FACTORS MAINTAINING SORGHUM [*Sorghum bicolor (L.) Moench]* LANDRACE DIVERSITY IN NORTH SHEWA AND SOUTH WELO REGIONS OF ETHIOPIA.

by
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A Thesis submitted to
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in partial fulfilment of
the requirements for the degree of

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The undersigned hereby recommend to
the Faculty of Graduate Studies and Research
acceptance of the thesis,

"Factors maintaining Sorghum [*Sorghum bicolor (L.) Moench]*
landrace diversity in north Shewa and south Welo regions of
Ethiopia"

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ABSTRACT

Sorghum landrace diversity, ethnobotanical knowledge and the agricultural systems in north Shewa and south Welo regions of Ethiopia have been studied to : 1) examine intraspecific variations of *Sorghum* landraces grown by the farmers and to test the consistency of folk taxonomy; 2) quantify the relationships between *Sorghum* landrace diversity at the field level and environmental factors (field size, altitude and soil organic matter content, textures and pH) and farmers' selection criteria; and 3) measure the susceptibility of stored-sorghum landraces to *Sitophilus oryzae*, and compare farmers' knowledge of storability to the laboratory findings of resistance to *S.oryzae*. Data were collected from 260 randomly selected fields across the study area, including 177 accessions.

Each accession was identified by the farmer who indicated why she/he grew that landrace. Fourteen phenotypic characters were chosen for taxonomic classification of these 177 accessions. Multivariate analyses grouped the accessions into three clusters with some linking of phenotypic characters. A botanical key was established. The five most common landraces named by the farmers, which constituted 44 of the accessions, formed dissimilar groups, suggesting that farmers' naming of these *Sorghum* landraces was consistent. Farmers used the salient morphological characters of juiciness, midrib color, grain color, grain size, glume color, glume hairiness, and grain shape to distinguish the *Sorghum* landraces. These characters, with the exception of midrib color, were the subset of important morphological characters identified by the numerical taxonomic investigation grouping the landraces into three clusters and confirmed a good agreement between the farmers' folk taxonomy and the numerical taxonomy.

Linear and polynomial regressions indicated that *Sorghum* landrace diversity at the field level had significant relationships with altitude, field size and farmers' selection criteria. In the polynomial regressions farmers' selection criteria explained 21% of variations, while altitude 62%. Multiple regression analyses showed that soil pH and clay content along with the terms that were significant in the linear and polynomial regressions, had significant relationships with *Sorghum* landrace diversity at the field level. Of particular interest is that the diversity increases as the number of farmers' selection criteria increases. This relationship was not a result of the interaction between selection criteria and environmental factors, because the farmers' selection variable was significant after statistically correcting for the effects of environmental variables. The total number of selection criteria applied to individual landraces ranged from one to six, and the number of selection criteria used per field ranged from two to nine.

The resistance to *S.oryzae* of 16 Ethiopian stored-sorghum landraces was measured by F_1 emergence, oviposition, weight loss, development period, and Dobie Index. The ANOVA (LSD) multiple range test indicated that the stored-sorghum landraces represented a range of susceptibilities which were significantly different and grouped into 11 and 13 classes based on adult emergence and on oviposited eggs. Comparison with the farmers' consensus index of storability indicated clearly that farmers know the storability of their germplasm. Farmer accuracy was remarkable; R^2 values greater than 0.85 were found for several susceptibility parameters.

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DEDICATION

I am honoured to dedicate this work to the Ethiopian farmers, particularly north Shewa and south Welo, for their farming ingenuity by which they made Ethiopia one of the centers of origin and diversification for a number of globally important crop plants.

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This research is dedicated to the north Shewa and south Welo farmers who, along with the other Ethiopian farmers, made our country one of the centers of origin and diversification for a number of nationally, regionally, and globally important crop plants. These farmers work hard against all odds of external impositions from generation to generation to generate and maintain the highly striking crop diversity for which Ethiopia is renowned. I thank all the farmers who taught me and allowed me, without any reservations, to go into their fields and gather the data that are the foundations of all the research findings in this document. Thus, all the knowledge, information and research findings documented in this work belong to the north Shewa and south Welo farmers.

I hope this work will contribute to the recognition of the farming systems, the knowledge and skills of the north Shewa and south Welo farmers through partnership with formal sciences from which these farmers and their communities will benefit. The recognition and the link between the local expertise and formal sciences are essential to the maintenance of biological diversity, agricultural sustainability and food security at the field, regional and global levels.

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CHAPTER ONE
GENERAL INTRODUCTION

INTRODUCTION

World agriculture faces the double challenge of having to increase food production to feed the fast-growing human population while simultaneously assuring that the biophysical resources of agricultural habitats are not degraded irreversibly. Essential elements of strategies for meeting this double challenge are the continued use and maintenance of the genetic diversity of the traditional agricultural systems, and the retention of the farmers' knowledge of their crops and the cropping systems that produced them. Since the origin of agriculture some 10,000 - 12,000 years ago, farmers have developed these genetically diverse populations of different crop species under their traditional farming systems (Harlan, 1975; Hawkes, 1983).

