) = \exp(0.320 * DBH) \qquad R^2 = 0.988, SE=0.320$$

Where, TDW represents total dry weight; DBH represents Diameter at Breast Height

$$AGTDW(< 1year) = \exp(0.172 * DBH) \qquad R^2 = 0.87, SE=0.463$$
$$AGTDW(1 - 3\ year) = \exp(0.289 * DBH) \qquad R^2 = 0.87, SE=0.463$$
$$AGTDW(> 3\ year) = \exp(0.30 * DBH) \qquad R^2 = 0.99, SE=0.239$$

Where, AGTDW represents above ground total dry weight; DBH represents Diameter at Breast Height.

3.8.7 Biomass estimation

Biomass estimation was made employing the aforementioned functions and following similar methodology used in section 3.7.7 of this thesis.

3.8.8 Soil description and physico-chemical property analysis

One soil pit, 1.5 m by 1.5 m, was opened at the center of each plot. Soil depth, depth of A and B soil horizons, rhizoming depth and rooting depth were recorded (based on FAO, 2006). Three composite soil samples were taken from three depths (0-20 cm, 20-40 cm and 40-60 cm) from each plot (a total of

27 composite samples). Physical and chemical properties were determined at the National Soil Testing Laboratory and Addis Ababa University.

A soil and plant analysis manual by Sahilemedhin Sertsu and Taye Bekele (2000), developed from compilation of the different analytical techniques indicated under each type of analysis, was used for physical and chemical soil analysis. The oven drying method (SAA, 1977) was used to determine soil moisture content. Particle size fractions were determined by hydrometer after dispersion in a mixer with sodium hexametaphosphate (Bouyoucos, 1962). Soil pH was measured with a combination electrode in a 1:2.5 soil:water suspension. EC was determined by conductometric analysis using conductivity meter. Organic carbon was determined by dichromate oxidation (Walkley and Black, 1934). The total N content was determined by the Kjeldahl digestion using CuSO4 and Selenium powder as catalysts. Soil cation exchange capacity (CEC) and exchangeable bases were measured by using Ammonium acetate extraction method at pH 7. Calcium and magnesium were determined by atomic absorption spectrophotometry, while sodium and potassium were determined by flame emission spectrophotometry. Available P was analyzed according to the standard method described by Olsen *et al*. (1954).

3.9 The Effect of Silvicultural Management on Regeneration, Growth and Yield of Previously Unmanaged *A. alpina* Bamboo Stands

3.9.1 General description of the bamboo forest

One ha of communally owned bamboo stand (of WELELE landrace) was used for the study. The bamboo forest had been under private holding during the Hailesislase-I regime (1930-1974), but starting from the Dergue regime (1974) up to the present, it has been transferred to Geltima-Gank community to be managed and utilized communally. Though bamboo stands are manmade and mainly meant for culm production, management is hardly practiced. During dry seasons, bamboo stands are used for browse by livestock resulting in soil compaction. Besides, creating access for livestock browse by bending culms brought about dominance of poor quality culms and reduced value of the stand, from timber production point of view. The higher cutting position while felling and subsequent shoot abortion also resulted in undecomposed old stumps that might hinder further shooting. Though the community harvests matured bamboo culms every 3-4 years, illegal cutting is common in between two harvesting periods. In general, the bamboo forest is suffering from the “tragedy of the commons’’. Thus, these management problems reduced growth and productivity of the bamboo stands.

3.9.2 Experimental design

The experimental design used was Factorial Split Plot Design with two factors. Factor 1: organic fertilizer with two levels (with compost in 12 tonha^{-1} basis and without compost); Factor 2: other silvicultural management techniques (eight levels of soil and plant management techniques). Organic fertilizer was the main plot and silvicultural management techniques (Factors 2) sub plots splited on the main plot. Compost used in the experiment was prepared using livestock dung, green leaves, ash and local soil for two months. The total N (Kjeldahl method), organic C (dichromate oxidation method) and phosphorus contents (Bray I method) of the compost were 0.613%, 17.258% and 0.878 mg P/g of soil, respectively (determined at the Eco-Physiology Laboratory ofAddis Ababa University). Accordingly, the equivalent amounts of the compost used were 74 kg ha^{-1} N and 105 Kg ha^{-1} P. The experiment was replicated three times, making the total number of plots (including the control) 48. Plot size was 10 m x 5 m and distance between blocks was 20 m. The eight plant and soil management levels of Factor 2 (treatments) were (1) removing old stumps (ROS); (2) soil loosening and removing old stumps and (SL+ROS); (3) selective thinningand removing old stumps (ST+ROS); (4) soil loosening, selective thinning and removing old stumps (SL+ST+ROS+); (5) soil loosening (SL); (6) soil loosening and selective thinning (SL+ST); (7) selective thinning (ST) and (8) control. Selective thinning was done by removing all culms of >3 years of age.

3.9.3 Plot establishment

Establishment of the plots was conducted from 4-8 April 2009 (the time when growth is expected to be minimum because of the relatively long dry spell of the previous months). That time, the shooting season hadalso not started yet. Hand tools such as Mattock+pick axe, grab hoe, and axe were used for digging the soil, removing degenerated rhizomes and selectively thinning of old culms (Figure 7). Soil loosening was done by diggingthe soil, to 15-20 cm depth, with hand tools and mounding the soil around the culm base to cover exposed rhizome parts and create conducive soil conditions. Removing old stump was made mainly to avoid stumps that were degenerated but still maintained in the forest. Care was taken so as not to damage rhizomes and underground shoots by avoiding digging very close to the plant.

Selective thinning was done by removing all plants which were four and more years old. Bent stems were uncurved and intermingled branches were separated prior to removing the selected plants so as to ease thinning. After establishment of the experiment, the site was entirely protected from livestock and human interference, by fencing and guarding the experimental area.

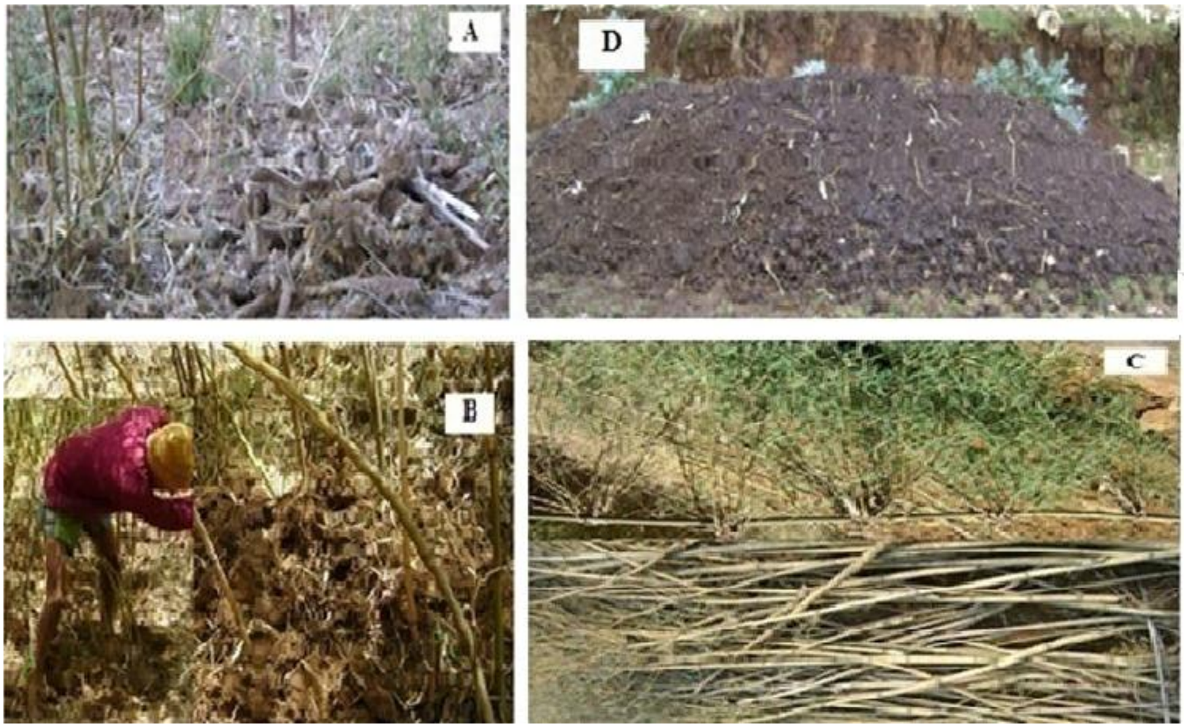

Figure 7. Applied silvicultural treatments: (A) removing old stumps; (B) soil loosening or ploughing the soil with hand tools and covering the rhizome area with excavated soil; (C) compost ready for application; (D) selectively thinned out culms

3.9.4 Plot characteristics (stocking, age structure and plant size-initial data)

The different attributes of each plot were assessed after plots were allocated for the different treatments, subplots and blocks. The age of each plant was identified as <1 year (2008 recruitments), 1-2 years (2007 recruitments) and ≥ 3 years (recruitments before 2007) and marked with permanent marker. The number of plants under the three age-groups (stocking) was then determined. Age determination was made following the criteria described in Section 3.7.2 (Table 2). The number of erect culms that were not deliberately bent while creating access to livestock browse by farmers was also enumerated.

Because of the diffuse clumping nature of the species, plants in the plots are more often homogenously distributed in single stem basis. Because of this, diameter at breast height and height of ten plants were taken randomly from the central clumps of each plot (Table 4).

Table 4. Stocking of plants of different ages and their size in blocks, main plots and subplots of the studied forest before treatment application (plot size 50 m^2, Mean ± SE; n=6)

Factor	No.	Number of plants plot^{-1} of age			Proportion of erect plants (%)	DBH (cm)	Height (m)
		<1year (2008 recruitments)	1-2 years (2007 recruitment)	≥3years (recruitments before 2007)			
Block	1	52 ± 5	22 ±2	46 ±4	33 ±4	2.7 ± 0.05	4.9± 0.14
	2	49 ±2	27 ±3	47 ±4	36 ±3	2.6 ± 0.03	4.5± 0.12
	3	108 ±15	21 ±4	64 ±5	51 ±5	2.6 ± 0.11	4.6± 0.11
Main plot	1	59 ±4	20 ±2	53 ±3	39 ±20	2.7 ± 0.04	4.6± 0.09
	2	79 ±12	27 ±3	51 ±5	41 ±4	2.6 ± 0.05	4.7± 0.07
Treatment	1	61 ±10	26 ±5	54 ±5	39 ±4	2.7 ± 0.10	4.8± 0.19
	2	55 ±12	24 ±4	48 ±11	38 ±6	2.6 ±0.12	4.5± 0.29
	3	71 ±12	19 ±3	36 ±6	39 ±40	2.8 ± 0.11	5.1± 0.28
	4	78 ±15	24 ±4	68 ±5	45 ±7	2.6 ± 0.07	4.6± 0.21
	5	94 ±39	28 ±10	47 ±6	49 ±12	2.7 ± 0.06	4.8± 0.12
	6	76 ±20	22 ±50	52 ±5	41 ±10	2.5 ± 0.05	4.4± 0.16
	7	52 ±7	20 ±3	56 ±12	33±5	2.7 ± 0.11	4.7± 0.22
	8	66 ±18	26 ±5	57 ±4	34±6	2.6 ± 0.04	4.6± 0.15

3.9.5 Data collection

Initial data ofstand structure and plant size of the previous years before the establishment of the experiment (2007 and 2008) were collected after identifying plant age as described in section 3.9.4 (Table 4). Data after establishment of the experiment was collected twice, 2009 shooting season (5 months after establishment) and 2010 shooting season (18 months after establishment). The data collected includes number of newly emerged shoots, number of recruited culms and aborted shoots after emergence of the whole plot. Besides, DBH and height of ten stems from the center of each plot was measured. The 2010 shooting season was an off-year for bamboo stand shooting in the area, hence had marginal shoot recruitment.

3.9.6 Data analysis

Combined analysis over years of two factor split plot ANOVA and one-way ANOVA were used to see the overall and single year effects of silvicultural management techniques and organic fertilizer during the shooting seasons. Duncan Multiple Range Test was used while statistically significant differences ($p<0.05$) were observed. Sigma Plot 10 was used to construct graphs.

3.10 Propagation Techniques for *A. alpina* Landraces

3.10.1 Site selection

The planting site used was a well drained soil, gently slopping and nearer to bamboo forests and other vegetations so as to use these forests as wind break. The availability of water source was also taken into consideration during site selection so as to provide supplemental watering during the dry spells of the experimental period.

3.10.2 Planting bed preparation and soil mix

The land used for planting was thoroughly cultivated with oxen plough. Plots of varying length (based on the length of the planting material) but a constant (2m) width were laid out and raised beds were prepared. The size of the planting pit also varied according to the size of the planting material to be tested. The offsets, farmers' method, were planted in 60-70 cm deep x 60 cm wide x 60 cm long pits. In this method, since the planting material was cumbersome and difficult to plant in upright position, it was planted by tilting to about 25-30^o by following the farmers' way of planting in the area. However the rhizome-offset and rhizome were fitted in 25-30 cm deep x 60 cm wide x 60 cm long pits, as only the rhizome part should be buried in the pit and no problem of heavy weight to support. The maximum depth of the trench for planting the whole culm and culm cuttings was 15 cm and its length varied based on the size of the propagules whereas branch cuttings were fitted in 5 cm deep pits. Thin layer of (about 5 cm) compost fortified with local soil was added at the base of propagules while planting. Compost was applied in order to make the soil porous and fertile.

3.10.3 Preparation of planting material

The plating materials (Figure 8) for this experiment were prepared following manuals for propagation of tropical bamboos by Banik (1995), NMoBA (2004) and Ronald (2005).

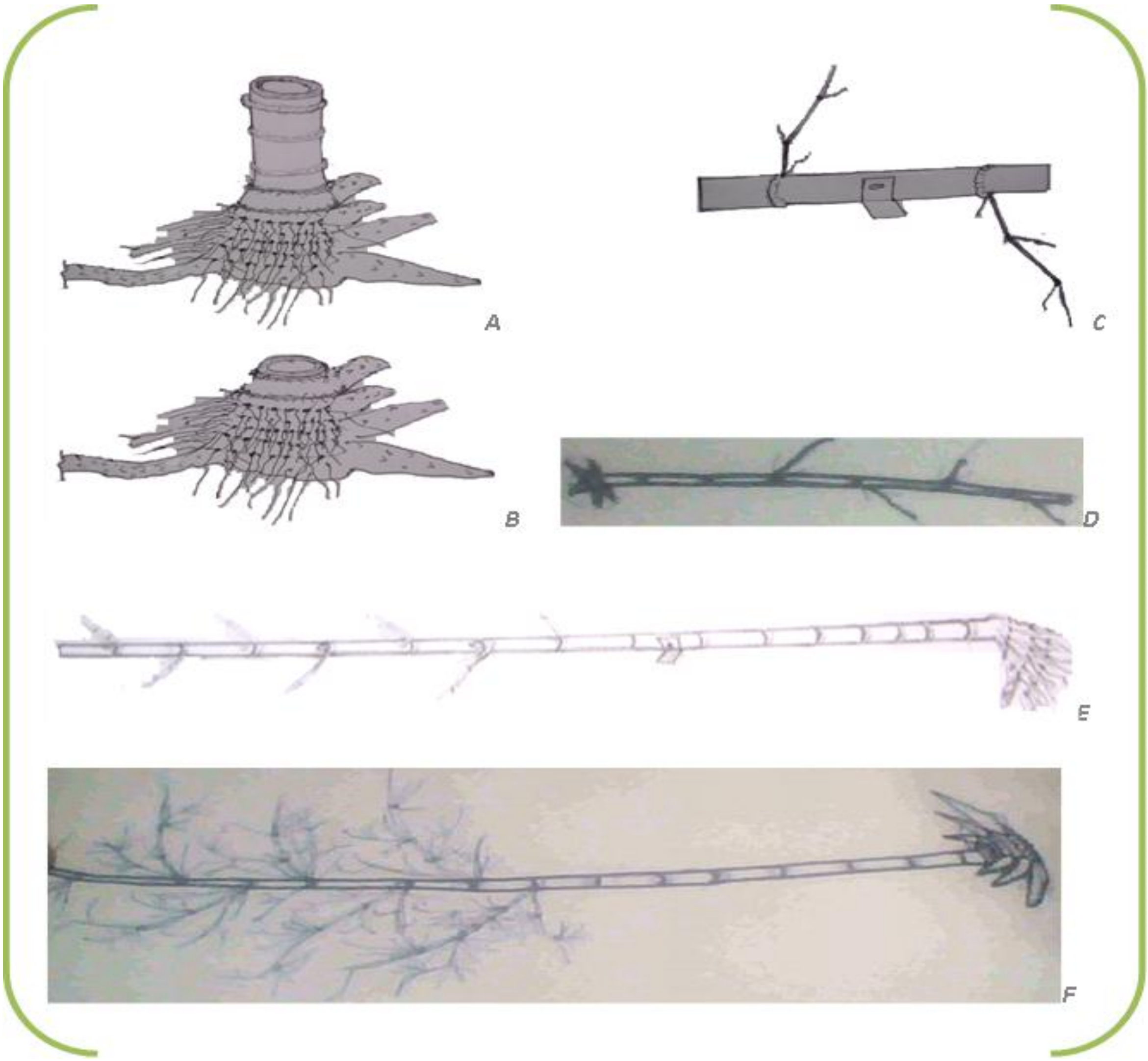

Figure 8.Planting materials used for the study: (A) Rhizome offset (stump); (B) Rhizome; (C) Culm cuttings of two nodes; (D) Branch cuttings with five internodes and roots; (E) Whole culm (all plant parts of the plants except branches and leaves), planting is done horizontally in a furrow; (F) Offset (the farmers' method); all parts of the plant except prunings of the top part after 15 internodes for big propagules. Planting is in upright position but with some 20-30^{O} inclination.

The rhizome used as treatment in this experiment was prepared by severing the whole rhizome together with the acompanying root system, using a sharp axe, from the parent rhizome. Preparation of the rhizome-offset (rhizome with culm-stock) was similar to that of the rhizome but in this case the base or lowermost portion of the culm (2-3 nodes) was retained. Offset (rhizome with roots and culm) or the traditional method was prepared by severeing the rhizome together with all above ground plant parts.The upper most part of the culm was removed, so that bigger portion (12-15 node for big culms) and the corresponding branches and leaves were retained. Under the whole culm method the culm together with the stump (that keeps moisture and can also produce new sprouts) was severed from the parent rhizome. The top was cut with a slanting cut leaving 12 to 15 nodes for big culms. All primary branches were pruned to two nodes.The rhizome used in this method need not be big like the offset, rhizome-offset or rhizome methods. For the method of culm cutting, culm segments of 2 nodes bearing healthy branches were used after trimming-off the branchlets to two internodes. The upper most and lower most parts of culms were not included.Primary branches that had aerial roots at the base were used for the branch cutting technique. The branches were trimmed-off to two nodes before planting.

Age of mother plants of all the planting materials, except branch cuttings,was one year. Branch cuttings were severed from 3 to 4 years old plants, as plants of this age harbor branches developing adventitious aerial roots that was the basis of this technique.Planting was done on 10 July, 2009, when thesoil got sufficiently wet. Farmers in the area plant bamboo under this moisture regime. That time was also the starting time of the rainyseason hence adequate moisture was available. Supplemental watering was done when there was no rain for more than a day in September and October.A layer of mulch of barleystraw was applied to plots to retain moisture and protect them from weather extremes. Weeding and hoeing: was done twice in the rainy season of 2009 (August and September) and two times in 2010 rainy season (July and September).

3.10.4 Experimental design and treatments

The experimentaldesign used for this study was Factorial Randomized Complete Block Design (RCBD). There were two factors namely: landrace (3 levels) and propagation technique (six levels) giving a total of 18 treatment combinations. The three landraces were locally called TIFRO, WELELE and WONDE. The fourth landrace, ENKOTEKOT, studied under section 3.7 is not considered here so as to make the experiment manageable and because of the less dominance of the landrace as compared to the others. The six propagation techniques used as factors were: offset (farmers' practice), rhizome-offset, rhizome, culm cuttings, branch cuttings and whole-culm. Each treatment combination was replicated three times. Nine plants were used for each treatment combination.

3.10.5 Data collection

Data on number and growth (maximum height and corresponding diameter) of newly produced shoots from the different planting materials were collected two, four and fifteen months after planting (MAP). Data collected fifteen MAP also includes the number of alive propagules (planting materials). The diameter and height of the new shoots were measured using diameter caliper and 4 m long graduated ruler, respectively.

3.11 Data Analysis

Descriptive statistics was used before the actual analysis to see into the distribution of observations. The Levene’s test was employed to check the assumption of homogeneity of variances. Univarate analysis of the General Linear Model (One-Way-ANOVA and two-way-ANOVA) were then conducted. Tukey's Honest Significance Difference (HSD) test was used when statistically significant differences ($p<0.05$) were observed. Sigma Plot 10 was used to present the analyzed data in different graphs.