The variable and diverse crop plant populations of the traditional farming systems, which are known as landraces or folk varieties, have been used as the basis for modern commercial agriculture and the development of the high yielding varieties (HYVs) (Frankel, 1974). The HYVs are credited for the current surplus world grain production of wheat, rice and maize. When grown on prime agricultural land augmented by agricultural inputs of pesticides, fertilizers and mechanization, these HYVs can be highly productive and are currently touted by many as the way to meet the food requirements of the expanding world population. Unfortunately, most of the tropical world does not have sufficient agricultural land with the required ideal growth conditions (Huston, 1993; Beets, 1990; Ruthenberg, 1980), and the agronomic requirements of the HYVs are beyond the financial reach of the small farmers.

Although high yielding, the genetic uniformity of the HYVs makes them vulnerable to a host of environmental constraints, including diseases and pests (Brown, 1983; Wilson, 1985). This vulnerability of HYVs increases agricultural production costs and the risk of environmental damage due to the need to purchase and apply pesticides to deal with these diseases and pests, both in agricultural fields and in storage. The HYVs commonly have single gene resistance and hence short life spans before pests overcome their resistance, thereby requiring their replacement by new varieties with a different basis of resistance (Wilson, 1985; Brown, 1983). The plant breeders depend on landraces maintained by or collected from the traditional farmers for the genetic material required to develop new high yield varieties with the needed resistance to diseases and pests.

The traditional varieties are an extremely valuable genetic resource, but unfortunately the HYVs are currently in the process of or at risk of displacing the landrace populations in the centers of origin and diversification of the cultivated plant species. When the landraces are lost the traditional knowledge of cropping patterns and management practices and the ecological rationale behind them are also lost (Chambers, 1983). Ethiopia is one of the eight centers in the world where crop plant diversity is strikingly high and is a center where some crop species were domesticated (Vavilov, 1926, 1951). Ethiopia is also a region where the traditional farming systems have coevolved with the diverse landraces over millennia. According to Harlan (1969), the Ethiopian agricultural systems provide unique opportunities to compare and study primary and secondary centers side by side.

A variety of cereals, oil crops, pulses, root crops, and stimulants are cultivated in appropriate agroecological regions of Ethiopia using a variety of agricultural systems including seed planting, shifting cultivation, pastoral and "ensat" complexes (Westphal, 1975). Until the early 1970s, these Ethiopian agricultural systems were largely uninfluenced by exotic agricultural practices or new seed varieties (Worede, 1992). Since then, however, the situation has changed. The country experienced the severe droughts and famines that also afflicted other parts of Africa in the 1980s. During these years, the landraces were replaced by introduced genetically uniform crop varieties at an accelerated rate as farmers were forced to eat the seed they would normally save for planting. Where HYVs were planted the land use systems changed to meet their demands, with resulting habitat destruction in both the wild and managed ecosystems of the country (Worede, 1992).

The importance of the Ethiopian gene center for plant breeders throughout the world has been documented by numerous authors including Vavilov (1926, 1951), Frankel (1974), and Harlan (1975). Genes from Ethiopian barley, wheat, coffee, and sorghum have demonstrated their global importance by helping to reduce the vulnerabilities of commercial agriculture (Hawkes and Worede, 1991). An Ethiopian barley is resistant to yellow dwarf virus (Qualset, 1975). Some of the Ethiopian sorghum germplasms are resistant to shoot fly (Maiti et al., 1984) and grain mould (ICRISAT, 1985), and have high grain quality (ICRISAT, 1985), high sugar content (Subramanian et al., 1987), high lysine and protein content (Singh and Axtel, 1973), and cold tolerance (Singh, 1985).

The International Board for Plant Genetic Resources (IBPGR, 1981b) [now called the International Plant Genetic Resources Institute (IPGRI)], realizing the global importance of the genetic heritage of the Ethiopian crop plants, designated Ethiopia as one of the regions of highest priority, identified *Sorghum* as one of the crops in the highest priority category, and included Ethiopia in its effort to collect, characterize, evaluate, conserve, and store global crop genetic resources. Also, a programme known as Seeds of Survival Programme for Africa (SoS/Africa) was co-funded by the Canadian International Development Agency (CIDA) and the Unitarian Services Committee of Canada (USC/Canada) and implemented in collaboration with the Plant Genetic Resource Center of Ethiopia (PGRC/E). SoS/Africa is actively engaged in conserving, enhancing and utilizing the landraces that have been maintained by the small farmers of the central highlands of Ethiopia. These activities of PGRC/E, SoS/Africa, and IPGRI in Ethiopia derive from the recognition of the importance of the Ethiopian germplasm to the sustainability of global agriculture. The SoS/Africa activities are also intended to help Ethiopia improve its food production capabilities by making better use of its range of genetic materials. The genetic conservation and development programs operating in Ethiopia (like the other global operations) have concentrated on collecting, characterizing, evaluating, and conserving germplasm for national and international breeding programs and, unfortunately, have largely neglected/bypassed the study of the farmers' knowledge and the traditional agricultural systems that generated and maintained the diverse genetic resources.

In the current study, the sorghum landrace diversity and the ethnobotanical knowledge of traditional farmers in north Shewa and south Welo regions of the central highlands of Ethiopia have been studied in an effort to improve our understanding of the farming systems and of the farmers' knowledge of the attributes of *Sorghum*. *Sorghum*, as a crop plant, was domesticated (Vavilov, 1926, 1951; Doggett, 1988), and diversified (Harlan, 1969) in Ethiopia where it is currently grown at altitudes from 400 - 3000 meter above sea level in areas where annual rainfalls vary from 400mm -

2000mm.

Sorghum is grown as sources of food, feed and industrial raw material. It is the fourth most important world cereal, surpassed in area of production only by wheat, rice and maize. The high sugar contents from *Sorghum* crops are used to produce malt and also provide the starch in brewing and other industrial processes (Dendy, 1995). Because of its drought tolerance, *Sorghum* is grown over many of the drier areas of the world, including China where it is being grown up to 45° north (House, 1995). *Sorghum* has its greatest importance in the semi-arid areas of Africa, India and central Asia, where frequently little else can be grown to meet the basic needs of the human population. In Africa south of the Sahara, *Sorghum*, principally grown as a subsistence rather than a commercial crop, is second in importance after maize. In Ethiopia, *Sorghum* provides one third of the cereal diet and is grown almost entirely by the subsistence farmers.

THE STUDY AREA

The north Shewa and south Welo study area is in the central Highlands west of the great East African Rift Valley which bisects Ethiopia (Figure 1.1). It lies from 10'.10" - 11'.19" N, and 39'.38" - 40'.40" E, and the altitude range of the fields surveyed ranged from 1,200 to 2,400 meters above sea level. The study area is where SoS/Africa and PGRC/E are actively engaged in conserving, enhancing and utilizing the landraces that are cultivated by the small farmers. North Shewa and south Welo are the two most important sorghum growing regions of Ethiopia. Sorghum is an important component of the agricultural system of the regions and is grown by small farmers to meet a variety of needs.

SOIL and CLIMATIC RESOURCE

The major soil types of the research area are Vertisols, Alfisols, and Inceptisols (Teshome, 1990). Topographic situation is the main differentiating factor determining the location of the major soil orders in the study area. Steep slopes over most of the area lead to a high land degradation risk due to water erosion.

The Vertisols occur on gently undulating lands with slopes of 0 to 8%. They are grey-to-black, heavy-textured soils with high amounts of montmorillonitic clay. Their high clay contents give Vertisols a very high cation exchange capacity, which is fairly uniform with soil depth. These soils have high bulk density, slow permeability, crack when dry, are sticky when wet and are difficult to cultivate when either too dry or too wet.

The Alfisols are located mainly on land with slopes ranging from 8 to 15%. Alfisols are brownish or reddish in color, and have an argillic B-horizon as a result of translocation of silicate clays. They retain a high base saturation and are generally fertile with favourable texture.

The Inceptisols are found mainly on steeply dissected terrain with slopes ranging from 15% to 30%. Their color ranges from brownish to reddish. They are weakly developed soils that are more or less freely drained due to the abundant presence of stones and coarse soil particles.

Rainfall and temperature vary greatly within the study area: the mean annual rainfall ranges from 600mm to 1600mm; the mean monthly minimum temperature ranges from 3°C to 14°C; and the mean monthly maximum temperature ranges from 18°C to 30°C (EMA, 1993). The seasonality and variability of the bimodal rainfall regime of the study area dictates the cultivation, planting and harvesting activities (Teshome, 1990; Dyer et al., 1992, 1993). The unpredictability of rainfall for this primarily rainfed agricultural system leads farmer to employ a range of strategies, including stagger planting and/or diversification of the cropping system, to minimize the chances of crop failures.

AGRICULTURAL SYSTEMS

The following interpretations of the agricultural systems of the study area are largely based on my field observations, although some of them are derived from Westphal (1975).

The main crops of the study area include sorghum (*Sorghum bicolor*), maize (*Zea mays L.*), finger millet (*Eleusine coracana*), teff (*Eragrostis tef*), barley (*Hordeum vulgare L.*), wheat (*Triticum spp*), noog (*Guizotia abyssinica*), safflower

(*Carthamus tinctorius*), linseed (*Linum usitatissimum*), sesame (*Sesamum indicum*), Ethiopian mustard (*Brassica carinata*), chickpea (*Cicer arietinum*), lentil (*Lens culinaris*), field pea (Pisum sativum), and faba beans (*Vicia faba).*

The seed-farming complex (Westphal, 1975) is the most important agricultural system of the study area. This agricultural system is part of a highly developed, mixed agriculture in which livestock are used as a source of draft, transportation, and animal produce. All crops are grown from seeds which the farmer broadcasts over the prepared field and ploughs into the soil to facilitate germination and seedling emergence. Cereals, pulses and oil crops are the most important crops of the agricultural system; fruit trees, green vegetables and tuber crops are nearly absent from the study area. Irrigation is not widely practised, except along small rivers and streams, mainly due to topographic problems. The livestock graze on fallow fields or valley bottoms and also consume a good portion of the agricultural residues.