CHAPTER FOUR

4. RESULTS

4.1 Morphology, Growth and Biomass of *A. alpina* Landraces

4.1.1 Description of the rhizome

The rhizome proper (root bearing section) of all landraces is nearly vertically positioned (Figure 9). It is thicker than the rhizome neck and the attached culm. The root bearing nodes are close together and shorter than broad. Unlike the leptomorphic rhizome illustrated by McClure (1966), the rhizome of *A. alpina* landraces does not penetrate horizontally through the soil long distance producing new shoots along its way. The rhizome neck, the thinner joining section between the mother rhizome and the new rhizome, is basal to the rhizome proper.

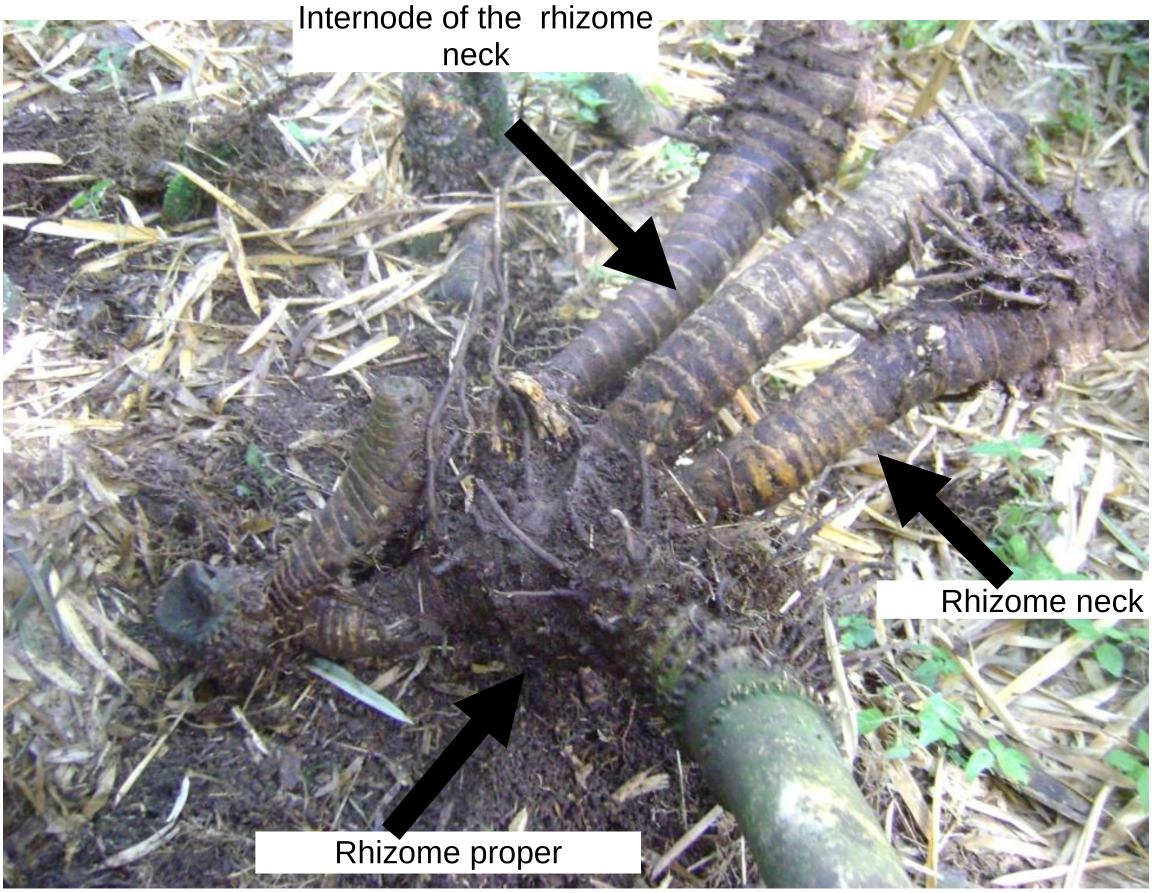

Figure 9. Parts of the rhizome (photo taken from an old plant, but still attached to the rhizome system of WELELE landrace during the field work in March, 2009).

The elongated rhizome necks are also observed above the soil in the same pattern as they are in the soil. However, rhizome necks above the ground and nearer to the culm base are shorter than those nearer to rhizome neck inside the soil. Moreover, they also curve downward probably with a purpose of anchoring the plant or because of geotropism (Figure 10).

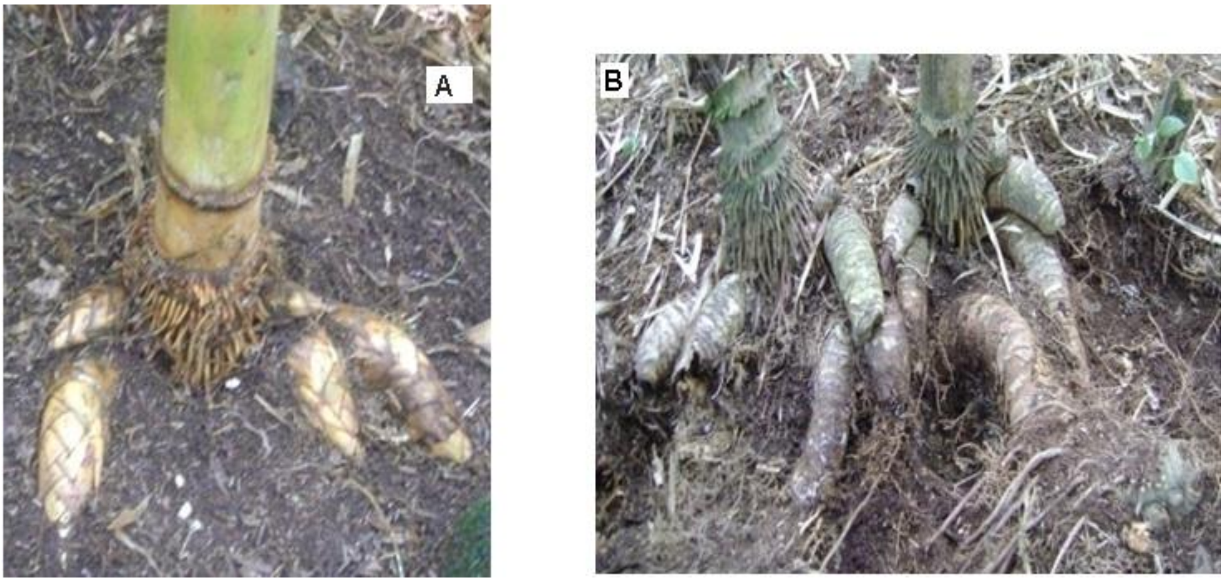

Figure 10. Collective feet of the rhizome illustrated from one year (A) and more than 10 years old (B) plants. The rhizome neck of an aborted shoot is seen protruding out from the lower part of the rhizome proper of the old mother plant (B)

Rhizome necks (the collective feet) are not haphazardly distributed over the rhizome proper, rather arranged along two sides in angular fashion leaving two-third of the circumference of the rhizome proper to its mother side (Figure 11). The portion of the circumference of the rhizome proper within the two colonizing sides is about one-third. Hence a rhizome always colonizes forward within one-third of its circumference. The rhizome has a true rhizome neck (Figure 12).

Figure 11. Appearance of rhizome morphology of a one year old plant, after detached from the rhizome system and excavated out from the soil. A) as seen from the direction of colonization; B) as seen from the direction of the mother plant of the rhizome; C) side view

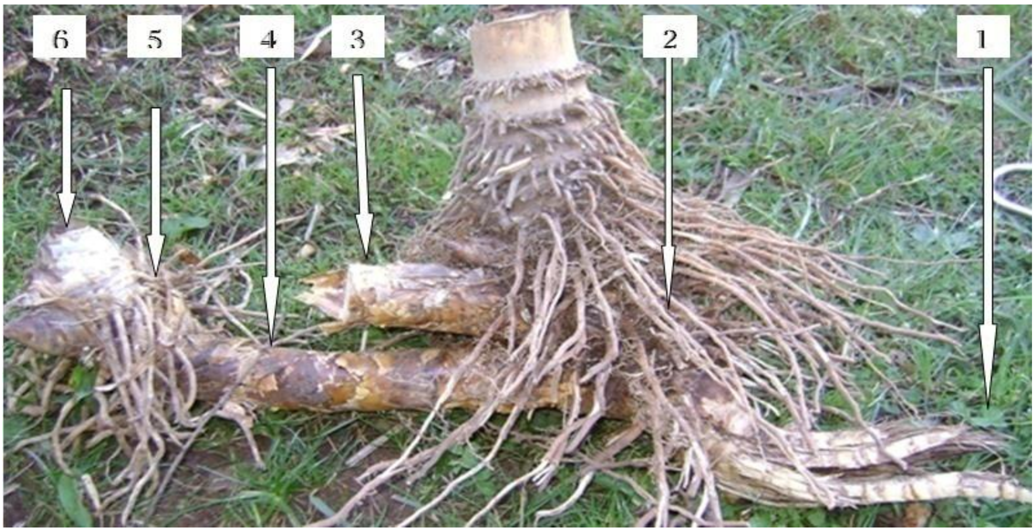

Figure 12. Parts of the rhizome system of a three year old plant: 1) the rhizome neck of the ex-mother plant, 2) rhizome covered with roots; 3 and 4) parallel rhizome necks along one of the two sides; 5) rhizome proper of an aborted shoot (all shoots do not grow into culm because of shoot abortion and management problems; 6) the base of an aborted shoot.

4.1.2 Characteristics of morphological parameters

The four *A. alpina* landraces showed statistical differences in allthe measured rhizome parameters. The rhizomes were taken from three age-groups (<1, 1-3 and >3 years). Age had no significant effect in any of the rhizome characteristics of the four landraces.

3.1.2.1 The rhizome neck

Average length of rhizome neck of TIFRO landrace (17.3 ±1.75 cm) was significantly higher (p=0.001) than WONDE (12.4 ± 1.58 cm), WELELE (11.0 ±1.30 cm) and ENKOTEKOT (8.5 ±0.91 cm) (Figure13). Diameter of rhizome neck of TIFRO (4.1 ± 0.22 cm), WONDE (3.8 ± 0.31 cm) and WELELE (3.7 ±0.31 cm) were significantly higher (p=0.004) than ENKOTEKOT landrace (2.7 ± 0.25 cm). Similarly, the number of internodes of TIFRO landrace (16 ± 1) was significantly higher (p= 0.002) than WELELE (8 ± 1) and ENKOTEKOT (10 ± 1) landraces. The value for WONDE landrace (14 ± 2) was not statistically different from that of TIFRO and ENKOTEKOT but higher than that of WELELE landrace.

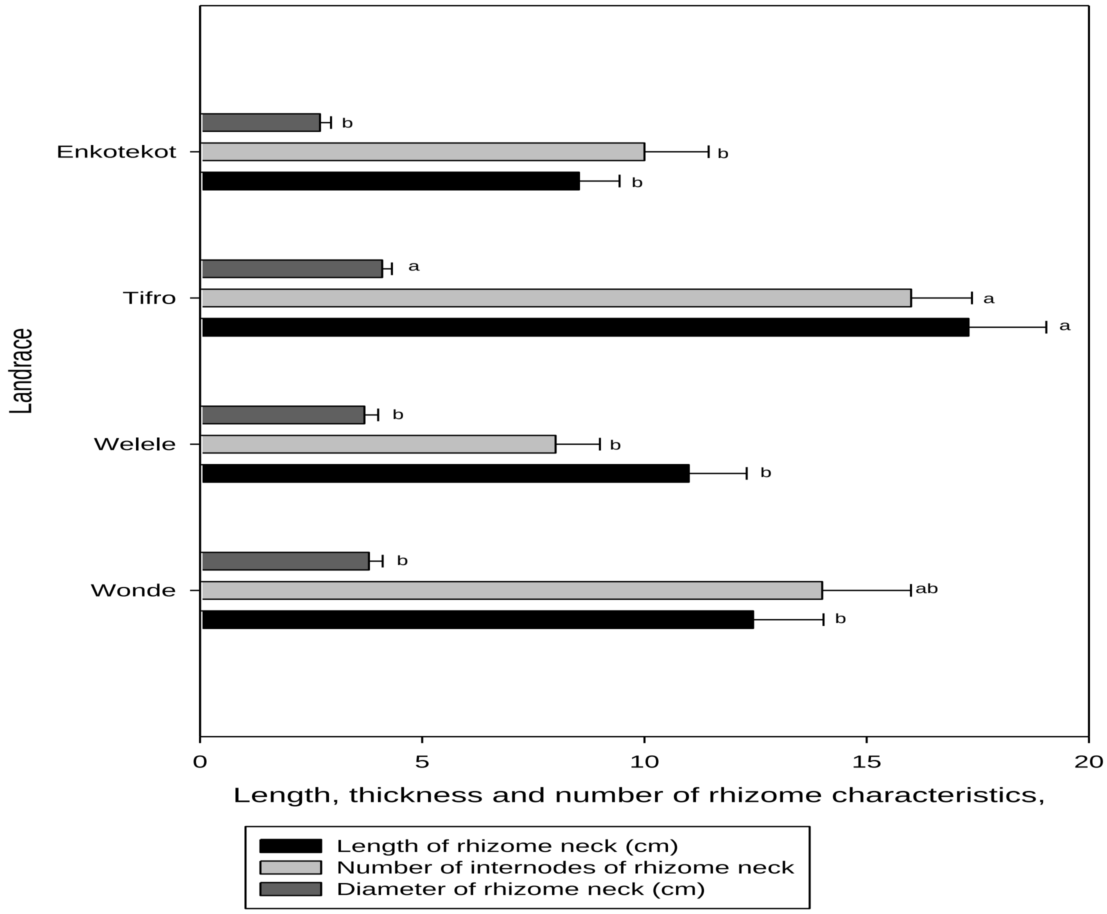

Figure 13. Characteristics of the rhizome neck of different *A. alpina* landraces (n=18, p=0.05, Tukey's HSD Post-hoc test)

4.1.2.2 The rhizome proper and its appendages

Length of rhizome proper of WONDE (19.6 cm), WELELE (23.1 cm) and TIFRO (20.5 cm) was significantly higher (p= 0.001) than that of ENKOTEKOT (15.3 cm) (Table 5). Diameter of rhizome proper and diameter of the attached culm followed similar trend (p=0.001). The values were 14.6, 14.7, 15.1 and 11.0 cm for thickness of rhizome proper and 7.0, 6.6, 7.3 and 4.9 cm for thickness of the attached culm for WONDE, WELELE, TIFRO and ENKOTEKOT landraces, respectively. WONDE and WELELE landraces have significantly higher number of internodes (p=0.007) in their rhizome proper than ENKOTEKOT landrace. The value for TIFRO landrace was not statistically different from other landraces. The number of rhizome necks per rhizome proper has not shown significant difference among the four landraces. The values were six for ENKOTEKOT and seven for the other landraces. The maximum number of elongated necks ranges from 9-11 for all landraces.

Table 5. Characteristics of rhizome proper of the different landraces (n=18, p=0.05, Tukey's HSD Post-hoc test)

Landrace	**Length of rhizome proper (cm)**	**Diameter of rhizome proper (cm)**	**Diameter of attached culm (cm)**	**Number of internodes of rhizome proper**	**Number of elongated rhizome necks**
WONDE	19.6 a	14.6 a	7.0 a	13 a	7 (2, 10)
WELELE	23.1 a	14.7 a	6.6 a	13 a	7 (3, 9)
TIFRO	20.5 a	15.1 a	7.3 a	12 ab	7 (3, 11)
ENKOTEKOT	15.3 b	11.0 b	4.9 b	10 b	6 (2, 11)

Numbers in brackets under the last column indicate minimum and maximum values, respectively.

4.1.2.3 Stand structure and dynamics of *A. alpina* landraces

Bamboo stand structure is mainly concerned with the number of plants per unit area and the age composition (age structure). These parameters are important aspects in investigating bamboo stand dynamics and yield. The number of plants under the three age-groups and the interaction between landraces and age-groups were statistically significant at p<0.05. Plant size, growth rate and shoot mortality also significantly varied among landraces.

4.1.2.4 Stand density

Number of plants per ha of ENKOTEKOT landrace (15800 ± 1411) was significantly higher (p=0.06) than that of WONDE landrace (11467 ± 689). This value was also higher than those of TIFRO (14200 ± 1442) and WELELE (14767 ± 176) landraces but not significantly different (Figure 14).

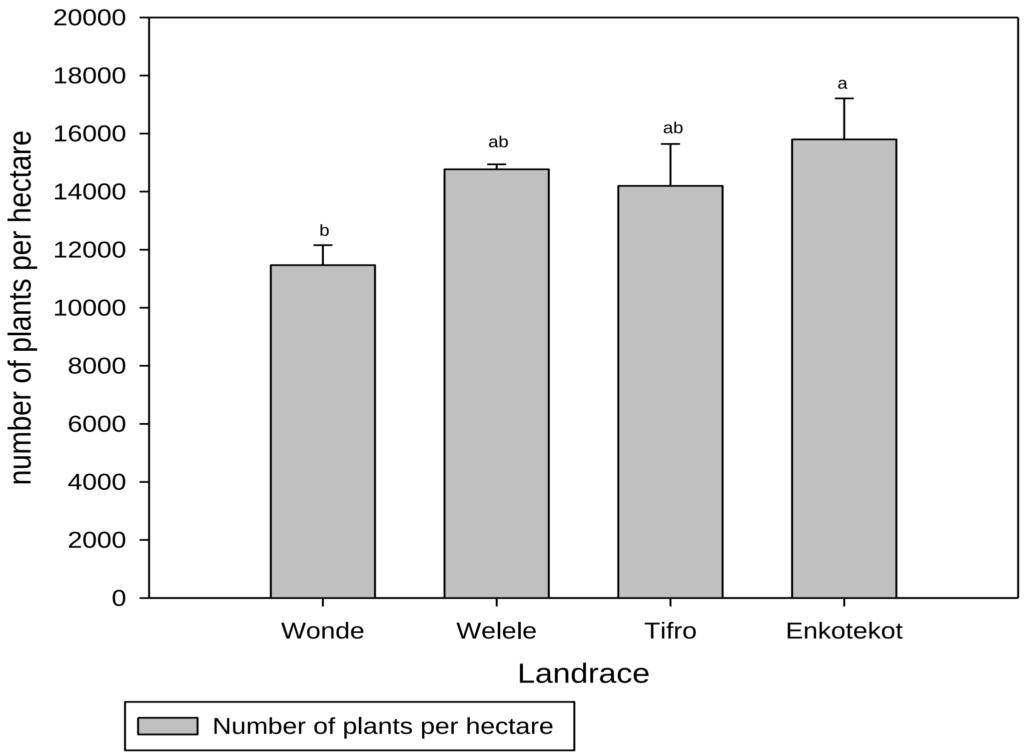

Figure 14. Number of plants per hectare of the four landraces (p=0.06, Duncan MRT, n=3)

4.1.2.5 Age structure

In general, from age structure data of all the landraces, more than 3 years old plants constitute 44% followed by 1-3 years old (33%) and < 1 year old plants (22%) forming a 3:2:1 ratio (Table 6). The number of plants per ha was not statistically different among age-groups for TIFRO and WONDE landraces. The values were 2133 ± 348, 4600 ± 252 and 4700 ± 1233 for WONDE and 4467 ± 338, 5267 ± 1017 and 4467 ± 742 for TIFRO landraces for <1, 1-3 and > 3 year old plants, respectively. Unlike that of WONDE and TIFRO landraces, the number of plants of age >3 are significantly higher than <1 and 1-3 years old plants in WELELE and ENKOTEKOT landraces (Table 6). The number of plants per hectare were1733 ± 186, 4967 ± 328 and 8100 ± 240 for WELELE landrace, 4100 ± 781, 4100 ± 600 and 7600 ± 529 for ENKOTEKOT landrace for <1, 1-3 and >3 year old plants, respectively. The significantly lower number of <1 year plants of WELELE landrace may be associated to the lower shoot recruitment in 2009 shooting.

Table 6. Number of plants per hectare of the four landraces under three age- groups (n=3, mean ±SE)

Age-group	**Landrace**				**Overall average**	**%**
	WONDE	**WELELE**	**TIFRO**	**ENKOTEKOT**		
<1 year	2133±348	1733±186[c]	4467±338	4100±781[b]	3108±411	22
1-3 years	4600±252	4967±328[b]	5267±1017	4100±600[b]	4733±297	34
≥3 years	4700±1233	8100±240[a]	4467±742	7600±529[a]	6217±592	44
Total	11467±689	14767±176	14200±1442	15800±1411	4686(331)	100

4.1.2.5 Growth characteristics

Both growth characteristics, namely culm diameter at breast height (DBH), culm height and total biomass per plant showed significantly different (p=0.000) results among the four landraces. Significantly higher DBH values were obtained from TIFRO (5.3 cm), WONDE (5.3 cm) and WELELE (4.9 cm) than ENKOTEKOT landrace (3.7 cm) (Table 7). Similar trend was observed for height (p=0.000) with values 11.00, 11.65, 11.50 and 7.10 m for WONDE, WELELE, TIFRO and ENKOTEKOT landraces, respectively.