The main agricultural operations of the seed-planting complex in the study area are: land preparation and planting, intercropping and crop rotation, fertilization, pest control, and seed selection and harvesting (Table 1.1). Soil and water conservation measures such as terracing (both stone and soil bunds) and contour ploughing are popular among all the farmers of the study area. The benefits of fallowing are also well understood by the farmers, but, due to land scarcity, only a few of them practise it. Among those practising fallowing, the duration of fallow does not exceed 4 years. While the farmland is not cultivated during the fallow period, livestock are allowed to feed upon the naturally regenerating plants.

Land preparation starts immediately after harvest and involves breaking up the land with the plough so as to encourage soil moisture accumulation. Preparation of the seedbed for good crop growth requires 3-4 ploughing operations and is a cultural measure pursued by the farmers to suppress the growth of weeds. In this rainfed agricultural system, rainfall seasonality and variability are crucial in the farmers' decisions of when to plant the desired genotypes for stable harvest. The decision of when to plant represents a big gamble for the farmers. They usually begin planting early enough to take advantage of a long growing season and harvest before a damaging rainfall pattern sets in (Table 1.1).

Farmers practise stagger cropping to avoid the risk of crop losses/failures due to dry spells and unexpected prolonged drought and will replant throughout the growing season if necessary. If the rains arrive late, quick-maturing varieties which rely on the soil moisture reserve until harvest time are planted.

Manure is used as a source of fertilizer for fields that are located close to livestock enclosures. Farmers transport the manure to these nearby fields during low work periods and create mounds of manure evenly distributed over the fields.

The manure is spread and incorporated into the soil at the time of cultivation.

Tilling the soil, preparing the seedbed for crops, and fertilization create a favourable environment for those wild and weedy species that are adapted to take advantage of the newly created agricultural habitat. Farmers tolerate some of these wild and weedy species, but remove the undesirable ones that may inhibit the growth and reproduction of the crop plant.

Striga (witchweed), armyworms, shootfly, aphids, stem borers and birds are among the agricultural pests that affect adversely the productivity of some *Sorghum* varieties in the research area. To control striga, a plant parasite that suffocates and kills sorghum plants (House, 1985), farmers uproot and remove it from the field just before it disperses pollen. In some cases where germplasm is available, farmers plant striga-resistant landraces where the parasite is tolerated to grow with the crop and later on just before pollen dispersal, the striga is uprooted, piled up and burned to contain its dispersion into other fields.

Most of the farmers, particularly those who own more-marginal land, rotate sorghum with other crop species to renew the fertility of the land and to gain cash revenue from the sale of agricultural produce (Table 1.2). The crop rotation practices involve temporal, spatial, and genetic components, with the rotations practised being dependent on the functional and structural requirements of the crops and the biophysical resource base on which the plants are growing. Teff, chickpea, beans, oil crops, and other non-cane crops are planted immediately after the harvest of sorghum because the farmers believe they renew the fertility of the land. Farmers know which crops to grow in mixture and which to grow singly. For example, noog and teff are never planted in mixture so as to avoid the shading effects of noog which decreases teff yields; farmers plant noog along the periphery of teff plots. Farmers thereby eliminate competition for light between the crops, meet their food requirements from teff and obtain cash from the sale of both crop species.

Before the harvest process begins, farmers walk around inside the fields of sorghum and select the sorghum heads that will be used as sources of seeds for the next planting season. The heads selected for seed are taken home and hung under the roof of the house where there is enough smoke to kill pests that might be lodging inside the sorghum head. After making sure that the grain is dry and insect free, the sorghum head is threshed and the seeds kept in small air-tight containers until they are required for planting.

During the harvest process, farmers fell each sorghum plant while the head is intact, remove the head using a sickle, throw it into a basket, and take the basket full to the threshing ground located in the field. Depending upon the need and the decision made by the farmer, threshing is done either in bulk mixture or each landrace is separated by its phenotypic appearance and is threshed separately. Livestock and human labor are used in threshing.

The harvest is taken home and stored. Depending on the amount of the harvest and the intended duration of storage, the grain is placed in air-tight underground pit storages or in above-ground container structures made of shrub sticks plastered with dung. Sacks, clay pots, calabash, and containers made of mud are also used as in-house storages. Weevils (*Sitophilus spp)* are the major storage pests damaging stored grains, including sorghum.

Both women and men participate in all agricultural activities, with the exception of sowing and transporting agricultural produce from the threshing ground to the storage, which are reported to be carried out only by men.

STUDY GOAL and ORGANIZATION

There are two major components to this dissertation: a field component that was conducted to interview farmers and to collect soil and plant samples from 260 randomly selected fields in communities cooperating in the SoS/Africa program; and a laboratory component involving classification, weevil resistance testing, and soil analyses, which were carried out in Ottawa, at Agriculture Canada, University of Ottawa, and Carleton University, respectively.

The overall goal of the study was to determine what factors influence the *Sorghum* landrace diversity grown by individual farmer at the field level in north Shewa and south Welo regions of Ethiopia. I conducted three interconnected field and laboratory-based experiments to answer the following questions: 1) How do the sorghum landraces differ? 2) Are the farmers consistent in their naming of the sorghum landraces grown in the research area? 3) How does sorghum landrace diversity at the field level change with: the number of farmers' selection criteria; altitude; field size; soil pH; soil organic matter content; percentages of sand, silt and clay? 4) What is the combined influence of farmers' selection criteria and these environmental variables in determining the intraspecific sorghum variations grown on a field? 5) What is the susceptibility of the Ethiopian stored-sorghum landraces to post-harvest infestation by *Sitophilus oryzae (L.)*? 6) How reliable is farmers' knowledge of sorghum landrace storability?

To answer questions 1 and 2, I used multivariate techniques on morphological data matrix to determine if the 177 accessions, that were collected randomly from farmers' fields and named by the farmers, form clusters based on their morphological characters, and to test the consistency of farmers' naming of sorghum landraces. After confirming the consistency of farmers' naming of sorghum landraces using the numerical taxonomic approach, the names given for each accession by the farmers were used in the second segment of the research to quantify the relationship between sorghum landrace diversity and the number of farmers' selection criteria and representative environmental variables documented at the field level.

To address question 3 and 4, I conducted single and polynomial regression analyses on the human and environmental variables collected from the 260 randomly selected fields to quantify independently the relationship between the number of farmers' selection criteria and the values of each of the representative environmental variables (field size, altitude and, soil texture, organic matter content, and pH) and the number of sorghum landraces measured on each field. I also conducted multiple regression analysis using the significant terms in the linear and polynomial analyses to determine the combined farmers' selection criteria and environmental variables relationship with sorghum landrace diversity at the field level.

To answer the question of susceptibility to *Sitophilus* attack and farmers' storability knowledge (questions 5 & 6), 16 Ethiopian stored-sorghum landraces that farmers had identified as being suitable for short-, medium- and long-term storage were exposed to *S.oryzae* to determine their resistance. Five susceptibility parameters (F_1 emergence, oviposition, weight loss, development period, and the Dobie Index) were measured and these laboratory indices of susceptibility were compared with the consensus index of the farmers in order to assess the reliability of the farmers' evaluation of storability of stored-sorghum landraces grown in the study area.

The thesis is structured in the form of three research papers along with their specific hypotheses which address questions 1) and 2), questions 3) and 4), and questions 5) and 6) in Chapters Two, Three, and Four, respectively. A synthesis of the full project is presented in Chapter Five wherein the implications of my work for food security, agricultural sustainability and biological diversity are elaborated.

Table 1.1. Field Observations on Agricultural Calendar Involving *Sorghum* Landraces in north Shewa and south Welo Study Area.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Cultivation	----	----	----		----	----	----					
Seeding			----	----	----	----	----					
Weeding						----	----	----				
Harvesting											----	----
Threshing	----											----

Table 1.2. Field Observations of Crop Rotations and Crop Combinations Involving *Sorghum* Landraces in north Shewa and south Welo Study Area.