Table 7. Diameter and height of plants per plot of the four landraces (n=12; p=0.05)

Landrace	Maximum DBH (cm)	Mean DBH (cm)	Maximum height (m)	Mean height (m)
WONDE	6.7±0.2	5.3±0.1 a	12.7	11.00±0.34 a
WELELE	6.5±0.1	4.9± 0.1 a	12.7	11.65±0.34 a
TIFRO	8.7±0.2	5.3±0.3 a	13.9	11.50±0.51 a
ENKOTEKOT	5.9±0.3	3.7±0.1 b	9.0	7.10±0.28 b

4.1.3 Growth rate and recruitment of *A. alpina* landraces

4.1.3.1 Height growth rate

Generally, from the growth curve (Figures 15 and 16) it is clear that height growth during the early stage of shoot growth was slow while it became abrupt after 4–5 measurements for WELELE, TIFRO and ENKOTEKOT landraces and after 6–7 measurements for WONDE landrace (Figure 16). This geometrical increment showed a declining trend for the later 2-3 measurements for the first three land races. Hence, growth of the selected sample plants i.e. from shoot emergence up to the start of sheathing-off, can be grouped into three significantly different growth rates or stages. Stage one**:** the slow growth period i.e. 03–19 August 2009; at this period, the growth rate per day was slow for all landraces with values ranging from 0.5–2.0 cm for WONDE, 1.7–6.1 cm for WELELE, 2.2–8.6 cm for TIFRO and 0.9-5.2 cm for ENKOTEKOT landraces. Stage two: fast growth period i.e. 23 August to 20 September 2009; at this period, the growth rate per day was continually increasing rapidly with values 2.8–30.0 cm for WONDE, 10.4–46.1 cm for WELELE, 10.5–36.5 cm for TIFRO and 7.8–24.9 cm for ENKOTEKOT land races. Stage three: the fast growth followed by declining trend i.e. 24 September 2009 and after; at this period, the growth rate per day showed declining trend, 18.4 cm and even less as time went on till it culminated height growth for WELELE landrace; 15.7 cm and less for TIFRO landrace and 8.9 cm and less for ENKOTEKOT landrace. However, still a rising trend was observed for WONDE landrace with a value of 53 cm, associated with the initial slow growth rates of the landrace. Unlike the other landraces, WONDE did not reached at its sheathing-off period (height growth rate was still rising), in two months time, but data was collected only up to this time so as to make comparison of all landraces in the same time period.

The maximum values recorded during the measurement period were 53 cm for WONDE, 58 cm for WELELE, 53 cm for TIFRO and 45 cm per day for

ENKOTEKOT landraces. The average height values at this stage (at the time of sheathing-off) were 7.62, 11.30, 10.72 and 6.71 m for WONDE, WELELE,TIFRO and ENKOTEKOT landraces, respectively. Average heights of mature plants of the respective landraces, from measurements taken for growth characterization and biomass determination (section 4.1.2.5) were 1100, 1165, 1150 and 710 cm, respectively (Table 7). These values are marked in Figure 15 to indicate trend of height growth during shooting season

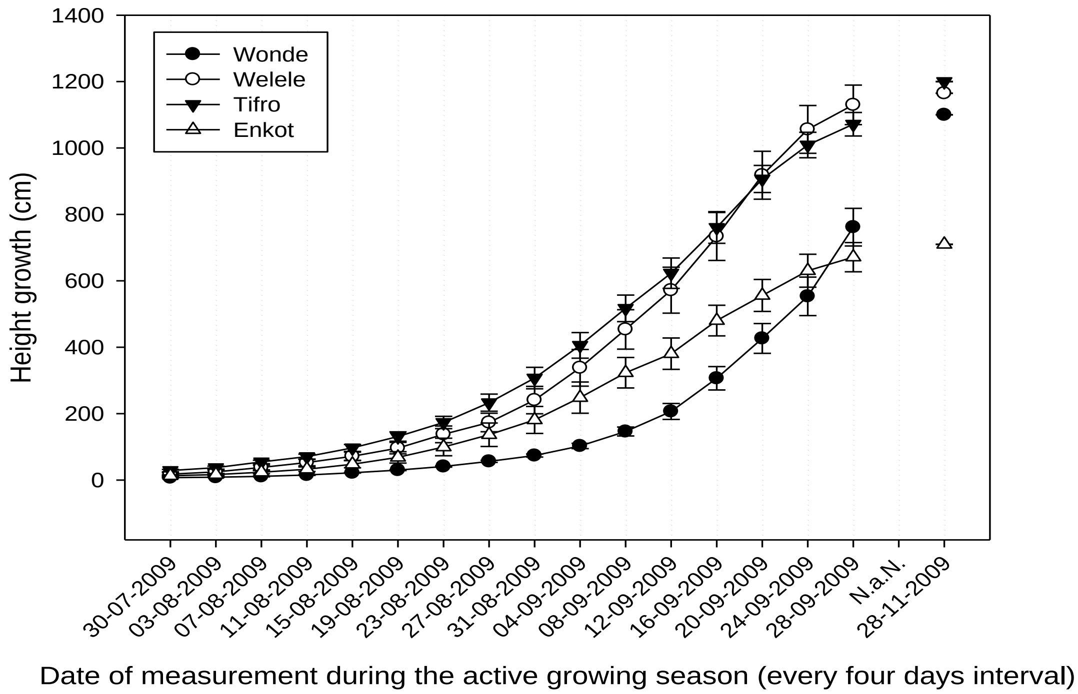

Figure 15. Height growth curve of four *A. alpina* landraces developed from data collected every four days in two months time

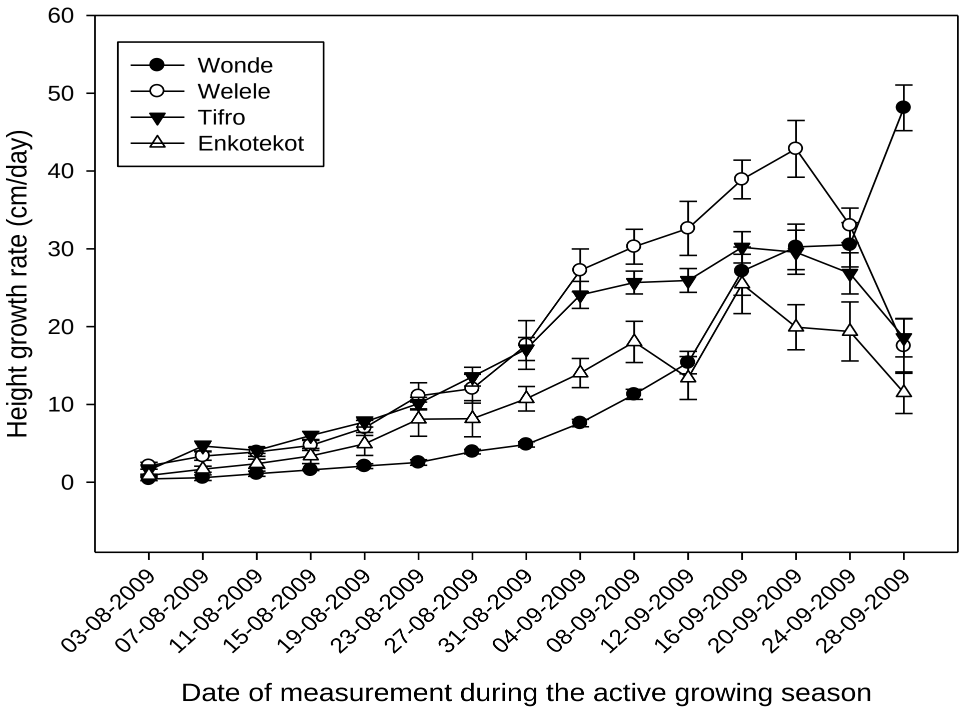

Figure 16. Height growth rate curve of four *A. alpina* landraces developed from data collected every four days in two months time

The growth rates were also regressed against the measurement periods/dates of measurement. The fitted curves using the regression-curve-fit option of PASW Statistics indicated exponential growth rates for the different landraces during the measurement period. The functions for the different landraces were as follows:

WONDE:
$\mathrm{GR}(\text{measurement period}) = \exp(0.228 * \text{measurement period})$, $R^2 = 0.98$, SE=0.385

WELELE:
$\mathrm{GR}(\text{measurement period}) = \exp(0.275 * \text{measurement period})$, $R^2 = 0.98$, SE=0.49

TIFRO:
$\mathrm{GR}(\text{measurement period}) = \exp(0.274 * \text{measurement period})$, $R^2 = 0.98$, SE=0.385

ENKOTEKOT*:*
$\mathrm{GR}(\text{measurement period}) = \exp(0.208 * \text{measurement period})$, $R^2 = 0.98$, SE=0.37

The measurements for growth rates were also subjected for ANOVA-analysis. The result indicates that TIFRO and WELELE have similar and significantly higher (p=0.000) growth rates as compared to the other two landraces. The mean growth rates for all the measurement periods were 17.8 cm day^{-1} for WELELE and 16.4 cm day^{-1} for TIFRO. WONDE and ENKOTEKOT have similar growth rates with value 12.3 cm $day^{-1}$and 10.3 cm day^{-1}, respectively, with in the two months measurement period; but WONDE might have closer maximum value to WELELE and TIFRO provided that extra time was given for further height measurement.

4.1.3.2 Shoot recruitment

The number of emerged shoots per plot was not statistically different among landraces. The values were 97, 67, 90 and 82 for WONDE, WELELE, TIFRO and ENKOTEKOT landraces, respectively (Figure 17). However, the number of aborted shoots was statistically different.The highest mortality (58 per plot or 58%) was from WONDE landrace, followed by WELELE (40 per/plot or 60%), and TIFRO landrace (26 per plot or 29%). Statistically lower mortality (13 per plot or 16%) was recorded from ENKOTEKOT landrace. Accordingly, the recruitment of ENKOTEKOT and TIFRO landraces (84 and 73%, respectively) was significantly higher (p=0.000) than those of WONDE and WELELE landraces (42 and 41%, respectively) (Figure 18).

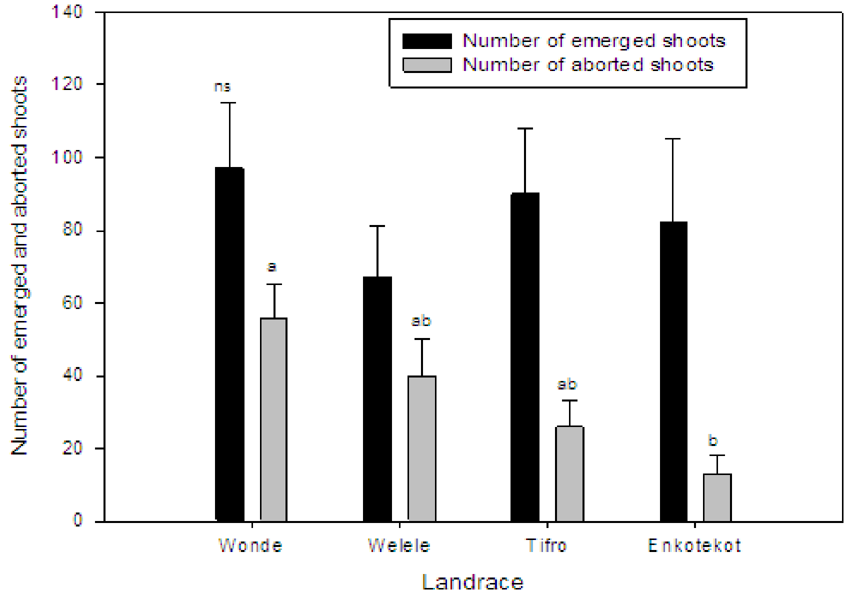

Figure 17. Shoot emergence and mortality of four *A. alpina*landraces per plot (100m^2)

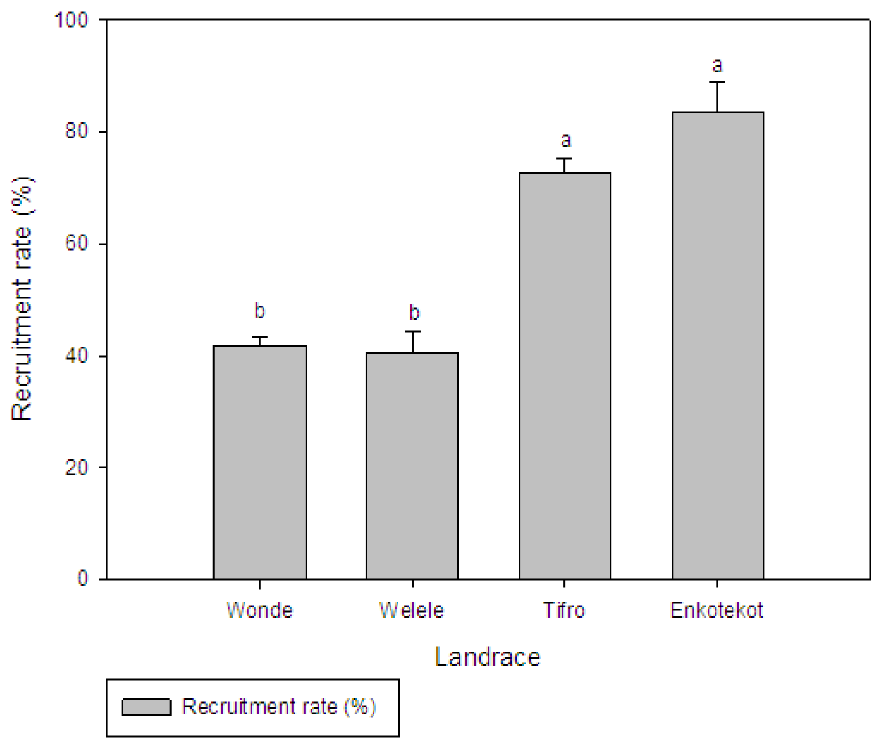

Figure 18. Shoot recruitment rate of four *A. alpina* landraces

4.1.4 Biomass accumulation and partitioning of the different landraces

4.1.4.1 Biomass accumulation per plant and unit area

Biomass of each plant in each plot was estimated using biomass models developed for the purpose. Total dry weight (TDW) and above ground total dry weight (AGTDW) were generated from plot estimates. Biomass per plant was generated from the randomly selected sample plants used for biomass estimation functions. Value for total fresh weight (TFW) and above ground total fresh weight (AGTFW) were estimated only on per plant basis. All parameters showed significant variation among landraces and among age-groups but not among the interactions of these factors (Table 8). The values of the fresh and dry weights of sample plants randomly selected from the four landraces and three age-groups are presented in Tables 9 and 10.

Table 8. Results of Two-way ANOVA of the fresh weight and dry weight of four *A. alpina* landraces and three arge-groups (p=0.05)

Factor (Group)	**Source**	**Type III Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
TFW (kg/plant)	Landrace	803.87	3	267.96	10.18	.000
	Age-group	157.00	2	78.50	2.98	.058*
	Landrace*Age-group	274.24	6	45.71	1.74	.128
	Error	1579.36	60	26.32		
AGTFW (kg/plant)	Landrace	634.47	3	211.49	13.49	.000
	Age-group	101.61	2	50.80	3.24	.046
	Landrace*Age-group	181.31	6	30.22	1.93	.091
	Error	940.35	60	15.67		
TDW (kg/plant)	Landrace	112.10	3	37.37	7.50	.000
	Age-group	101.10	2	50.55	10.15	.000
	Landrace*Age-group	53.80	6	8.97	1.80	.114
	Error	298.89	60	4.98		
AGTDW (kg/plant)	Landrace	94.09	3	31.36	8.62	.000
	Age-group	68.94	2	34.47	9.47	.000
	Landrace*Age-group	40.09	6	6.68	1.84	.107
	Error	218.39	60	3.64		
TDW (t/ha)	Landrace	485.63	3	161.88	3.41	.034
	Age-group	2890.87	2	1445.43	30.45	.000
	Landrace*Age-group	510.37	6	85.06	1.79	.143
	Error	1139.32	24	47.47		
AGTDW (t/ha)	Landrace	244.87	3	81.62	2.98	.051
	Age-group	1858.46	2	929.23	33.95	.000
	Landrace*Age-group	337.57	6	56.26	2.06	.097
	Error	656.94	24	27.37		

TFW=Total fresh weight, the sum total of all the plant components namely rhizome, culm, branch and leaf; AGTFW= above ground total fresh weight; TDW=Total dry weight; AGTDW= above ground total dry weight; Landraces: 1=WONDE, 2= WELELE, 3=TIFRO, 4=ENKOTEKOT; Age-group: 1=<1 year, 2= 1-3 years, 3=>3 years. (*) this value is a bit greater than 0.05 but still the significant difference is supported by Duncan MRT of the post hoc mean comparison.

Table 9. Fresh and dry weight of the randomly selected plants from each landrace for biomass study (n=18)

Landrace	**TFW**	**AGTFW**	**TDW**	**AGTDW)**
		(kg plant^{-1})		
WONDE	1 5.022	11.832	4.617	3.914
WELELE	15.267	11.305	5.436	4.487
TIFRO	16.547	13.316	5.811	4.846
ENKOTEKOT	8.012	5.510	2.583	1.893

Table 10. Fresh and dry weight of the randomly selected plants from each age-group for biomass study (n=24)

Age-group	**TFW**	**AGTFW**	**TDW**	**AGTDW)**
		(kg plant-1)		
< 1 year	12.633	9.597	2.964	2.445
1-3 years	15.8	12.17	5.696	4.748
> 3 years	12.703	9.706	5.175	4.70

Total plant dry weight per ha was statistically significant among landraces. WELELE landrace has the highest value (74±8.1 t ha^{-1}) followed by TIFRO (69 ± 11.7 t ha^{-1}) and WONDE (59±7.0 t ha^{-1}. The value for ENKOTEKOT landrace was significantly lower (45 ± 3.6 t ha^{-1}) than those of the other three landraces (Figure 19). Above ground total dry weight also followed the same trend to total above ground biomass. The values for WELELE, TIFRO and WONDE were 60±5.9, 55± 8.7 and 48±5.4 t ha^{-1}, respectively. The value for ENKOTEKOT landrace (39± 3.1 t ha^{-1}) which was statistically lower than those of the others.

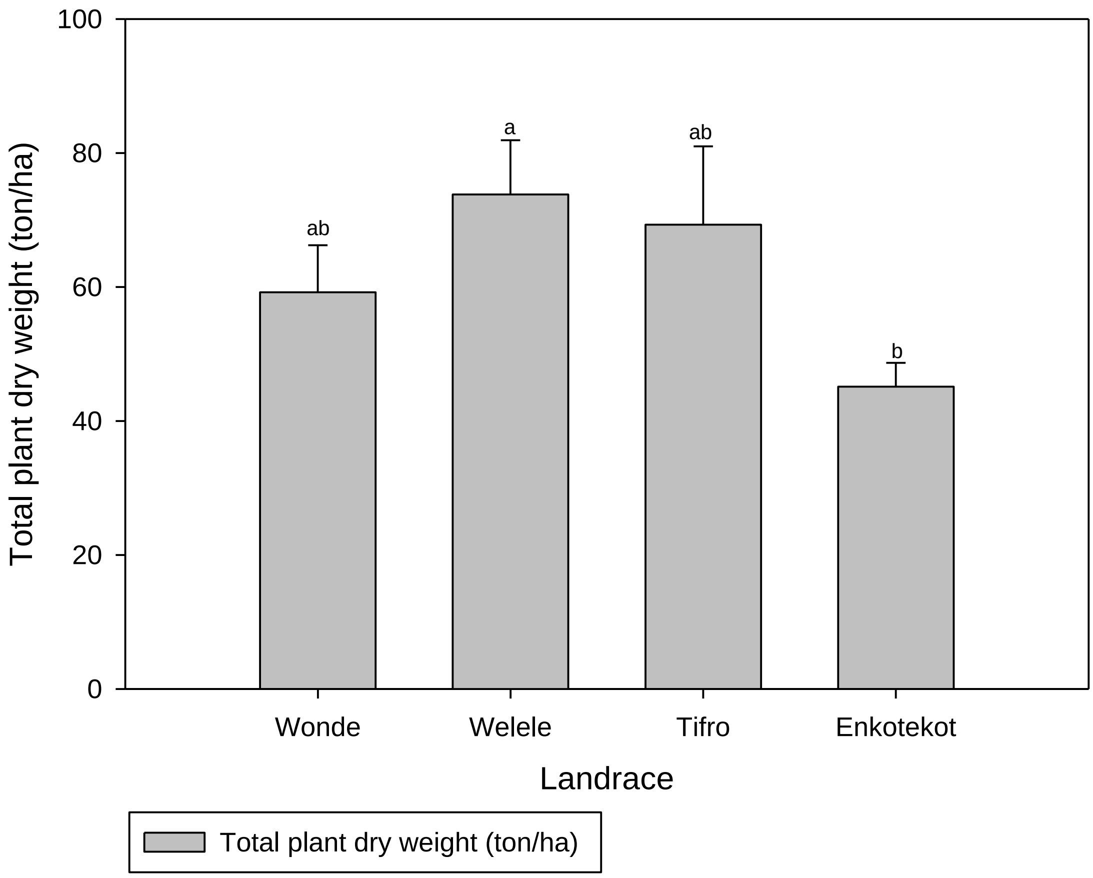

Figure 19. Total plant dry weight per hectare of four *A. alpina* landraces (n=3; p=0.05; Duncan MRT)

4.1.4.2 Biomass partitioning among plant parts

The order of biomass allocation to plant parts was found to be culm > rhizome > branch > leaf (Figure 20). The highest biomass allocation was allocation to culm (66, 67 and 65 and 55%) followed by rhizome (15, 17, 17 and 21%) and branch (13, 11, 11 and 14%) for WONDE, WELELE, TIFRO and ENKOTEKOT landraces, respectively. The least allocation was to leaf with values 5, 5, 7 and 9% for the respective landraces.

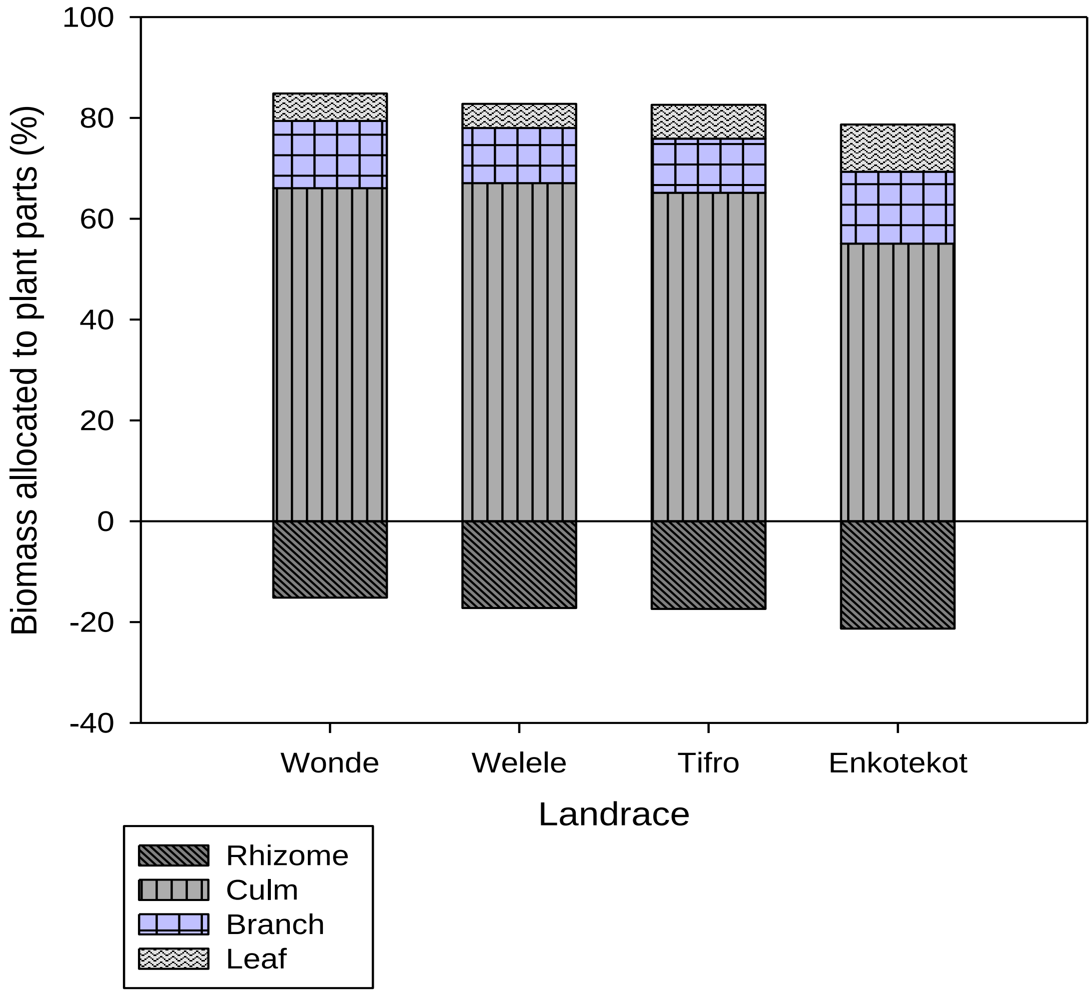

Figure 20. Biomass partitioning of four *A. alpina* landraces to four plant parts (n=24)

4.2 Stand Structure, Growth and Biomass of *A. alpina* Under Environmental Gradient

4.2.1 Stand structure and growth dynamics under different landforms

The number of plants per hectare, DBH, height, height growth rate and shoot recruitment were determined from data collected from each plot. All parameters showed significant variation among landforms (Table 11). The number of plants per hectare, DBH and height did not significantly vary among age-groups. The number of normal and aborted shoots per plot did not significantly vary among landforms but the recruitment rate was significantly different.

Table 11. ANOVA of number of plants per ha, culm size, shoot recruitment and height growth rate under three landforms

Parameter	Source	df	Mean Square	F	Sig.
Number of plants per hectare	Landform	2	3.24E+07	8.943	0.002
	Age-group	2	1.14E+07	3.145	0.067
	Landform*Age-group	4	1685926	0.465	0.761
	Error	4	5317778		
Diameter at breast height (cm)	Landform	2	54.75	37.61	0.000
	Age-group	2	0.27	0.18	0.832
	Landform*Age-group	4	0.71	0.48	0.747
	Error	45	1.46		
Culm height (m)	Landform	2	164.94	38.58	0.000
	Age-group	2	1.46	0.34	0.712
	Landform*Age-group	4	0.36	0.08	0.987
	Error	42	4.27		
Number of normal shoots	Landform	2	188.78	2.61	0.153
	Error	6	72.33		
Number of aborted shoots	Landform	2	60.11	1.8	0.244
	Error	6	33.33		
Recruitment rate (%)	Landform	2	381.03	13.4	0.006
	Error	6	28.44		
Daily height growth rate (cm day^{-1})	Landform	2	753.99	5.55	0.005
	Error	126	135.93		

4.2.1.1 Stand density and age structure

The 5-15% level-slopping landform had significantly higher density (20,467 plants per ha) than the 40-60% straight slope (11,300 plants per ha) and 40-60% concave slope (10,667 plants per ha) landforms (Figure 21). However the number of plants per hectare did not vary among plants of the three age-groups (Table 12). From the same Table, the ratio of <1: 1-3: > 3 year old plants for 40-60% concave slope, 40-60% straight slope and 5-15% level-slopping land was 2:4:5, 3:4:5 and 6:7:7, respectively.

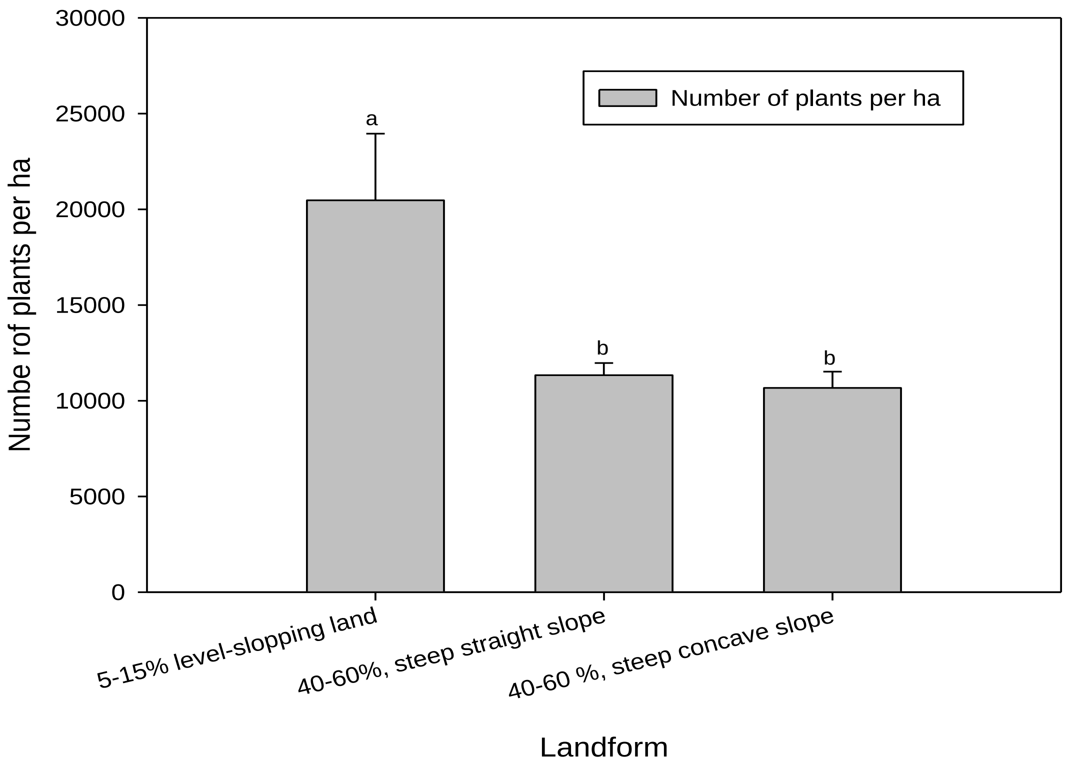

Figure 21. Number of plants per hectare under three landforms (n=3; p=0.05)

Table 12. Number of plants of different ages under the three landforms (mean ± SE; n=3)

	Number of plants per hectare			
Age (years)	**40-60% concave slope**	**40-60% straight slope**	**5-15% level-slopping**	**Total**
<1	1,533 ± 291	2,800 ± 1102	6,400 ± 721	10,633± 4318
1 - 3	3,733 ± 67	4,067 ± 882	7,200 ±1732	14,800±3208
>3	5,400± 1039	4,667 ± 1288	7,333 ± 1,593	17,000±2230
Total	10,667 ± 3359	11,300± 1570	20,467 ±733	14144±1913

4.2.1.2 Growth characteristics

The significantly higher (p=0.000) mean DBH (8.4 cm) and height (15.2 m) values were found from 40-60% concave slope followed by 40-60% straight slope (DBH=6.0 cm and height=10.7m) and 5-15% level-slopping land (DBH=5.0 cm and height=9.6 m) (Table 13). The maximum DBH and height values on 40-60% concave slope were 9.2 cm and 18 m, respectively. The 40-60% straight slope and 5-15% level-slopping land had max DBH 8.6 and 6.2 cm and maximum height of 13.0 and 12.7 m, respectively.

Table13. Diameter and height of plants per plot of the three landforms (n=9; p=0.000)

Landform	Maximum DBH (cm)	Mean DBH (cm)	Maximum height (m)	Mean height (m)
5-15%, level-slopping	6.2	5.0±0.2^{c}	12.7	9.6± 0.4^{b}
40-60%, straight slope	8.6	6.0± 0.4^{b}	13.0	10.7± 0.6^{b}
40-60%, concave slope	9.2	8.4±0.2^{a}	18.0	15.2± 0.5^{a}

4.2.2 Growth and recruitment of *A. alpina* under different landforms

4.2.2.1 Height growth rate

Generally, from the growth curve (Figures 22 and 23) it is observed that except for the measurements taken from 30 July to 07 August 2009 of 5-15% level-slopping and 40-60% straight slope landforms, height growth is continuously increasing up to 13 September, 2009, and then showed a declining trend. The 40-60% concave landform has significantly higher growth rate (p=0.000) than other landforms throughout the growth period. Average growth rate of this landform for all the measurement periods was 23 cm day^{-1} (maximum value 43 cm day^{-1} at the 13th measurement - 16 September 2009). The other landforms had average growth ratesof 15 and 17 cm day^{-1}. Maximum values of the 40-60% straight slope and 5-15% level-slopping land were 34 and 25 cm day^{-1}, respectively, on the 13th measurement.

The growth rates were also regressed against the measurement periods (dates of measurement). The fitted curves using the regression-curve-fit option of PASW Statistics indicated exponential growth rates for the different landforms during the measurement period. The functions for the different landraces were as follows:

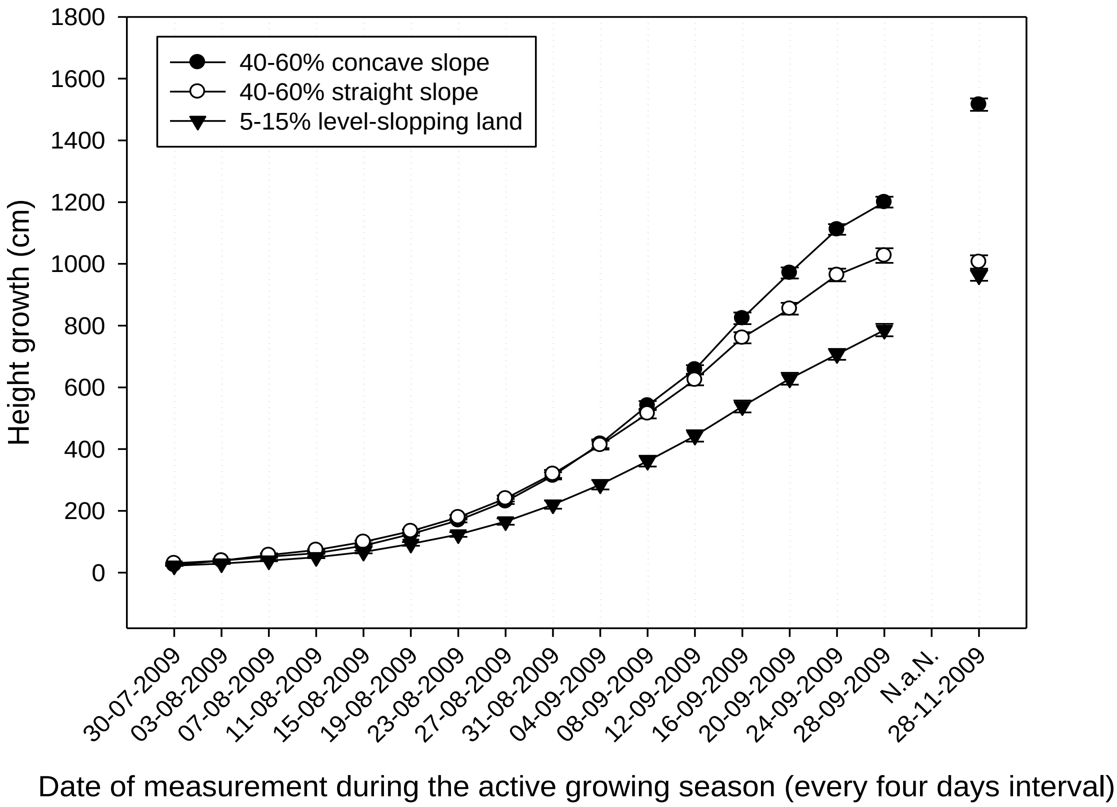

Figure 22. Height growth of newly growing bamboo culms calculated from data collected at four days interval during active growing period on different landforms

$40-60\%$ concaveslope:
$\mathrm{GR}(\text{measurement period}) = \exp(0.299 * \text{measurement period})$, R^2= 0.94, SE=0.758

$40-60\%$ straight slope
$\mathrm{GR}(\text{measurement period}) = \exp(0.282 * \text{measurement period})$, R^2= 0.94, SE=0.664

$5-15\%$ level $-$ slopping land:
$\mathrm{GR}(\text{measurement period}) = \exp(0.268 * \text{measurement period})$, R^2= 0.91, SE=0.779

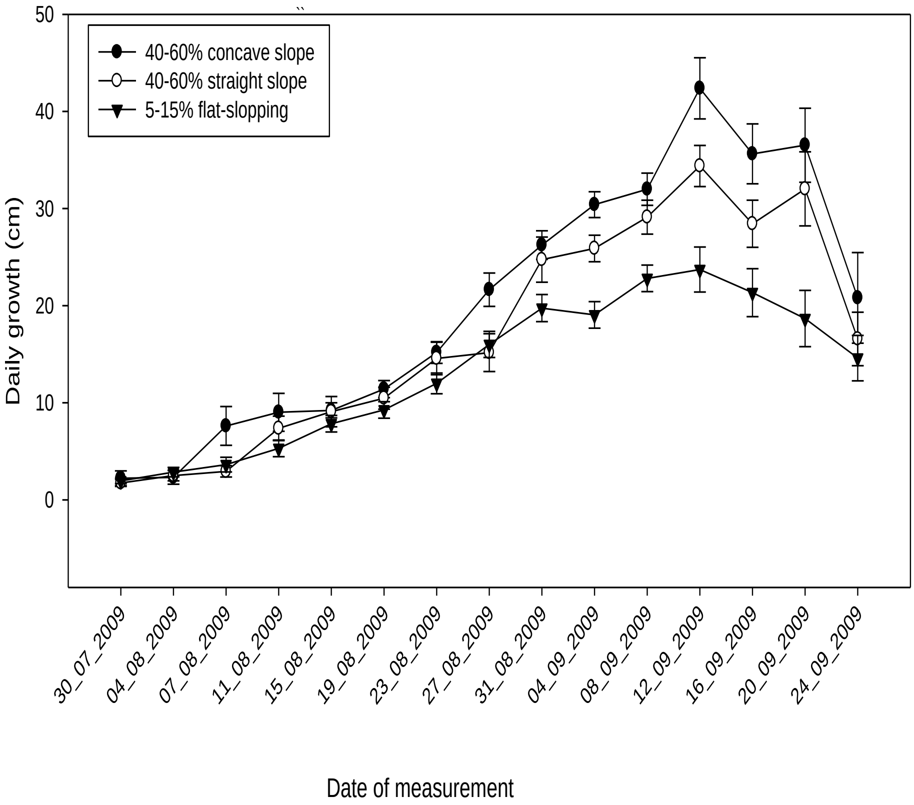

Figure 23. Daily height growth rates of newly growing bamboo culms calculated from data collected at four days interval during active growing period on different landforms

4.2.2.2 Shoot recruitment

Shoot recruitment rate was determined as the ratio of recruited shoots to the total shoots emerged during the shooting season. Recruitment rate for landform 5-15% level-slopping land (87%) was significantly higher (p=0.006) than 40-60% concave slope (65%) and 40-60% straight slope (72%) (Figure 24).

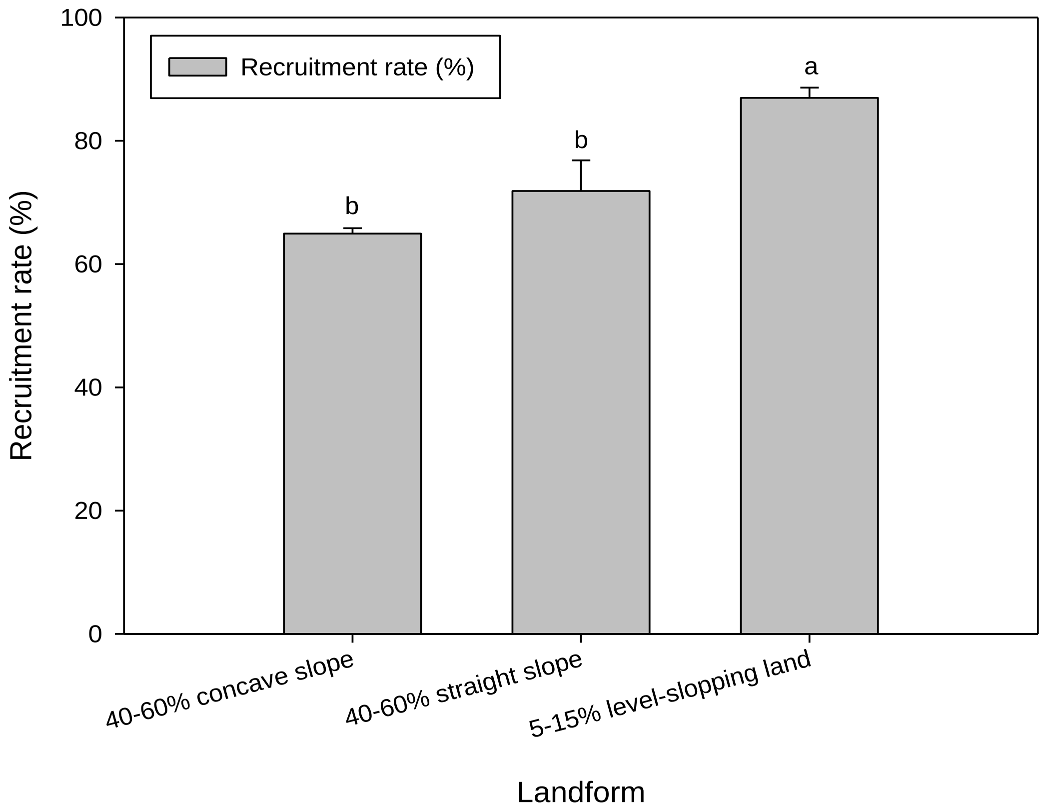

Figure 24. Recruitment rate of stands under three landforms

4.2.3 Biomass of *A. alpina* under different landforms

Per plant basis estimates for TFW, AGTFW, TDW and AGTDW were significantly different among landforms (Table 14). However, estimates made on per hectare basis were not statistically different. TDW and AGTDW were also statistically varied among age-groups. However, values of the interaction between landform and age-groups were not significant for all the fresh and dry weight per plant and per hectare basis estimates.