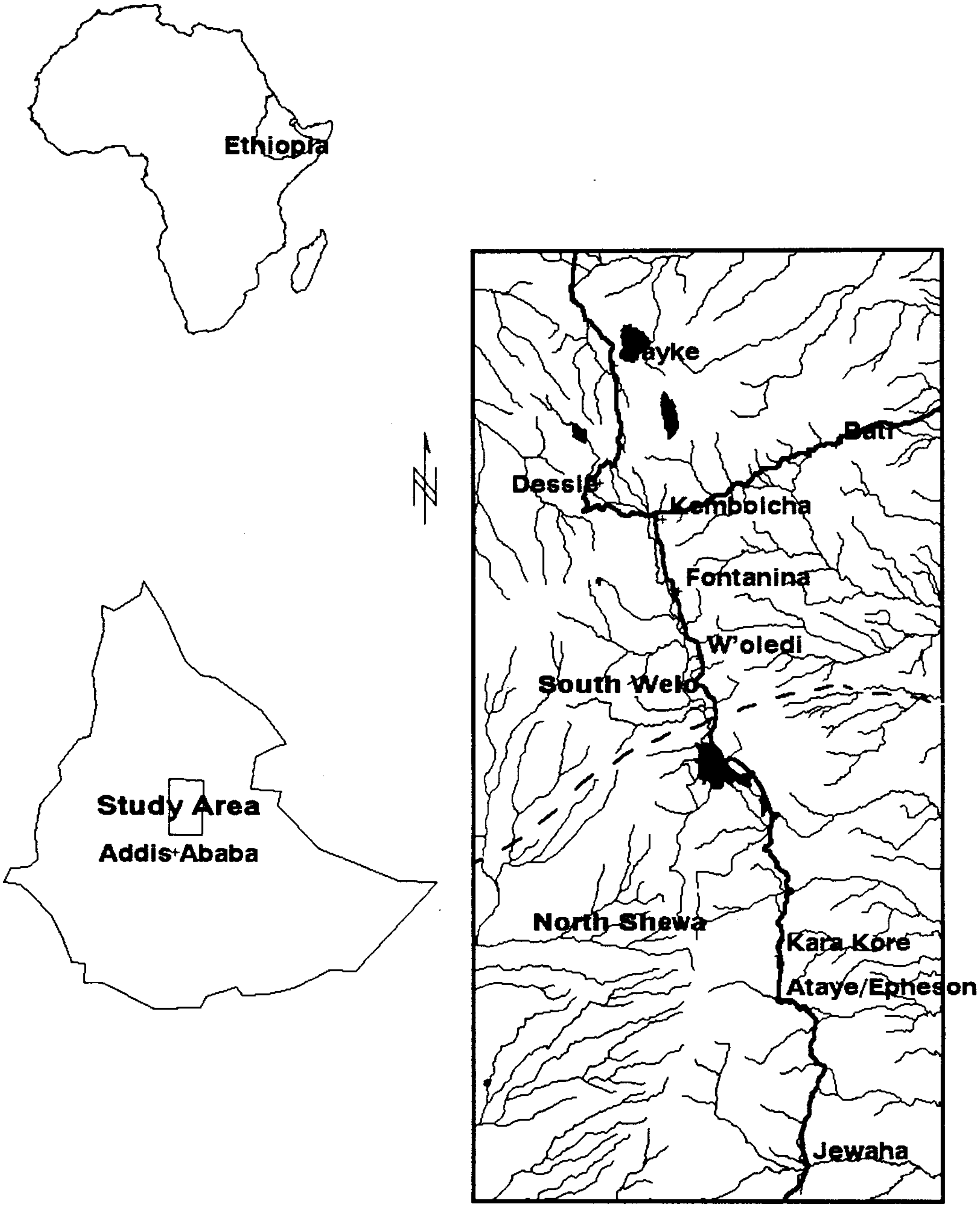
COMPANION CROPS

Intraspecific sorghum landraces
Sorghum+Maize
Sorghum+Sesame
Sorghum+Faba beans
Sorghum+Sesame+Maize
Sorghum+Legume+Sesame
Sorghum+Teff+Sesame
Sorghum+Noog+Sesame
Sorghum+Pulses+Sesame
Sorghum+Maize+Pulses
Sorghum+Sesame+Maize+Pulses+Brassica
Sorghum+Sesame+Maize+Pulses

CROP ROTATIONS ENCOUNTERED

	CROPPING SEASONS			
1st	2nd	3rd	4th	5th
Sorghum	Barley	Oat	Faba beans	Sorghum
Teff	Chickpea	Sorghum	Faba beans	Sorghum
Teff	Sorghum	Lentils	Faba beans	Sorghum
Teff	Chickpea	Sorghum	----------	----------
Teff	Sorghum	Sorghum	Sorghum	Chickpea
Teff	Maize	Chickpea	Sorghum	Sorghum
Teff	Sorghum	Wheat	Oat	----------
Teff	Sorghum	----------	----------	----------
Teff	Sorghum	Teff	Chickpea	Pulses
Sorghum	Teff	Sorghum	----------	----------
Chickpea	Sorghum	Teff	----------	----------
Teff	Sorghum	Teff	Chickpea	Sorghum

Figure 1.1 North Shewa and South Welo Study Area, Ethiopia


Ethiopia
Study Area
Addis Ababa
Hayke
Bati
Dessie
Kombolcha
Fontanina
W'oledi
South Welo
North Shewa
Kara Kore
Ataye/Epheson
Jewaha
N

CHAPTER TWO

SORGHUM [Sorghum bicolor (L.) Moench] LANDRACE VARIABILITY AND CLASSIFICATION IN NORTH SHEWA AND SOUTH WELO, ETHIOPIA

INTRODUCTION

Highly variable and complex taxa are known to offer challenges of classification to taxonomists and biosystematists. *Sorghum* is one of the domesticated crop plants which presents this challenge due to its wide diversity (House, 1995; Serna-Saldivar et al., 1995). In 1794, Moench established the genus *Sorghum* and brought all the sorghums together under the name *Sorghum bicolor (L.) Moench* (House, 1978; Clayton, 1961). Snowden (1936) classified *Sorghum* into 52 species composed of 31 cultivated, 17 wild, and 4 weedy species. On the basis of the absence of genetic barriers among the *Sorghum* taxa, De Wet and Huckabay (1967) combined the 52 species into a single species. Harlan and de Wet (1972), using inflorescence type as a grouping criterion, divided all the cultivated sorghum taxa of the world into five races and fifteen intermediate races, under *S. bicolor* ssp. *bicolor*. Four of the five major races of the cultivated *Sorghum* and one intermediate race are found in Ethiopia (Stemler et al., 1977).

These and other approaches to classification and estimation of genetic variations have their own inherent advantages and disadvantages, particularly in the primary center of origin of *Sorghum,* Ethiopia, where it was domesticated (Vavilov, 1926, 1951) and diversified (Harlan, 1969). Folk taxonomy and botanical taxonomy should be taken into consideration to facilitate the understanding of the challenges of variability and diversity for today's needs of holistic, comprehensive, yet clearly defined and scientifically acceptable biotic classifications.