Biomass estimation was made employing the functions developed for the three age-groups. Total dry weight estimates for 40-60% concave slope, 40-60% straight slope and 5-15% level-sloping landforms were 117± 28.8, 64±8.3 and 90±22.6 t ha^{-1}, respectively (Figure 25). The values were not statistically significant. Number of stems for the 40-60% concave slope was statistically lower than the other landforms, but because of the higher biomass values of individual plants, its biomass per ha was still higher, though not statistically different from the other land forms. Above ground total dry weight also followed the same trend to total dry weight. The values for 40-60% concave slope, 40-60% straight slope and 5-15% level-slopping landforms were 99 ±23.7 and 56±6.6 and 80±19.9 t ha^{-1}, respectively.

Table 14. Two-Way ANOVA results of biomass under three landforms and three age-groups

Parameter	Source	df	Mean Square	F	Sig.
TFW	Landform	2	2449.5	40.79	**0.000**
(kg/plant)	Age-group	2	98.17	1.63	0.206
	Landform * Age-group	4	18.91	0.31	0.867
	Error	45	60.05		
AGTFW	Landform	2	1653.71	40.51	**0.000**
(kg/plant)	Age-group	2	32.55	0.8	0.457
	Landform * Age-group	4	13.95	0.34	0.848
	Error	45	40.82		
TDW	Landform	2	306.64	27.41	**0.000**
(kg/plant)	Age-group	2	136.62	12.21	**0.000**
	Landform * Age-group	4	12.96	1.16	0.342
	Error	45	11.19		
AGTDW	Landform	2	233.77	29.16	**0.000**
(kg/plant)	Age-group	2	119.57	14.92	**0.000**
	Landform * Age-group	4	16.1	2.01	0.109
	Error	45	8.02		
TDW (t/ha)	Landform	2	2520920578	1.7	0.292
	Age-group	2	10899331244	7.36	**0.046**
	Error	4	1481134044		
AGTDW	Landform	2	174.49	0.67	0.522
(t/ha)	Age-group	2	2138.01	8.25	**0.003**
	Landform * Age-group	4	310.51	1.20	0.345
	Error	18	259.06		

TFW= Total Fresh Weight; AGTFW=Above Ground Total Fresh Weight; TDW= Total Dry Weight; AGTDW=Above Ground Total Dry weight

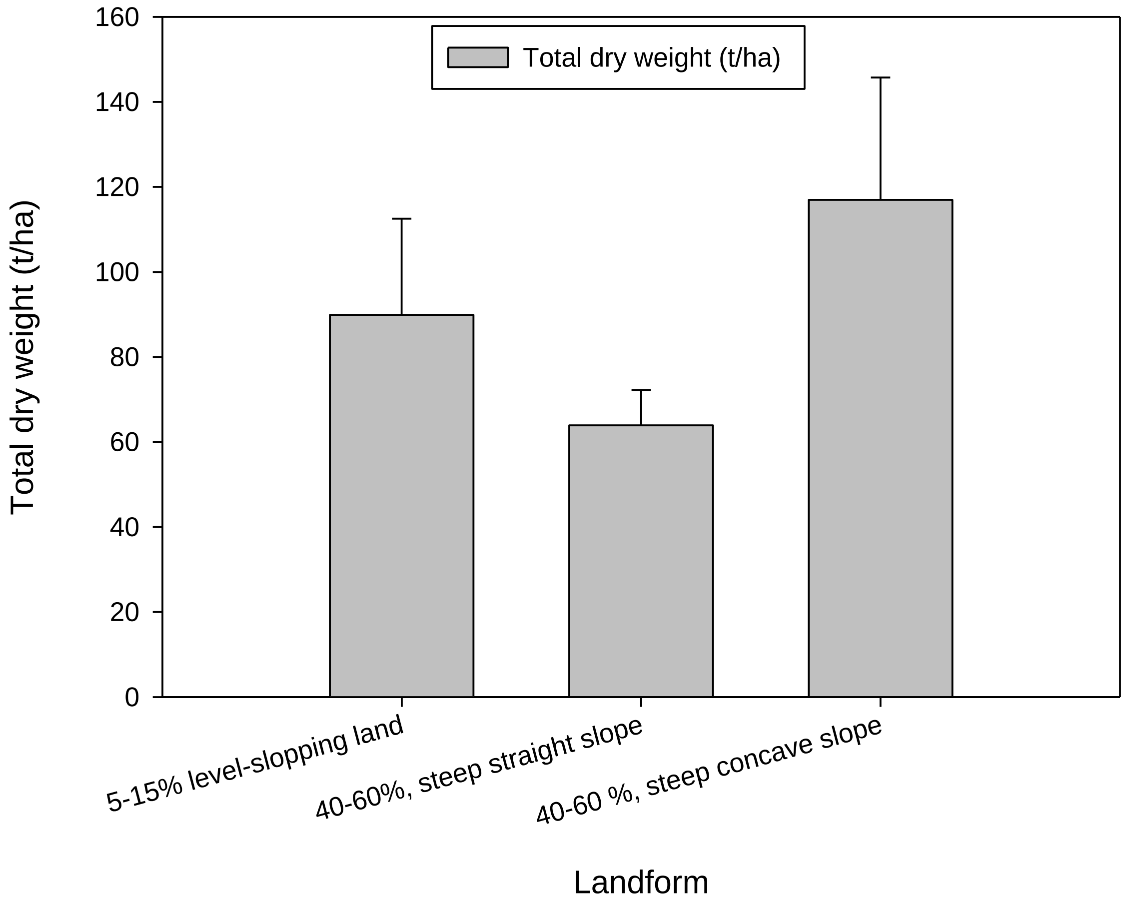

Figure 25. Biomass per ha of bamboo plants under three land forms (n=3)

4.2.3.1 Biomass distribution among age-groups

Growth among the three age-groups indicated that biomass accumulation per plant of <1 year plants was significantly lower than higher age-groups. Biomass per plant for <1 year old plants was 4 kg, while for the 1-3 and >3 years old plants it was 9 and 10 kg plant^{-1}, respectively (Figure 26). Thus, the values for >3 and 1-3 year old plants were more than double that of the <1 year old plants. Diameter and height were not different among the different age-groups. Unlike other timber plants, diameter and height growth of bamboo are accomplished within 2-3 months time; from that time onwards there are no increments in diameter and height because bamboo lacks cambial growth.

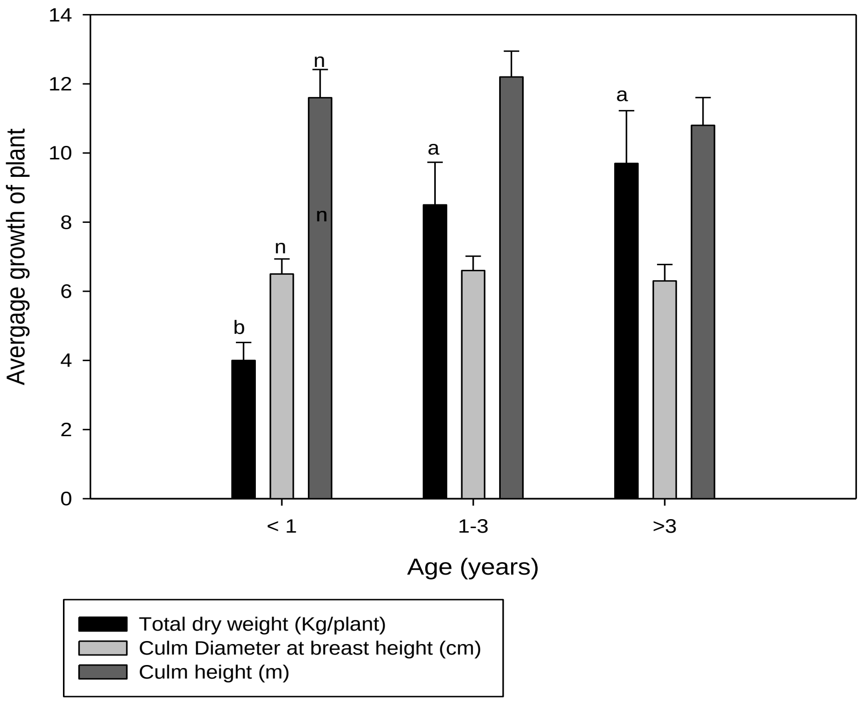

Figure 26. Diameter, height and biomass of plants under three age-groups of the studied plots (n=9, Tukey HSD test); n=non significant

4.2.3.2 Biomass partitioning among plant parts

Allocation to plant parts was not statistically different among landforms. The proportion of allocation to culm was 65, 67 and 69 % for 40-60% concave slope, 40-60% straight slope and 5-15% level-sloping landforms, respectively. The values for rhizome, branch and leaf parts of the respective landforms were 17, 17 and 14; 13, 9 and 12; and 5, 6 and 5%, respectively (Figure 27).

Accordingly, the proportion of allocation to above ground and belowground plant parts were 79 - 89 % and 13- 17%, respectively, resulting in the belowground to above ground ratio of 0.15 for 5-15% level-sloping landforms and 0.20 for the other two landforms.

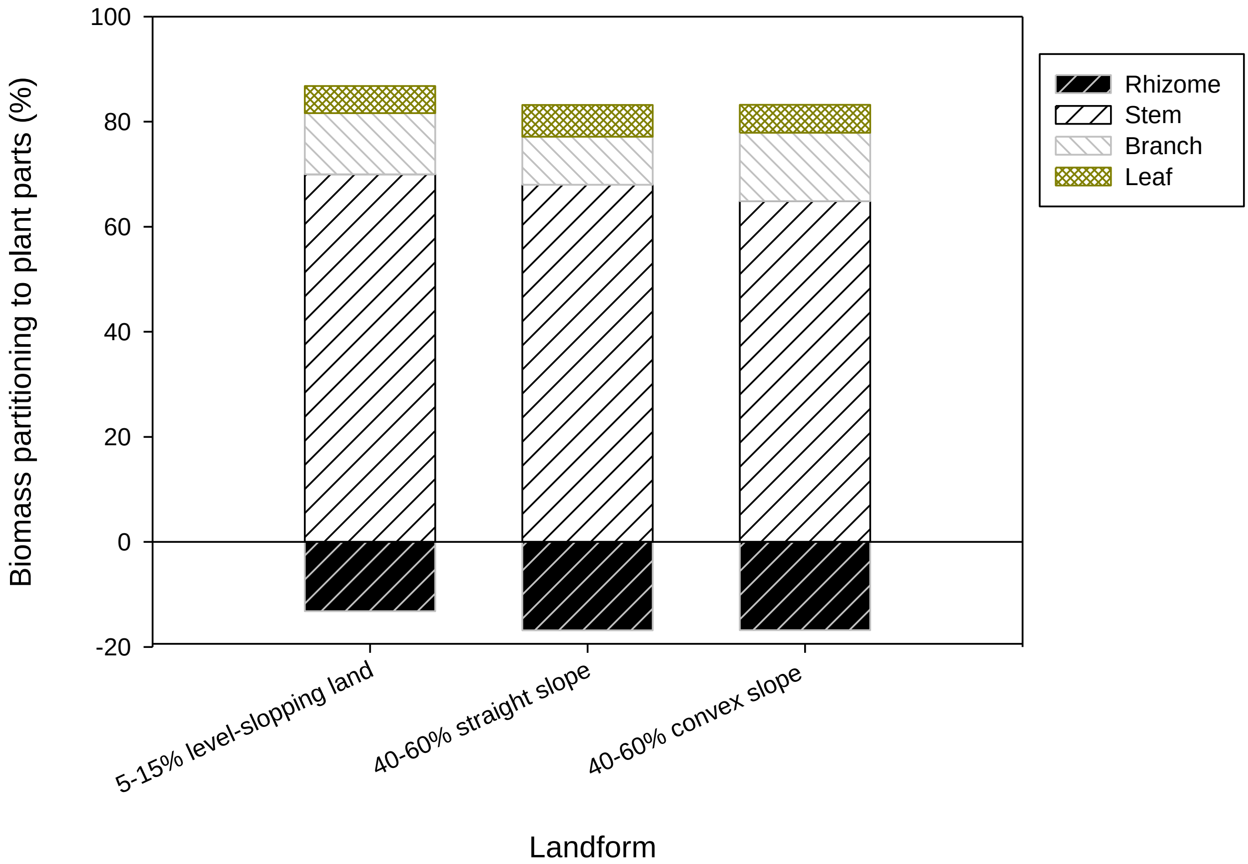

Figure 27. Biomass partitioning (% of total) of *A. alpina* among the different parts under three landforms (n=54)

4.2.4 Soil propertiesunder different landforms

4.2.4.1 Soil physical properties

The 5-15% level-slopping landform had statistically lower sand (38%) but higher silt content (39%) as compared to the 40-60% steep straight slope. The 40-60% concave slope had also lower silt content (23%) but statistically higher clay content (41%) as compared to the 40-60% straight slope landform. Texture did not exhibit significant difference along soil depth (Table 15). Soil texture classes were also categorized using the Soil Texture Triangle used in soil texture classification (FAO, 2006). Thus, the texture class was found to be clay for 40-60% concave slope and clay-loam for the other landforms. The average soil depth for 40-60% straight slope, 5-15% level to slopping land and 40-60% concave slope was found to be 123, 124 and 100 cm, respectively (Table 15). Bamboo rhizome is found distributed within 44-72 cm depth with rooting depth of 90 -119 cm for all the three landforms. Abundant rooting zone of the landforms was limited to a shallow depth and had a narrow range (30 - 37 cm) for the three landforms.

4.2.4.2 Soil chemical properties

The pH of the three landforms was statistically different (p=0.05). The 5-15% level-slopping landform had the highest value (6.26) followed by the 40-60% steep straight slope (6.03). The least pH value (5.92) was determined for the 40-60% concave slope (Table 16). EC was not statistically different among landforms. Soil depth had significant effect only for EC, in which the 0-20 cm depth had higher value than the 20-40 and 40-60 cm depths. Soil pH did not exhibit significant difference along depth.

Table 15. Texture and moisture content of soils under three landforms

Texture, Moisture content	Landform					Soil Depth (cm)			F-value	P-value
	40-60%, concave slope	40-60%, straight slope	5-15%, level-sloping	F-value	P-value	0-20	20-40	40-60		
Sand (%)	22.78^{b}(1.78)	34.22^{a} (3.90)	23.44^{b} (2.44)	5.089	0.014	31.11 (3.61)	26.00 (3.46)	23.33 (2.39)	1.525	0.238
Silt (%)	36.22(1.90)	34.89 (1.60)	37.56 (0.65)	0.809	0.457	35.33 (1.33)	35.56 (1.14)	37.78 (1.87)	0.833	0.447
Clay (%)	41.00^{a} (2.06)	30.89^{b} (3.72)	39.00^{ab}(2.79)	3.332	0.053	33.56 (2.85)	38.44 (3.43)	38.89 (3.30)	0.853	0.439
MC (%)	23.80^{a} (0.96)	22.12^{ab} (0.50)	20.30^{b}(0.68)	5.590	0.010	22.00 (0.95)	21.92 (0.77)	22.30 (0.95)	0.051	0.951
Texture class	clay	Clay-loam	Clay-loam	_	_	_	_	_	_	_
Soil depth (cm)	100.33 (8.37)	123.33 (23.33)	124.00 (17.01)	2.484	0.164	_	_	_	_	_
Rooting depth (cm)	90.33 (10.33)	118.67 (26.31)	96.00 (17.01)	0.620	0.569	_	_	_	_	_
Rhizoming depth (cm)	44.33 (4.33)	72.43 (12.16)	47.00 (11.14)	0.603	0.577	_	_	_	_	_

MC=Moisture Content

Table 16. pH and EC of soil under three landforms and along three soil depths

Soil property	Landform					Soil Depth (cm)				
	40-60%, concave slope	40-60%, straight slope	5-15%, level-sloping	F-value	p-Value	0-20	20-40	40-60	F-value	p-Value
pH_H_2O	5.92^{b} (0.04)	6.03^{ab} (0.12)	6.26^{a} (0.08)	3.54	0.045	6.07 (0.09)	6.056 (0.11)	6.09 (0.11)	0.27	0.973
EC	0.12 (0.02)	0.107 (0.01)	0.13 (0.02)	0.599	0.557	0.17^{a} (0.01)	0.106^{b} (0.01)	0.08^{b} (0.01)	27.07	0.000

Means (n=9)± standard errors. Different letters within one column indicate significant differences (p<0.05, Tukey's HSD test);

The three important soil fertility parameters namely, total Nitrogen, organic carbon and their ratios (C:N ratio) did not show significant difference among the three landforms. The values for total Nitrogen were 0.393, 0.387 and 0.383 for the 5-15 % level-slopping, 40-60 % straight slope and 40-60% concave slope, respectively (Table 17). The corresponding values for organic carbon were 4.247, 3.963 and 3.890%, respectively. Available Phosphorus, Potassium and Magnesium showed significant difference among landforms. The highest available P (86.19 ppm) was found on the 5-15% level-slopping landform and followed by the 40-60% straight slope (79.74 ppm). The least value (4.87 ppm) was found on the 40-60% concave slope.

The highest K (2.39 Cmol (+)/kg) was found on the 40-60% straight slope, followed by the 40-60% concave slope (1.67 Cmol (+)/kg) and 5-15% level-slopping landform (0.64 Cmol (+)/kg). Mg was significantly higher (6.72 Cmol (+)/kg) at the 5-15% level-slopping land followed by the 40-60% straight slope (5.23 Cmol (+)/kg). Values for the 40-60% concave slope (4.93 Cmol (+)/kg) was the least among the three landforms. There were no statistical differences in the concentration of Na and Ca among landforms. The values ranged from 0.23 to 0.39 for Na and 20.59 to 22.3 for Ca. The difference in CEC and base saturation were also not significant among landforms. The range was 40.35 to 42.73 for CEC and 62.23 to 69.78% for base Saturation.

Table 17. Soil chemical properties under three landforms

Land-form	Unit	5-15% level-slopping land	40-60% straight slope	40-60 % concave slope	F-Value	p-value
N	%	0.39±0.05[ns]	0.39±0.30	0.38±0.03	0.014	0.986
C	%	3.96±0.57 [ns]	4.25±0.44	3.89±0.43	0.152	0.860
C:N	ratio	9.89±0.59 [ns]	10.83±0.26	9.96±0.40	1.412	0.263
Av. P	ppm	86.19±21.96[a]	79.74±31.49[ab]	4.87±0.97[b]	4.156	0.028
Na	Cmole/kg	0.23±0.02 [ns]	0.39±0.06	0.31±0.06	0.780	0.470
K	Cmole/kg	0.64±0.11[b]	2.39±0.26[a]	1.67±0.57[ab]	5.847	0.009
Ca	Cmole/kg	22.27±0.76[ns]	21.33±0.30	20.59±3.17	0.350	0.709
Mg	Cmole/kg	6.72±0.41[a]	5.23±0.27[ab]	4.93±0.65[b]	4.180	0.028
CEC	Cmol/kg	42.73±0.75[ns]	40.35±1.68	42.12±3.54	0.288	0.752
BaseSat.	%	69.78±1.32[ns]	68.67±2.25	62.23±4.77	1.634	0.216

Mean (n=9) ± standard error. Different letters within one row indicate significant differences ($p<0.05$, Tukey's HSD test); ns=mean values in the row are not statistically significant

Total N at top 0-20 cm was significantly higher (0.492%) than at the middle 20-40 cm (0.370%) and bottom 40-60 cm (0.30%) depths. The trend was similar also for organic Carbon. Values for organic Carbon at 0-20 cm depth (5.41%) were significantly higher than the 20-40 (3.775%) and 40-60 cm (2.913%) depths. The C:N ratio for 0-20 cm depth was significantly higher (11.19.) followed by 20-40 cm depth (10.14). The value for 40-60 cm depth was the lowest (9.44). However, the values for available P, base cations and base saturation did not show significant difference along soil depth (Table 18).

Table 18. Soil chemical properties along soil depth

Soil property	Unit	Soil depth (cm)			F-value	P-value
		0-20 cm	20-40 cm	40-60 cm		
N	%	0.49 ^{a}(0.04)	0.37 ^{b}(0.02)	0.30^{b}(0.03)	11.568	0.000
C	%	5.41^{a}(0.31)	3.77 ^{b}(0.31)	2.91^{b}(0.34)	15.707	0.000
C:N	ratio	11.10 ^{a}(0.30)	10.14^{ab}(0.46)	9.44^{b}(0.40)	4.481	0.022
Av. P	ppm	59.00(21.32)	56.80(27.73)	55.00(27.60)	0.006	0.994
Na	Cmole/kg	0.30(0.06)^{ns}	0.33(0.06)	0.31(0.06)	0.184	0.833
K	Cmole/kg	1.75(0.41) ^{ns}	1.46(0.40)	1.53(0.55)	0.090	0.914
Ca	Cmole/kg	22.63(2.01) ^{ns}	20.96(2.43)	20.62(1.92)	0.827	0.449
Mg	Cmole/kg	5.62(0.50) ^{ns}	5.51(0.57)	5.74(0.56)	0.043	0.958
CEC	Cmol/kg	42.77(2.24) ^{ns}	42.66(2.57)	41.32(2.36)	0.480	0.625
Base Sat.	%	69.38(3.23) ^{ns}	64.22(3.71)	66.33(2.95)	0.887	0.425

Means (n=9)± standard errors. Different letters within one row indicate significant differences ($p<0.05$, Tukey's HSD test); NS=mean values in the row are not statistically significant

4.3 The Effect of Silvicultural Management on Regeneration, Growth and Yield of Previously Unmanaged *A. alpina* bamboo stands

4.3.1 Culm recruitment and shoot mortality rate

Combined analysis of the two factor split plot ANOVA indicated that shoot recruitment, significantly varied between the two shooting seasons of 2009 and 2010 (Table 19). The 2009 shooting season had significantly higher number of recruited culms than the 2010 shooting season. The number of recruited culms was also significantly different among silvicultural management practices. The combined analysis showed that soil loosening accompanied by selective thinning and removal of old stumps (Treatment 4) yielded 37% higher number of recruited culms than the control plot (Figure 28 D).