In the present investigation, morphological characters were used to estimate the levels of variability among the sorghum landraces grown in north Shewa and south Welo regions of Ethiopia. I hypothesized that if farmers are selecting and maintaining landraces, a consensus folk taxonomy must exist with some degree of consistency with conventional botanical taxonomy. The main objectives were: 1) to examine the variability of sorghum landraces and to examine if the landraces form clusters based on their morphological similarities, and 2) to assess the consistency of farmers' naming of the sorghum landraces they grow.

The terms landrace and accession are used throughout this chapter. Landraces are defined as variable plant populations adapted to local agroclimatic conditions which are named, selected and maintained by the traditional farmers to meet their social, economic, cultural and ecological needs. In the absence of farmers' manipulations, landraces may not exist in the ecological dynamics that are known today. Thus, landraces and farmers are interdependent, in need of each other for their survival.

An accession is a sample collected from farmers' fields for research purposes. An accession or group of accessions would be labelled according to the farmers' description of the

Sorghum landrace. Thus, the term accession will be used throughout this chapter until the point where farmers' naming of landrace is found to be consistent in the analyses.

MATERIALS AND METHODS

To study the phenetic similarities of the *Sorghum* landraces grown by the farmers, 230 accessions were randomly collected from a total of 457 hectares of farmers' fields in north Shewa and south Welo regions of Ethiopia. The study area ranges altitudinally from 1,200 to 2,400 meters above sea level. After discarding the incomplete or contaminated samples, 177 accessions were analyzed for their variability using clustering and multivariate statistics (Sneath and Sokal, 1973; Morrison, 1967; Pimentel, 1979). The number of accessions of the *Sorghum* landraces identified by individual farmers ranged from one to nineteen.

To characterize each plant taxonomically, fourteen phenotypic characters were chosen. Table 2.1 lists the morphological characters and their codes used in the analyses. The morphological characters chosen were easy to score, quick and simple to evaluate, often without requiring for high levels of technical skill unlike biochemical or molecular markers. Most of the selected characters could be described with little difficulty by the farmers, and many are related to the essential reproductive functions of sorghum.

Size and shape factors of seeds were determined by means of an image analyzer, Interaktives Bild - Analysen System (IBAS2, 1990), located at the Plant Research Center of Agriculture Canada in Ottawa. To determine the size and shape of each accession approximately 100 seeds from each accession were mounted on a petri dish. For matching purposes, ranges of figures representing the various sizes and shapes of the landrace seeds were taken from a chart of simple symmetrical plane shapes (Exell, 1960, 1962) and mounted on two petri dishes. The image analyzer then analyzed the reference figures and the actual *Sorghum* seeds using the same scale, camera and light requirements and generated size and shape factor scores for each seed accession and the reference seed figures. The accession size factors were categorized into 3 groups (Table 2.1), while the shape factors formed 5 classes (Table 2.1).

Lodicules were boiled in water, dissected and mounted on microscopic slides with lactophenol (Sass, 1958). Lodicule hair distribution and lodicule nerve patterns were examined, photographed and scored with the aid of a Carl Zeiss microscope with Nomarski interference contrast optics. The photographs were used to look for differences in lodicule hair distributions and nerve patterns. Five classes of lodicule hair distribution and three classes of nerve patterns were observed among the accessions (Table 2.1). Seed colour, glume colour and midrib colour were examined and scored using the Munsell colour chart (1957). IPGRI's (International Plant

Genetic Resource Institute) sorghum descriptor manual (1993) was employed to categorize each accession according to its grain plumpness and percent grain covering by the awn.

During accession collection farmers provided the information on the stem juiciness of each accession. The presence of awns, and glume hairiness and constriction were observed and scored in the laboratory. Sorghum inflorescence, used by Harlan and de Wet (1972), Stemler, Harlan and de Wet (1977) and Doggett (1988) as a discriminant character in global sorghum classification, was also used.

The 14 morphological characters (Table 2.1) were scored to make a 177 x 14 data matrix on which clustering and various univariate and multivariate analyses were conducted. Figure 2.1 shows the steps undertaken in the analyses of variability and clustering of *Sorghum* accessions, and consistency of sorghum landrace naming by farmers.

SAHN (Sequential, Agglomerative, Hierarchical, and Nested) clustering methods (Sneath and Sokal, 1973) were used to generate dendograms for the 177 accessions. The data were also subjected to Modeclus (SAS, 1992), a non-parametric clustering method using Euclidean distance, to determine if the accessions form significant groupings.

Canonical Discriminant Analysis (CDA) (Pimentel, 1979; Morrison, 1967) was employed to assess various *a priori* criteria for potential groupings of the accessions and to evaluate the clusters obtained from Modeclus procedure (Figure

2.1). CDA was instrumental in identifying the morphological characters with higher discriminatory power. The *a priori* criteria for the grouping solutions in CDA were stem juiciness and grain plumpness. CDA was also used to find altitudinal ranges as grouping criteria. The *a priori* selected characters were useful in testing if the groupings were justified or supported by the characters not used as group criteria. When CDA was used to evaluate the clustering from Modeclus, the group criterion was cluster membership instead of any particular character (Figure 2.2).