Table 19. ANOVA of the combined analysis of 2009 and 2010 culm recruitments as affected by silvicultural management techniques and organic fertilizer application

Source	**df**	**Mean Square**	**F-value**	**Prob.**
Year	1	147501.760	443.47	0.0005
Organic fertilizer	1	14.260	0.04	0.8366
Year x Organic fertilizer	1	21.094	0.06	0.8019
Error	4	637.427		
Silviculturaltreatment	7	976.070	2.93	0.0097
Year x Silviculturaltreatment	7	714.332	2.15	0.0502
Organic fertilizer x Silviculturaltreatment	7	460.070	1.38	0.2269
Year x Organic fertilizer x Silviculturaltreatment	7	310.570	1.2077	0.3139
Error	56	257.162		
Total	95			

Five months after application of the treatments (September 2009), the number of newly recruited culms was statistically significant ($p=0.05$, Duncan MRT) among treatments (Table 19; Figure 28A). Soil loosening+selective thinning

+removal of old stumps (Treatment 4), removing old stump + selective thinning (Treatment 3) and soil loosening (Treatment 5) had 40, 28 and 8% more recruited culms (Figure 28A) and 60, 72 and 76% lower shoot mortality rate than the control plot, respectively (Figure 28B). The number of recruited culms in 2010 shooting season was incomparably lower than the 2009 shooting season. There was no statistical difference in the number of recruited culms among treatments (Figure 28C) in the 2010 shooting season.

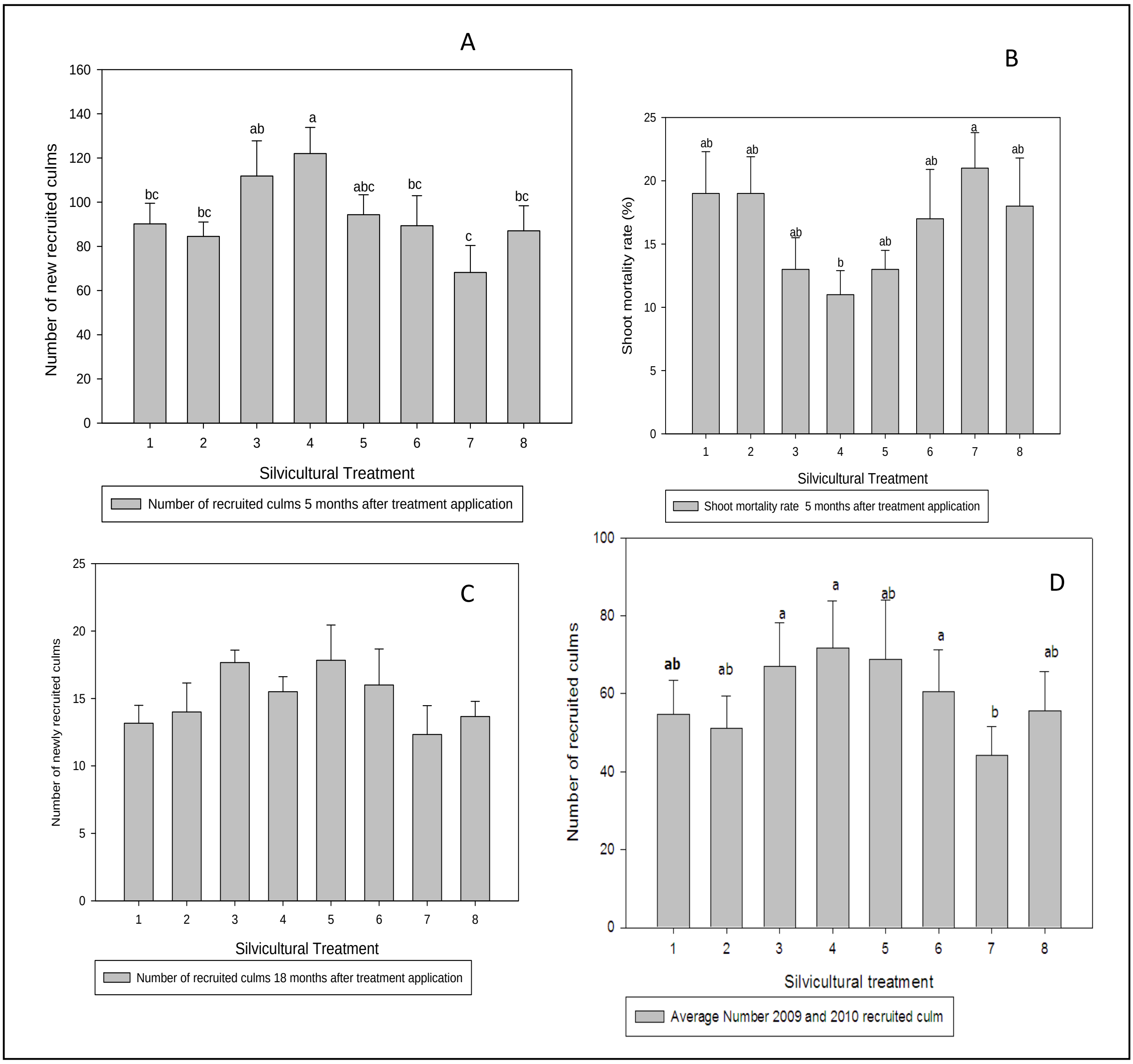

Figure 28. Culm recruitment and shoot mortality as affected by application of silvicultural management techniques (treatments): (A) culm recruitment 5 months after treatment; (B) shoot mortality rate 5 months after treatment; (C) culm recruitment 18 months after treatment; (D) two years average (5 and 18 months after treatment)culm recruitment

Treatments (1) removing old stumps, (2) soil loosening+removing old stumps, (3) selective thinning + removing old stumps, (4) soil loosening + selective thinning + removing old stumps, (5) soil loosening, (6) soil loosening + selective thinning, (7) selective tinning and (8) control. Bars with same letter are not statistically different.

4.3.2 Culm size

Combined analysis of the two factor split plot ANOVA indicated that DBH and height significantly vary between the 2009 and 2010 shooting seasons (Table 20 A and B). The 2010 DBH and height values were significantly higher than the 2009 shooting season. Mean DBH values were also statistically significant among silvicultural treatments and among the interaction of organic fertilizer x silvicultural treatment. Mean DBH and height values were not statistically different five months after application of the treatments (Table 21); however, eighteen months after application of the treatments soil loosening + selective thinning (Treatment 6) showed significantly higher DBH as compared to soil loosening + selective thinning+removing old stumps (Treatment 4) but not with other treatments. The DBH of Treatment 4 was not statistically different from the control plot. Applied compost did not show significantly different values both in terms of DBH and height at 5 and 18 months after treatment application. DBH and height of recruited culms had significantly increased during the second shooting season.

Table 20. ANOVA of combined analysis of 2009 and 2010 DBH measurements (A) and height measurements (B) as affected by silvicultural management techniques and organic fertilizer application

A

Source	**df**	**Mean Square**	**F-value**	**Prob.**
Year	1	42.135	380.40	<0.0001
Organic fertilizer	1	0.375	3.39	0.0702
Year x Organic fertilizer	1	0.004	0.03	0.8546
Error	4	0.121		
Silvicultural treatment	7	0.474	4.28	0.0006
Year x Silvicultural treatment	7	0.113	1.02	0.4277
Organic fertilizer x Silvicultural treatment	7	0.349	3.15	0.0062
Year x Organic fertilizer x Silvicultural treatment	7	0.084	0.7397	
Error	56	0.114		
Total	95			

B

Source	**df**	**Mean Square**	**F-value**	**Prob.**
Year	1	48.337	63.42	<0.0001
Organic fertilizer	1	0.608	0.80	0.3750
Year x Organic fertilizer	1	0.380	0.50	0.4826
Error	4	1.273		
Silvicultural treatment	7	1.366	1.79	0.1032
Year x Silvicultural treatment	7	0.599	0.79	0.6011
Organic fertilizer x Silvicultural treatment	7	1.076	1.41	0.215
Year x Organic fertilizer x Silvicultural treatment	7	0.661	0.8252	
Error	56	0.800		
Total	95			

Table 21. Average DBH and height of *A.alpina* unmanaged community bamboo stand based on application of silvicultural treatments, 5 and 18 months after treatment application

Silvicultural Treatment	DBH (cm)		Height (m)	
	5 MAP	18 MAP	5 MAP	18 MAP
1 ROS	3.0	4.4±0.08^{ab}	6.8	8.5
2 SL+ROS	2.9	4.4±0.09^{ab}	6.9	8.5
3 ST+ROS	2.9	4.1±0.16^{ab}	6.5	7.5
4 SL+ST+ROS	2.6	3.7±0.16^{b}	6.5	7.0
5 SL	2.9	4.3±0.16^{ab}	6.5	8.0
6 SL+ST	2.9	4.5±0.12^{a}	6.7	8.7
7 ST	3.1	4.3±0.19^{ab}	6.7	8.0
8 control	3.1	4.2±0.26^{ab}	6.6	8.3
Compost (main plot)				
0 t ha^{-1}	3.0	4.3+0.1	6.7	7.9
12 t ha^{-1}	2.8	4.2+0.1	6.6	8.2

ROS=removing old stumps; SL = soil loosening; ST = selective thinning of >3 years old stems. Bars with same letter are not statistically different.N=8; Alpha <0.05, Duncan MRT.

4.3.3 Culm production across years

The culm production (number of recruited culms) trend of the mismanaged stand, both treated and control plots, had big variation from year to year. The two shooting seasons (2009 and 2010) after treatment application and the preceding year (2008) had significant difference in culm production. Culm production of 2010 growing season was the least (Figure 29). This year, all the stands including outside the experimental area and under private and church holdings demonstrated very marginal shooting. Treatments were applied in April 2009, hence their effect was expected to be evident in 2009 and also in 2010. But the dramatically declining of shooting in 2010, one year after treatment application, for all the plots and also to all bamboo stands outside the experimental area was unexpected. Average values of recruited culms of 2008, 2009 and 2010 were 69, 93 and 15 culms plot^{-1}. Average values of the control plots of the respective years were 66, 87 and 14 culms plot^{-1} (Table 4; Figure 29). Culm recruitment (Figure 29) and rainfall amounts of June, July and August (Figure 31, section 4.3.4) 2008, 2009 and 2010 had weak correlation (r=0.084).

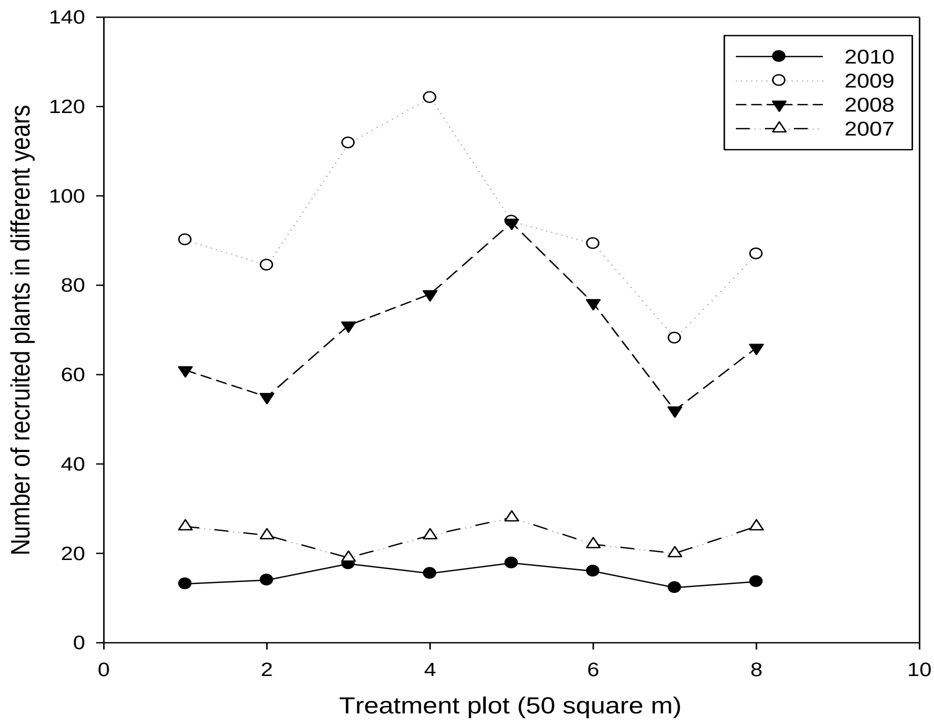

Figure 29. Number of recruitments of the studied plots across years. Recruitments of 2007 and 2008 are before application of treatments (as indicated in Table 4) but recruitments of 2009 and 2010 and after application of treatments.

In general, growth in diameter and height of the studied mismanaged stand, including the control plot, showed an increasing trend (Figure 30) across years. The diameter and height of the control plot increased from 2.62 cm and 4.63 m before application of treatments to 4.18 cm and height of 8.30 m 18 months after treatment application, respectively.

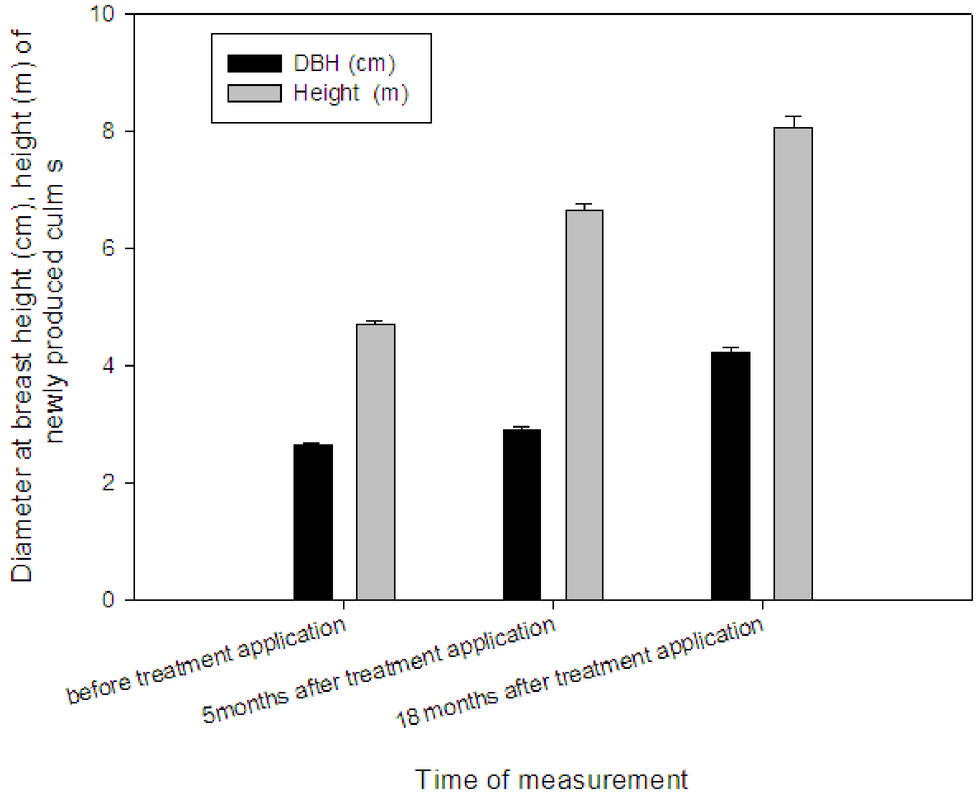

Figure 30. Diameter and height growth of newly recruited shoots across years

4.3.4 Rainfall and temperature pattern across years

The total rainfall of the years 2008, 2009 and 2010 was 1275, 1185, 1476 mm, respectively. From distribution point of view, only two months (February and March) of 2008 had no rain (Figure 31). The distribution followed a sigmoid pattern, the highest being in August (271 mm) and July (259 mm).

The rainfall distribution of 2009 had more irregularities and shorter shooting season. Unlike other years, May 2009 was dry and rainfall in September was also marginal (only 68 mm). The year 2010 had the highest rainfall distributed throughout the 12 months in a sigmoid pattern, maximum in July (340 mm) and August (277 mm).

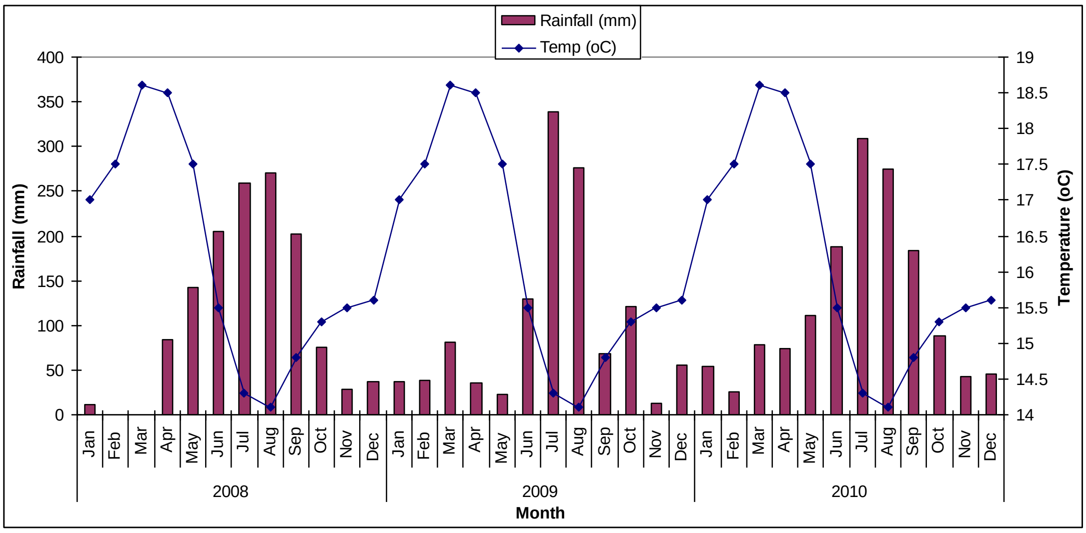

Figure 31. Rainfall and temperature pattern across treatment years, including the previous year (2008)

4.4 Propagation Techniques for *A. alpina* Landraces

4.4.1 Days to shoot emergence

Days to shoot emergence for propagules under the different propagation techniques significantly varied (p=0.000) ranging from 21 to 30 days. The fastest shoot emergence (21-22 days) was from rhizome, stump and whole culm. Culm cuttings took 26 days to produce new shoots. The longest time taken for shoot emergence was from branch cuttings (Table 22). Only 2 shoots emerged from offset after 26 days. Days to shoot emergence also significantly varied (p=0.005) among landraces. Shoot emergence from propagules of WELELE landrace took 21 days, followed by TIFRO (23 days) and WONDE (24 days).

Table 22. Days to shoot emergence after establishment of propagules under different propagation techniques and landraces

Factors	Days to shoot emergence
Propagation technique	
Rhizome	21[b]
Stump	21[b]
Offset	-
Whole Culm	22[b]
Culm cutting	26[ab]
Branch cutting	30[a]
Landrace	
WONDE	24[a]
WELELE	21[c]
TIFRO	23[b]

n=9, Tukey HSD (p<0.05), (-) indicates that the offset method didn't sprout more than two shoots to be statistically compared among propagation techniques.

4.4.2 Number and size of sprouts two and four months after establishment (2009)

4.4.2.1 Propagation techniques

There was statistically significant difference (p=0.000) in the number of new shoots among the different propagation techniques. The number of new shoots was significantly higher for the whole-culm (10 new shoots per propagule) than other propagation techniques (Table 22). The rhizome (3 new shoots per propagule) and rhizome-offset (2 new shoots per propagule) had also significantly higher values than the offset and branch cuttings. The average number of new shoots per propagule for offset and branch-cuttings was negligible. Culm cuttings had two new shoots per propagule two months after planting (MAP).

There was also statistically significant difference (p=0.000) in average maximum diameter of the newly emerged shoots from the different planting materials (Table 22). The whole-culm had statistically higher average maximum diameter (3 cm) followed by rhizome (2.3 cm) and rhizome-offset (2.2 cm). The height of the newly emerged shoots from rhizome (47 cm) and rhizome-offset (42 cm) was significantly higher (p=0.000) than offset (5 cm), culm-cutting (16 cm) and branch-cutting (10 cm).

The values for number, diameter and height of new shoots 4 MAP showed a similar trend to that of 2 MAP. But during that time, the rapid shoot elongation of bamboo shoots was clearly seen. The height of shoots increased to 262, 233 and 193 cm for rhizome-offset, rhizome and whole-culm, respectively. The DBH values of shoots 4 MAP was the highest for the whole culm (1.5 cm) followed by rhizome (1.1 cm) and rhizome-offset (1.0 cm) (Table 22).

4.4.2.2 Landraces

The effect of landraces was statistically different only for height 2 MAP. Average maximum height of TIFRO and WELELE landraces was significantly higher (p=0.000) than that of WONDE landrace 2 MAP (Table 23). The number of shoots per propagule was statistically different among landraces 4 MAP. TIFRO and WELELE landraces had significantly higher number of new shoots (p=0.042) than that of WONDE landrace. Values on DBH and average maximum height were not statistically different among landraces 4 MAP.

Table 23. Total number of shoots per propagule, average maximum DBH and average maximum height of sprouts of rhizome-based propagation techniques two and four months after planting (MAP)

	df	Number of sprouts per propagule		Average maximum diameter of sprouts (cm)		Average maximum height of sprouts (cm)	
		2MAP	4MAP	2MAP	4MAP	2MAP	4MAP
Propagation technique							
Branch cutting		0.20^{cd}	0.09^{c}	_	_	10.43^{b}	26.20^{c}
Culm cutting		1.70^{bc}	0.14^{c}	_	_	17.57^{b}	36.90^{c}
Offset		0.04^{d}	0.05^{c}	_	_	5.00 ^{b}	37.00^{c}
Rhizome		2.50^{b}	2.21^{b}	2.33 ^{ab}	1.10^{b}	46.57^{a}	233.00^{ab}
Rhizome offset		1.70^{bc}	1.82^{b}	2.15^{b}	1.03^{b}	41.63^{a}	262.00^{a}
Whole culm		10.00^{a}	5.90^{a}	3.01^{a}	1.53^{a}	27.00^{ab}	193.00^{b}
Landrace							
WONDE		2.33	1.46^{b}	2.79	1.36	20.14^{b}	185.70
WELELE		2.58	1.90^{a}	2.34	1.16	31.60^{a}	152.90
TIFRO		2.83	1.76^{ab}	2.40	1.05	31.93^{a}	128.70
Corresponding ANOVA							
Propagation technique (PT)	5	**	**	**	**	**	**
Landraces (LR)	2	ns	*	ns	ns	*	ns
PT X LR	10	ns	ns	ns	ns	*	ns
Error	28						

*Significant at 0.05, **significant at 0.001, ns= non-significant; (-) indicates that the new shoots from branch cutting, culm cutting and offset were less than breast height (1.3 m) diameter 4 MAP hence DBH not measured. Average maximum diameter 2 MAP was measure at the root collar while 4 MAP at 1.3 m above ground.

4.4.3 Performance of the whole culm propagation technique along the different culm positions

Two MAP, the number of shoots per propagule at the top position (8 shoots per propagule) was significantly higher (p=0.000) than at the middle (2 shoots per propagule) and butt (1 shoot per propagule) (Table 24; Figure 32). The lower one-third of the culm position had no shoot sprouts hence there are no data for all the variables. WELELE and TIFRO landraces had significantly higher (p=0.05) number of new shoots, each three shoots per propaguole, than WONDE landrace (2 shoots/propagule). Root collar diameter was significantly higher (p=0.05) for the butt (3.2 cm) followed by rhizome (2.7 cm) and rhizome-offset (1.3 cm). Average maximum height of new shoots was not statistically significant 2 MAP.

Similar trend followed for data collected 4 MAP, but this time the values were generally lower. But during that time, the rapid shoot elongation of bamboo shoots was clearly seen. The height increased to 215, 88 and 147 cm for the butt, middle and top positions, respectively. The values at the butt, middle and top positions were significantly different (p=0.000) (Table 24). All the measured variables did not show significant difference among landraces 4 MAP; though not significant, values for WELELE and TIFRO showed increasing trend for number and height of shoots.

Table 24. Total number of shoots per propagule, average maximum root collar diameter and average maximum height of new shoots at different positions of the whole culm method two and four months after planting

Factor	**df**	**Number of new shoots per propagule**		**Average maximum diameter (cm)**		**Average maximum height (cm)**	
		2	**4**	**2**	**4**	**2**	**4**
		Months after planting					
Position							
Butt		0.8[c]	1.04[b]	3.2[a]	1.43	36.9	215[a]
Lower		-	-	-	-	-	-
Middle		2.4[b]	1.42[b]	2.7[ab]	0.40	28.7	88[b]
Top		7.5[a]	3.54[a]	1.3[b]	0.6	36.8	147[ab]
Landrace							
WONDE		2.2[b]	1.5	3.0	1.0	30.2	132
WELELE		2.6[ab]	2.03	2.3	1.1	37.5	169
TIFRO		3.2[a]	2.31	2.45	1.3	38.5	150
CorrespondingANOVA							
Position	2	**	**	*	ns	ns	**
Landrace (LR)	2	*	ns	Ns	ns	ns	ns
LR X Position	4	ns	ns	Ns	ns	ns	ns
Error	9						
Total	20						

*Significant at 0.05, ** significant at 0.001, ns= non-significant, (-) indicates that the lower position of the whole culm had no new shoots sprouted. Average maximum diameter 2 MAP was measure at the root collar while 4 MAP at 1.3 m above ground. (n=9 for position and 12 for landrace; $p<0.05$; Tukey HSD)

Figure 32. New sprouts (shoot and root) from three positions of the culm and at its butt of TIFRO landrace 15 months after establishment (upper layer); new sprouts of the top position magnified (bottom layer)

4.4.4 Number and size of new shoots 15 months after establishment (2010)

The number of shoots per propagule was the highest (p=0.01) for the whole culm, stump and offset methods 15 MAP with values 4, 2 and 2 new shoots per propagule, respectively (Table 25). Diameter at breast height of the new shoots was the highest (p=0.01) for the offset (1.9 cm) and whole culm (1.4 cm) methods followed by rhizome (1.1 cm) and rhizome-offset (1.0 cm) methods. Survival rate of the offset method (85%) was significantly higher (p=0.000) than whole culm (26%), rhizome (20%) and rhizome-offset (17%) methods. Branch cutting and culm cutting did not survive up to this time, hence there wereno data presented for the parameters. The effect of landraces was not significant for number of new shoots, DBH and height.

Table 25. Number and average maximum diameter of new shoots and survival rate of propagules of vegetative propagation techniques 15 months after establishment

	df	Number of shoot Per plant	Average maximum DBH (cm) of shoots	Average maximum height (cm) of shoots	Survival rate (%) of propagules
Propagation technique					
Rhizome		1.3^{b}	1.1^{b}	196^{ab}	20^{bc}
Stump		1.6^{ab}	1.0^{b}	170^{ab}	17^{bc}
Offset		1.9^{ab}	1.8^{a}	267^{a}	85^{a}
Whole culm		3.5^{a}	1.4^{ab}	146^{b}	26^{b}
Landraces					
WONDE		1.4	1.6	220	23
WELELE		2.4	1.2	187	27
TIFRO		2.6	1.4	181	23
Corresponding ANOVA					
Propagation technique (PT)	3	**	*	*	**
Landrace (LR)	2	ns	ns	ns	ns
PT X LR	5	ns	ns	ns	ns
Error	13				

*Significant at 0.05, ** significant at 0.001, ns= non-significant; (n=18 for landraces and 9 for propagation techniques; p<0.05, Tukey HSD)

CHAPTER FIVE

5 DISCUSSION

5.1 Morphology, Growth and Biomass Variation of *A. alpina* Landraces

5.1.1 Rhizome morphology

Our investigation showed that rhizome branching pattern of *A. alpina* is sympodial, that is in agreement with Meredith (2001) and Kigomo (2007) but different from reports by Kassahun Embaye *et al.* (2005) and Seyoum Kelemework (2005). The rhizome proper was longer than the rhizome neck and thicker than the attached culm for all the landraces. Unlike rhizomes of monopodial bamboos described by McClure (1966), rhizome proper of the species was nearly vertically oriented, not horizontally positioned (Figure 11). The rhizome proper was also attached to collective rhizome necks meant for production of successive rhizomes and shoots (those around the base of the rhizome proper) and probably for support purposes (those on the upper part of the rhizome proper).

In this study, *A. alpina* bamboo landraces grown under similar soil and climatic conditions for the past more than 50 years showed statistical difference in size of their rhizome characteristics. The average length of rhizome neck (17.3 cm, max 30 cm), diameter of rhizome neck (4.1 cm, max 5.3 cm) and the number of internodes of the rhizome neck (mean 16 and max

24) for TIFRO landrace were significantly higher than other landraces (Figure 13). PROTA (1989) describes *A. alpina* as evergreen bamboo with short rhizome up to 10 cm thick. But values of rhizome neck length and length of rhizome proper of *A. alpina* landraces in our study are higher than this value.

5.1.2 Stand structure

Bamboo stand structure is mainly concerned with the number of plants per unit area and the age composition (age structure). These parameters are important aspects in investigating bamboo stand dynamics and yield. Average standing culm density of the four landraces ranged from 11,467 to 15,800 plants ha^{-1} (Table 6). This value is by far higher than the rational density of *Phyllostachys pubescens* (*a* monopodial bamboo) stands in China (3000 plants ha^{-1} with DBH of 6–18 cm and height over 20 m) and natural stands of *Gigantochloa scortechinii* (a sympodial bamboo) in Malaysia (8,018 plants ha^{-1} with respective maximum DBH and height of 7.7 cm and 18 m, after fertilizer application)(Yegen, 1992; Othman, 1994; Jinhe, 2000; Azmy *et al.,* 2004) but within what Wimbush (1945) noted from an undisturbed bamboo crop of *Arundinaria alpina* (10,000-17,000 plants ha^{-1}).

The higher stand density of *A. alpina* seems principally associated with the nature and colonization pattern of its rhizome as compared to the two bamboo species in Asia (*G. scortechinii* and *P. pubescens). A. alpina* has rhizome necks of variable length that are attached to the nearly vertically positioned rhizome proper; those towards the base of the rhizome proper are longer than those near the culm base (Figures 9 and 11) and produce uniformly distributed culms with in the stand (Figure 6). The rhizome necks are longer than that of many clumping species like *G. scortechinii* that have tightly packed culms in compact clumps (Wong, 1986) and found in isolated patches with in the stand. Hence, *A. alpina* can have higher standing density when calculated in per ha basis as compared to *G. scortechinii*. Despite culms of *A. alpina* are uniformly distributed, the spacing between culms might not be as far as the monopodially branching species, *P. pubscens*, hence still the standing density might be higher.

The higher standing culm density for WELELE and ENKOTEKOT landraces is expected as it has shorter rhizome necks (Figure 13) more shoots flourish around a mother plant within a smaller area than other landraces. The lower standing culm density in WONDE and higher values in TIFRO landraces might be associated with their shoot mortality rates (Figure 18).

The ratios of the number of plants per hectare of the four landraces under three age-groups (<1, 1–3 and >3 years) were 2:4:4, 1:3:5, 3:3:3 and 3:3:5 for WONDE, WELELE, TIFRO and ENKOTEKOTE landraces (extrapolated from Table 2), respectively. The number of plant per ha for WELELE landrace was similar to TIFRO (Figure 14) but the number of <1 year old plants was lower in proportion and dominance of old age plants, was evident in this landrace. TIFRO landrace exhibited silviculturaly recommendable age structure followed by ENKOTEKOT and WONDElandraces but WONDE had still lower number of<1 year old culms next to WELELE that might be explained by its high shoot mortality rate (58%).

5.1.3 Shoot recruitment, height growth rate and biomass

Shoot mortality of *A. alpina* landraces ranged from 16-60% depending on the landraces (Figure 18). This value is within the range of natural mortality of emerging shoots (9–69%) depending on eco-physiological conditions such as soil moisture, food shortage, clump congestion and genetic make-up of each clump or species (Banik, 1997). In the tropics, bamboo is adapted to restrict culm elongation to the mid to late-wet season when soil moisture is greatest and most reliable (Duff *et al.,* 1997). In *A. alpina,* shooting and development of the shoot-culm system is limited only within the high moisture available period (June to September). Rapid elongation of culms by intercalary expansion during a single “grand period of growth” is the most demanding part of the growth process (Li *et al.,* 1998a; Franklin, 2005), hence upon limitations of the different eco-physiological conditions, shoot mortality may result. The higher biomass allocation of WONDE landrace to branches might cause high rainfall interception loss from plants especially in earlier seasons of the main rainy season. Rainfall interception is directly related to the degree of canopy cover (Jackson, 2000) that may affect soil temperature, light and soil moisture (Ritter *et al.*, 2005). The congested rhizome nature of WELELE landrace (Figure 13) might cause food shortage. The higher mortality rate of emerging shoots determined in this assessment implies that management practices that can maximize shoot recruitment rate may be critical for WONDE and WELELE landraces.

The slow-quick-slow rhythm height growth rate of the four landraces that exhibited exponential curves, with R^2 0.98 and SE 0.37-0.49, is in agreement with a report by Jianghua (2005). WELELE and TIFRO had similar growth rate while WONDE and ENKOTEKOT showed a similar trend. The highest elongation rate recorded from WELELE (58 cm day^{-1}), TIFRO (53 cm day^{-1}) and WONDE (53 cm day^{-1}) in two months time after emergence are similar to maximum daily elongation rate of *Dendrocalamus giganteus* (58 cm day^{-1}) (Banik, 1997). While these values are higher than the peak elongation rates of *Bambusa arnhemica* (15–30 cm)(Franklin, 2005) and less than that of *Phylostachyus pubescens* (90 cm day^{-1}) and *P. reticulate* (121 cm day^{-1})(Banik,1997; Jinhe, 2001). Biomass of the landraces ranged from 45 to 74 t ha^{-1} for total dry weight and 39-60 t ha^{-1} for above ground total dry weight (Figure 19). The above ground total dry weights found in this study is similar to what was reported by LUSO (1997) (51 t ha^{-1}) from Masha natural bamboo forest but less than what Wimbush (1945) noted (100 ton air-dry weight of culms). It is highly influenced by site factors and lack of proper management.

5.2 Stand Structure, Growth and Yield of *A. alpina* along Environmental Gradient

5.2.1 Stand structure

The standing culm density recorded for the three landforms (11,000-20,000 plants ha^{-1}) under this study was higher than what was reported from Masha natural bamboo forests (8,840 plants ha^{-1}) by Kassahun Embaye (2003) but closer to what Wimbush (1945) noted from an undisturbed bamboo crop of *Arundinaria alpina* (10,000-17,000 plants ha^{-1}).

The higher standing density in this study as compared to government bamboo forest of Masha might be associated with the appreciable harvesting system followed and protection of the forest by private land owners. In this plantation bamboo stand, the individual bamboo owners selectively harvest mature culms, that restrict further shooting if maintained for long time within the stand, every year. This stand might also have relatively better protection as compared to natural (government) bamboo stands that have no protection what so ever from illegal harvesting, encroachment and clear felling and have no practical arrangements to manage, protect and utilize the forests (UNIDO, 2007).

In general, the ratio of the number of the three age-groups of the plants (<1, 1-3 and >3 years) of the three landforms was 3:4:4 (Table 12). This proportion showed that the forest is in a recommendable age structure as compared to the proportion reported by Kassahun Embaye, *et al.* (2005), from Masha natural bamboo forest (<1 year 13%, 1–3 years 24% and >3 years 63%). The rational age structure of plants in all the landforms was impressing. As the farmers in the Choke Mountain selectively harvest older culms every year, the rational age structure and its productivity could be maintained.

Average values of DBH 5–8 cm (maximum 9.9 cm), height 10–15 m (maximum 20 m), total dry weight 5–12.5 kg plant^{-1} and total fresh weight 13–32 kg plant^{-1} (Table 13) are comparable to what was reported by LUSO (1997) for the same species, by Jinhe (2000) for *P. pubescens* and by Azmy *et al.* (2004) for *G. scortechinii.* DBH of *P. pubescens* bamboo ranges from 6–18 cm and height over 20 m (Jinhe, 2000). The maximum diameter and height of *G. scortechinii*, with fertilizer application was 7.7 cm (5 to 7 cm) and 18 m (most culms 11 to 14 m), respectively (Azmy *et al.,* 2004). The lower values in DBH and height under the 5-15% slope than other landforms in this study may be associated with the generally negative relationships between plant size and plant density (Tateno and Takeda, 2003) and the effect of the underling soil and topographic conditions (Tables 15 and 17). Water logging especially at the end of July and in August, might contribute for the lower values of DBH and hight. It might mainy affect underground rhizome growth particularly growth of the rhizome neck that is formed earlier (Wong, 1986) at the time of the previous shooting season. Farmers in the area use deep ferrows to discharge excess water from their farms that are meant for annual crop production such as wheat, barrly and potato, under this landform. However, draining excess water is not practiced for bamboo stands.

5.2.2 Shoot- recruitment, height growth rate and biomass

Mortality of emerging shoots for the three landforms ranged from 13% (for 5-15% level-slopping land) to 35% (for 40-60% concave slope), i.e. recruitment rate of 65-87% (Figure 24). This value is within the range (9–69%), depending on eco-physiological conditions, reported for natural mortality of emerging shoots (Banik, 1997). During the period of rapid growth of new shoots, limited availability of required nutrients that are absorbed directly from the soil or carbohydrate originate from current photosynthesis and stored photosynthates in older (≥1-year-old) plants may result in food shortage (Li *et al*., 1998a; Kleinhenz and Midmore, 2001). Clump congestion, soil moisture, and genetic make-up of each species and clump may also affect natural mortality rate of emerging shoots (Banik, 1997). The higher mortality rate of emerging shoots determined in this assessment implies that management practices that can maximize shoot recruitment rate may be critical for the 40-60% concave slope.

Average height growth rate of *A. alpina* measured during the two months rainy season on the three landforms ranged from 15-23 cm day^{-1} (with average maximum value ranging from 25-43 cm day^{-1}). This value was similar to what was reported for the daily growth rate of *Dendrocalamus giganteus* (10-30 cm, but reaches 58 cm day^{-1})(Banik, 1997) and *Bambusa arnhemica* (peak elongation rates of 15–30 cm day^{-1}) in Australia (Franklin, 2005) and *Bambusa bambos (*five month average 30 cm day^{-1}*)* in India (Shanmughavel and Francis 1996). Besides soil and topographic factors, competition for light in valley areas (Tateno and Takeda, 2003) may be one of the factors that resulted in higher height growth rate in the 40-60% concave slope landform.

Despite the higher shoot mortality rate and lower number of plants per hectare, the 40-60% concave slope showed higher biomass (117± 28.8 t ha^{-1})

as compared to 5-15% level-slopping landform (90±22.6 t ha^{-1}) and 40-60% straight slope landform (64±8.3 t ha^{-1}) (Table 13; Figure 25). This finding does not agree with what was reported by Zhang *et al.* (1996) in which slope and biomass had negative relationships in six locations in China. This study indicated that besides slope gradient, shape of the slope influences the productivity of bamboos. The total dry weight and above ground total dry weights found in this study were higher than what was reported by LUSO (1997) (51 t ha^{-1} total above ground biomass) from Masha natural bamboo forest but withinwhat Wimbush (1945) noted (100 ton air-dry weight of culms) and 110 tha^{-1}total above ground biomass estimates of Kassahun Embaye (2003) from Masha natural bamboo forest. Nevertheless this value is lower than what was reported from Northeast India (122 t ha^{-1} above ground stand biomass) for *Bambusa cacharensis*, *Bambusa vulgaris* and *Bambusa balcooa* (Nath *et al.*, 2009)

The increment or biomass of <1 year plants investigated in this study ranged from 6-26 tha^{-1}. This value is higher than what was reported from Masha natural *A. alpina* bamboo forest (8.6 tha^{-1}) by (LUSO, 1997) and for a semi-natural lowland stand of *Phyllostachys pubescens* (7.7 t ha^{-1} per year) in Zhejiang Province, China by Qiu *et al.* (1992). But it is lower than what wasreported by Shanmughavel and Francis (1996) for *Bambusa bambos* grown with fertilizer and irrigation having an equivalent average above ground productivity of 47 t ha^{-1} $year^{-1}$ in southern India.

In light of the above, it may be concluded that TIFRO landracestands of the Choke Mountains have comparable yield and productivity with high yielding sympodial bamboos like *Bambosa bamboos* that is widely planted in India and with giant monopodial bamboos like *P. pubescens*, the extensively planted species in China (Scurlock *et al.,* 2000).

The relative contribution of various components to the standing state of biomass was in the order of culm>rhizome>branch>leaf. Similar trend for the above ground biomass was reported fromSiwalik bamboo forest in the Garhwal Himalaya, India (Joshi *et al.*, 1991). Allocation to the belowground plant part was higher for landforms having steep slopes (Figure 21). This is expected, as the plant tends to allocate more on itsrhizome that grow scrambling in up-slope and down-slope directions, with asymmetric architecture, so as to modify the distribution of mechanical forces into the soil and increase its stability (Chiatante *et al*., 2002).

5.2.3 Physico-chemical soil properties

In general, the total N (0.38–0.39 %) and organic C (3.89–4.25) contents determined under this study (Table 17) are slightly lower than what was reported by Fantaw Yimer (2007) from the Bale Mountain protected forests (N: 0.59%; OC: 5.31%) but higher than what was reported by Taye Kufa (2011) from wild coffee forest soils of southeastern and southwestern Ethiopia (N: 0.18–0.24, OC 1.27–2.83). The C:N ratios under all the landforms lie within the typical C:N ratio (9-12) described by Batjes and Dijkshoorn (1999).

The P, K, and Ca values were higher than what was reported by Kassahun Embaye *et al*. (2005) from Masha Natural bamboo stand in the Southwest Ethiopia (N: 0.64%; P: 0.002%; K: 0.017%; Ca: 0.07%; pH: 4.6).

The concentration of total N and organic C has similar status for the three landforms. However, higher available P (86.19 ppm) and mg (6.72 Cmole kg^{-1}) concentration than the other landforms were recorded on the 5-15% level-slopping land. The soil texture class of the 40-60% concave slope was clay, with higher moisture content (23.80%) and of the other two landforms clay-loam, with lower moisture content. The 40-60% concave slope landform (valley) is found at the lower part of the watershed in the complex landscape setup of the Choke Mountain, hence it would be expected to have more clay and improved hydrological condition, on the other hand it is steep in slope hence had good drainage. Since the concave slope is characterized by bidirectional steep slopes, its role in obstructing direct sunlight, at least for some hours a day, might cause reduction in evapo-transpiration hence higher moisture of the soil (Table 15). On the contrary, the level land, though seasonally water logged, it is exposed to longer sunlight hours hence there might be more evapo-transpiration than in other landforms.In bamboo growth and physiology, factors related to moisture regime (moisture content and drainage) were found to be more affecting than nutrient status (Cirtain *et al.,* 2004) hence higher plant size and biomass on the 40-60% concave slope could be associated with the higher moisture holding capacity of the clay textured soil and steep slope that enhance good drainage.

5.3 The Effect of Silvicultural Management on Regeneration, Growth and Yield of Previously Unmanaged *A. alpina* Bamboo Stands

5.3.1 Culm recruitment and plant size

Depending on the nutrient reserve, current photosynthesis and optimal growth conditions, newly emerged shoots might either be recruited to full grown culms or abort some days after emergence and growth. The present study showed that soil loosening accompanied by selective thinning and removal of old stumps (Treatment 4) yielded the highest culm recruitmentand the lowest shoot mortality rate. It may be because application of silvicultural treatments enhanced the amount of resources potentially available for growth, increased the ability of plants to acquire those resources and influenced the distribution of resources among different plant parts using the improved ecophysiological conditions (Long *et al*., 2004). Our results were in line with the reports of Fu and Banik (1995) and Zheng *et al.* (1996). Loosening the compacted soil and covering the culm base with soil (soil mounding) together with removal of unproductive plant parts could have greatly improved physical soil conditions (moisture and aeration) and increased access to light. Therefore, improvements in availability of above ground and belowground resources promote early but prolonged emergence of new shoots so that higher recruitment could be possible.

The lowest shoot emergence (lowest culm recruitment) and highest shoot mortality rate was observed in plots which received only selectivel thinning (Treatment 7) with no soil loosening and no removal of old stumps. Selective thinning is one of the silvicultural management techniques both in bamboo management and other forests particularly timber stands in forest science (Huberman, 1959**;** Xu *et al.*, 2008). The lowest recruitment observed in this previously unmanaged forest might be associated with the decrease in photosynthetic area due to thinned-out old and bent culms that had been harboring abnormally enormous leafy branches (Figure 28C). Removal of all these culms might have contributed to lowering down of translocated food from current photosynthesis of mother plants, as young shoots do not produce food by their own. According to Zeide (2001), thinning inevitably results in lower stand growthin the short term, because of reduced canopy and leaf area following thinning; but a stand returns to its prethinning stand-level leaf area within a certain duration of time that depends on the stand age, site quality and the intensity of thinning (Juodvalkis *et al*., 2005).

The statistically insignificant difference in culm DBH and height five months after treatment application may be associated with the performance of underground shoot growth that happened simultaneously or immediately after shoot-culm growth of the previous year (2008). Underground shoot growth (rhizome bud differentiation in to nodes, internodes and other parts of the underground shoot) is highly influenced by bamboo stand condition of the sprouting time (Jianghua, 2005). Besides, bamboo diameter is predetermined at the time of underground rhizome bud differentiation (Meredith, 2001).

Though shoot recruitment was generally lower 18 months after treatment application, DBH and height showed higher values that might indicate the improved ecophysiological conditions helped underground shoot development during the previous shooting season (5 months after treatment) of the currently recruited culms.

In this study, organic fertilizer was used as main plot, considering its importance in improving productivity to be less than other silvicultural practices considered at sub plot level. As compared to fertility status of agricultural soils described by EIAR (2001) the initial soil fertility status of bamboo stands in the study area (Table 1, Section 3.2) was in the high to very high range. However, bamboo as a very aggressively growing perennial plant was assumed to require additional fertilizer. Accordingly, compost with equivalent rates of 74 kg ha^{-1} N and 105 kg ha^{-1} P was applied in this study. This rate is higher than the equivalent rates (72 kg ha^{-1} N and 46 kg ha^{-1} or 5 t ha^{-1} compost) recommended for maize production in western Oromia, Ethiopia (Wakene *et al*., 2001; EIAR, 2001). However, there was no statistical difference in culm recruitment and plant size between the two main plots. The possible reasons may be associated with (1) problem of net nitrogen immobilization or assimilation of N in the compost by soil microbes that inturn results from application of organic materials that have high C:N ratios (Florian *et al*., 2003; Larcher, 2003). The C:N ratio of the applied compost was 28:1. Unlike inorganic fertilizers, the response might be slower immediately after application but could exert a longer-lasting effect on growth (Wang *et al.*, 1985). But the generally lower culm recruitment (off-year) during the second year might also have influenced the full effects of organic fertilizer. (2) Besides, effect of organic fertilizer application may become more pronounced when applied continuously for a long period of time to build up the soil organic matter and enhace its mineralization (Fernandez, *et al.,* 2003) as bamboo has never been negatively affected by high doses of organic fertilizer (Kleinhenz and Midmore, 2001).

5.3.2 Culm production across years

Culm recruitment was highest in 2009 growing season, immediately after treatment application. However, culm production of the next year, 2010, was unexpectedly low as compared to the 2009 and also to 2007 and 2008 recruitments (Table 4). The weak correlation between amount of rainfall and number of recruited culms and the relatively good rainfall distribution in 2010 (Figure 31) shooting season indicated that the dramatically reduced number of recruited culms in the year is not because of problems related to moisture deficit. The possible reason for the dramatic decline may be because of higher population of old leaves that are not photosynthetically efficient (off-year).

Bamboo is subjected to an integral system of growth phase that depends upon the age structure of plant leaves (Kleinhenz and Midmore, 2001).The extent of available photosynthetically active leaves (photosynthetic carbon fixation) in a particular growing season is the basic determinant for shoot emergence and recruitment (Quantai *et al.*, 1993). *A. alpina* is in the sympodial bamboos group (Meredith, 2001; Phillips, 1995) hence age and photosynthetic efficiency of leaves in a bamboo stand should be variable. The life span of leaves of sympodial bamboos extends up to six years with average value 2-5 years (Franklin, 2005; Kleinhenz and Midmore, 2001; Li *et al.,* 1998b). So far, there is no information on leaf lifespan of *A. alpina*. Further study on this aspect may describe its on-year and off-year more precisely and come up with silvicultural methods of regulating culm production of the species.

Despite the on-off year culm production during the study period, the significant difference among treatments and variation in the control plot across years and the increasing trend in diameter and height, indicated that beyond silvicultural management problems, problems of stand protection from livestock interference and encroachment are important yield limiting factors in the study area. Comparison of culm production of 2007 (before treatment), that also had intermittent protection from livestock and human encroachment, with the 2009 (after treatment) culm production showed that silvicultural management and protection can maximize culm yield of communal bamboo stands by 158-589%.

5.4 Propagation Techniques of *A. alpina* Landraces in the Choke Mountain

5.4.1 Rhizome-based propagation techniques

A propagule must promote the development of roots, rhizome and shoots if propagules are to survive after being planted (van Dorssor and Faulds, 1991). The rhizome and stump methods produced big size shoots starting from 21 days after establishment. They also manage to produce roots as checked late in the growing season, three months after establishment. The number of new shoots exhibited dynamism across the two seasons, more shoots for rhizome and stump the first season and more for offset the second season (Tables 22 and 24). Performance of rhizome andstump was higher for the first four months; the number of newly produced shoots per propagule, their diameter and height were superior. But survival rate of mother propagules and persistence of newly produced shoots 15 months after establishment was lower than the offset (traditional) method.

5.4.2 The whole culm propagation techniques

This technique usually achieves high survival of plantings and has been one of the best ways of vegetative propagation using culm materials (Ronald, 2005) except large culm lengths are difficult to handle and the method requires a lot of plant material. Under this study, the performance of this method is remarkable. The difference in number of shoots along culm position was clearly demonstrated. The number of shoots per propagule was also high. Average maximum diameter of new shoots had also reasonably high value. At 15 MAP, rhizome production of the rooted shoots was observed. Rhizome production in propagating materials is recognized when new shoots (culms) appearance from the rooted material (Banik, 1995). This method can be use to get starting materials for macropropagation purposes so that mass propagation of rooted plants is possible under nursery conditions, as pre rooted and pre shooted planting materials may enhance the success of the vegetative propagation methods (van Dorssor and Faulds, 1991).

5.4.3 Culm and branch cuttings

Though cuttings produced shoots 26-30 days after planting, there was no root development during the two months period for both landraces. Similar result was also reported from a laboratory study, conducted for seven weeks, that used planting material from southern Ethiopia (Kassa Oyicha, 1997). The absence of initial roots before planting, unlike rhizome-based techniques, makes propagation by culm and branch cutting method risky (Ronald, 2005).

Considering the good performance of big size planting materials (the rhizome-based and whole-culm techniques) in this study, the poor performance of cuttings (small sized planting materials) seems related to the lower amount of food reserve. A similar study indicated that regenerative capacity of planting materialis is positively related to their carbohydrate reserve (Berdowski and Siepel, 1988). As compared to culms, relatively higher amount (about wenty percent) of carbohydrates and important macronutrients (N, P, and K) required for the construction of new shoots is generated from the rhizome; large proportion of the remaining 80% is derived from actual photosynthesis (Li *et al*., 1998a). Besides, branches of *A. alpina* have no prominent and stout branches that might have stored more energy and promoted satisfactory shoot and root development.

5.5. Conclusion and Recommendation

5.5.1 Conclusion

The four landraces of *A. alpina* demonstrated sympodial rhizome branching pattern and pachymorph rhizome type. Accordingly, grouping highland bamboo in the leptomorph group does not agree with the generated information. However, unlike other pachymorphic bamboos, all *A. alpina* landraces have clear rhizome neck that makes them have diffuse culm spacing (culms that are widely spaced, arising singly rather than in groups). Rhizome of *A. alpina* landraces are different from pachymorphic bamboos like *Giantochloa scortechinii*, *Dendrocalmus asper*, and *Dendrocalmus gigantus* that produce impenetrable clumps. However, it is somehow similar to *Guadua* *angustifolia* of South America that has nearly vertically positioned rhizomes with long rhizome necks.

TIFRO and WELELE can be considered as top priority landraces in terms of productivity and suitability for manufacturing bamboo products. TIFRO landrace is more suitable for construction purposes and producing materials that require strength and support. Industrial application of this landrace could be tremendous. Further afforestation of this landrace is recommendable as it has desirable plant size, high recruitment rate, growth and biomass. It also grows in wider environmental conditions (different landforms) without requiring intensive management. Because it has the longest rhizome neck, shoot recruitment is very high. Further afforestation of WELELE landrace mainly on sites having adequate moisture and good soil conditions is important. But unlike TIFRO landrace, this landrace requires intensive management to reduce shoot mortality that might be associated with its shortest rhizome neck hence culm congestion. This landrace is highly preferred for weaving for its flexibility and strength and ease of manufacturing. Industrial application of this landrace could be enormous. It has also highest plant size and biomass.

WONDE and ENKOTEKOT landraces could be preferred for their higher allocation to branches. Enkotekot also allocates more on its leafe hence may be preferred for browse; it also allocates more on its rhizome hence may be preferred for planting for soil and water conservation purposes. WONDE may require intensive management as shoot mortality that might be associated with its higher allocation to its crown is the highest.

Age structure of the landraces indicated that there is need to manage the bamboo stands based on the belowground and above ground competitions prevailing in the stands. It seems that competition for food and lack of adequate moisture caused by rain water interception by the top crown and by the mulched litter especially for WELELE and WONDE landraces and lack of optimum temperature (because of heavy crown of WONDE landrace) reduced recruitment of new shoots. Developing a harvesting system that maintains the age structure, promotes recruitment and biomass is also critically needed.

Diameter was found to be the best predictor variable and age a highly influencing factor for biomass. Thus, biomass functions used to estimate biomass of *A. alpina* landraces under this study were based on age and diameter. The functions can also be used for biomass estimation under similar environmental conditions and for the age-group they are developed for.

In our study, all parameters, except the number of plants per hectare, are higher in the lower slope position (40-60% concave slope). On the other hand, except clay content and soil moisture, soil physical and chemical properties have higher status on 5-15% level to sloping land followed by the 40-60% straight slope than the 40-60% concave slope landforms. The only two soil properties that showed significantly higher value on the 40-60% concave slope were soil texture and moisture content. Big diameter (average 8.4 cm) and emerging height culms (average 15 m), highest growth rates (average 23 cm day^{-1}, maximum 43 cm day^{-1}) and high biomass (117 t ha^{-1}) were obtained in 40-60% slope landform. Hence, it can be concluded that topography is more influential than nutrient availability for performance of *A. alpina* (TIFRO landrace) in the Choke Mountain.

Our study also indicated that soil loosening combined with removal of old stumps and selective thinning of old culms increases culm yield by 40% more and decrease shoot mortality by 61% less than the control plot. Culm diameter showed increasing trend across the two seasons after establishment. The study also indicated that with improved management, including protection of the stand from interference, culm yield of communal bamboo stands can be maximized 158-589% more than the present yield.

The three propagation techniques (rhizome, rhizome-offset and whole culm), other than the traditional method, can be used for establishing bamboo stands, but further silvicultural management techniques that can increase the persistence of young shoots from strong wind and also in relation to moisture retention need to be developed. Rhizome and rhizome-offset methods can be directly established in the field but the whole culm method can preferentially be used to produce planting materials for mass propagation in a bamboo nursery. Culm and branch cutting propagation techniques are not promising techniques either for field planting or mass propagation in bamboo nurseries for all *A. alpina* landraces.

5.5.2 Recommendation

Provided that the current bamboo resource is scientifically and intensively managed, the supply can significantly increase; hence address problems of wood resource shortage in the country. Besides, inline with the increasing demand for wood products, further afforestation of agriculturally marginal sites with bamboo can guarantee sustainable supply. We believe that bamboo, like other economically important crops such as coffee and oil crops can be vital for economic growth and ecological stability in Ethiopia. Scientific information, on-farm research, extension and training should also go consistently. Information generated in this thesis can be of help in good understanding of the resource and maximized production under the available land. However, a lot remains to be addressed. Emerged research ideas in this study and recommended for further action are as follows:

1) The result of this study showed that *A. alpina* landraces are different in their morphology and growth. Their internal morphology (anatomy) also showed difference that is inline with information obtained from farmers and bamboo processors (Apendix A). Further genetic research may help to confirm their differences if they can be classified into different species.
2) Standardizing the harvesting cycle and intensity of harvesting that maintains optimum stand structure is highly important to increase stand productivity. Therefore, research on developing management and harvesting guidelines is top research priority.
3) Research on improved management of bamboo on level lands and investigating the performance of the other landraces than TIFRO on

different micro-sites can give broader picture for further afforestation endeavors.

4) Flowering of *A. alpina* is not common, seed viability is also low and growth performance requires long time (more than ten years) for attaining commercial size, the use of vegetative propagules is important. Production of rooted plants and nursery management are also not yet practiced. The issue of rooted plant production using vegetative techniques is critical.

5) Standardizing production of rooted plants at nursery level by using propagules from the whole culm method is important; as it requires technical issues on macro-propagation, watering or sprinkling, shading, soil mix for potting poly bags and determining nursery period for out planting. This work needs trials and continual follow up of activities till the experience is build up.

6) Further research on discovering the causes of shoot mortality and counter measures to increase recruitment rate will have high impact on Investigating the performance of the other landraces than TIFROon different micro-sites,

7) Shooting of *A. alpina* has an on and off-year, hence calculation of the proportion of new to old plants may not be consistent from year to year. Shooting is believed to be highly related to moisture however the year 2009 was an on-year while rainfall amount and distribution was not as good as the 2010 rainy season. Hence investigating what governs the on and off year shooting, studies on techniques for transforming on-off-year *A. alpina* stands into the even-year onesis required.

8) Research on annual cycle of underground and aboveground growth of plant parts is also required. Unlike other tropical countries in Asia, bamboo shooting in Ethiopia is limited only to one season. So, generating information that can be applied under Ethiopian condition is relevant.
9) On-farm research, bamboo agroforestry, working with the people in further afforestation and intensive management of current stands can have of paramount importance.

Based on the study, the following management guidelines can be followed to maximize yield (quality and quantity) of previously unmanaged bamboo stands, particularly communally owned stands:

1. Soil loosening by cultivating the compacted soil to a depth of 15-20 cm using hand tools such as mattock+pick axe, grab hoe and mounding the soil around the culm base and cover exposed rhizome parts
2. Removal of old stumps comprising degenerated rhizomes maintained in the forest that may hinder emergence of new shoots using sharp tools
3. Selective thinning out of four and more year old and malformed culms should be done after uncurving the bent culms in the stand so as to make thinning easier
4. Protection of the forest from livestock and human interference
5. After the forest is rehabilitated, probably within 3 to 4 years, a rational harvesting intensity that maintains sustainable yield and productivity of the stand should be put in place. One to two year old culms are required to maintain productivity for bamboo stands,hence young culms mustnot be harvested while older culms could be harvested in a certain ratio.

Retaining old culms that are meant to stabilize productivity should be limited to a small fraction. Experiences of private owners in the area indicated a rational age structure (ratio) of stands 3:4:4 for <1: 1-3: >3 years old culms, which can be used while selectively harvesting old culms.

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APPENDICES

Appendix A. Characterization of *A. alpina* bamboo landraces by communities of the Choke Mountain, group discussion held in 2009 at the start of this thesis research

Land race	Peculiar physical characteristic		Regeneration and management			Utilization	
	External appearance	Size (diameter and height)	Distance between a mother plant and its young shoot	Management Intensity required and growth	Number of shoots per plant	Wood working property	Best for
Tifro	– Adventitious root at every node – Light blue culm with 'flours' when young; dark grey stem color when matured	biggest	long up to 1 m	– does not need intensive management, – grows in different soil conditions, altitudinal and topographic ranges – matures slowly	low	– difficult to slice because of the adventitious had nodes	housing, furniture, main frame for doors and baskets
Wolele	– Light green when young, yellowish when matured – Tapering is small (uniformly thick culm to higher portion of its height, – Long internodes	medium	short	– Needs organic fertilizer application, – Prefers riverine areas (moisture reach areas), – Mature in a short time	Very high	– easy to slice and weave (the most liked property of this land race)	– Different three dimensional bamboo products, – strips (rope)
Wonde	– Light blue culm with 'flours' when young; light grey when matured – Tapering is high – More branches & leaves	medium	short	– Needs organic fertilizer application,	medium	– Medium workability, – suitable for designing (easy to drill)	Furniture
Enkotekot	– White colored strips on green background on the culm, – Short internodes	short	short	*	medium	– Highly suitable while working the products it is best for	flower pot, fruit and vegetable plates

*Note: * Indicates that the information is not well recognized by the community*

Appendix B. Major highland bamboo growing area and forest type in Ethiopia

Bamboo area	Region	Type	Area in ha
Injibara	Amhara	Farmers'	-
Agaro	Oromiya	Farmers'	-
Gera	Oromiya	Farmers'	-
Bale mountains	Oromiya	natural	56,851
Shenen, Jibat mountain	Oromiya	natural	1,774
Gera bamboo forest	Oromiya	natural	1,052
Gera- Lola (50 m from Gera)	Oromiya	natural	34,493
Agere-selam- Bore	South Eth. P. Admin	Farmers'	-
Chencha	South Eth. P. Admin	Farmers'	-
Indibir-Jembero	South Eth. P. Admin	Farmers'	-
Jima-Ameya	South Eth. P. Admin	Farmers'	-
Mizan Teferi-Kulish	South Eth. P. Admin	Farmers'	-
Wushwush-Bonga	South Eth. P. Admin	Farmers'	-
Bonga-Ameya (10-20 km to S)	South Eth. P. Admin	natural	7,997
Masha	South Eth. P. Admin	natural	18,652
Shashemene (20-50 km NE)	South Eth. P. Admin	natural	4,183

Source: LUSO (1997).

Note: Farmers' bamboo forests are privately owned by the farmers, while natural bamboo forests are under the ownership of the government.

Declaration

I, the undersigned, declare that this Thesis is based on my original work and that it has not been presented for a degree in any other university. All sources of materials have been duly acknowledged.

Yigardu Mulatu Signature______________________________

This Thesis has been submitted for examination with my approval as supervisor of the Thesis.

Prof. Masresha Fetene Signature______________________________