The magnitude of the F-value from the analysis of variance in CDA was used for ranking according to order of importance and for selecting the most important variables among the 14 morphological characters used as group criteria in the clustering of the 177 accessions. The five most common landraces, as named by the farmers, with 5 or more accessions each were subjected to CDA so as to test the consistency of farmers' naming of sorghum landraces in the research area. The magnitudes of the F-value from CDA were also instrumental in ranking the morphological characters most useful in naming sorghum landraces by farmers.

The computations were conducted using SAS (1992) release 6.10 and NTSYS-pc (Rohlf, 1992), on a Dell pentium computer.

RESULTS

The dendograms generated by the parametric clustering method (Figure 2.1, Box 1) demonstrated extensive variability of the accessions but no clear taxonomic structure. The univariate analyses of frequencies, means, variances and standard deviations for each of the 14 morphological descriptors indicated clearly that the accessions were variable (statistics not shown here).

A Priori Grouping Using CDA

When stem juiciness was used as the primary grouping criterion the Mahalanobis distance between the two centroids of the juicy and non-juicy landraces was 3.19. The F-value (6.13) testing the Mahalanobis distance between the multivariate centroids indicated that the two groupings are not equal ($P < 0.0001$). In descending order, grain plumpness ($F=33.24$; $P<0.0001$), grain shape ($F=19.96$; $P< 0.0001$) grain size ($F=19.68$; $P< 0.0001$), glume hairiness ($F=9.86$; $P< 0.002$), grain covering ($F=4.53$; $P<0.035$), and awn presence ($F=4.46$; $P<0.036$) played the greatest roles in segregating the accessions into two groupings when stem juiciness was used as the primary grouping criterion. The Wilks' lambda (0.67) indicated that the two groups are independent ($F= 6.48$, $P < 0.0001$). In the membership analyses, there were 144 non-juicy and 33 juicy accessions. Figure 2.3 shows the two accession groupings as juicy and non-juicy linked by a few intermediates when stem juicy was used as a membership criterion.

Using grain plumpness as a membership criterion generated 122 accessions with dimple and 55 with plump grains. With grain plumpness as a membership criterion, some of the accessions of one group overlapped into the other (Figure 2.4). The Mahalanobis distance (3.86), the F-value (11.44) and the Wilks' lambda (0.54) indicated that the two accession groupings formed by grain plumpness are significantly different (P < 0.0001). Grain covering (F=45.78; P<0.0001), stem juiciness (F=33.24; P<0.0001), glume constriction (F=26.31; P<0.0001), and grain color (F=21.91; P<0.0001), grain shape (F=14.80; P<0.0002), grain size (F=8.51; P<0.004) and glume hairiness (F=5.71; P<0.01) were the leading morphological characters in decreasing order of importance in grouping the accessions into dimple and plump grain types, when grain plumpness was used as the primary membership criterion. The Wilks' lambda (0.54) suggested that the two grain plumpness groupings are significantly different (F=11.4, P < 0.0001).

The inflorescence as a group criterion indicated clearly the representation of four of the five global races and one of the 15 intermediate races proposed by Harlan and de Wet (1972), Stemler, Harlan and de Wet (1977) and Doggett (1988). Stem juiciness (F=27.57; P<0.0001), midrib color (F=15.37; P<0.0001), grain shape (F=15.06; P<0.0001), grain size (F=10.99; P<0.0001), grain covering (F=10.73; P<0.0001), grain color (F=10.52; P<0.0001), grain plumpness (F=8.82; P<0.0001), awn presence (F=5.64; P<0.0003), glume hairiness (F=5.46; P<0.0004) and glume constriction (F=3.37; P<0.01) played the greatest roles in decreasing order of importance in grouping the accessions into five groups (P < 0.0001) when inflorescence was used as a clustering criterion. There were 40, 44, 24, 29 and 40 accessions in each of the five inflorescence grouping.

Three altitude classes were used as class criterion in grouping the accessions into three clusters. There were 81, 74 and 22 accessions in the lowland (< 1,500m), intermediate (1,500-1,900m) and highland (>1,900m) altitudinal ranges, respectively. In descending order, glume hairiness (F=18.51; P < 0.0001), midrib color (F=6.21; P < 0.0025), grain color (F=5.47; P < 0.0050) and stem juiciness (F=5.40; P < 0.0053) were the most important morphological characters in the three altitude-based accession groupings (P < 0.005).

Clustering (Figure 2.1, Box 3)

With Modeclus, the first area of stability of cluster number as a function of K (Fig. 2) is with K=9-14 with three clusters. The second area of stability is with K=15-36 (Fig. 2) with two clusters. The two cluster membership solution yielded 141 accessions that fell in cluster one and 36 accessions in cluster two. CDA of the two clusters generated the following statistics. The Mahalanobis distance (65.17) indicated that the centroids of the two clusters are significantly different (F=123.58; P < 0.0001). In decreasing order of importance Stem juiciness (F=1533.47; P<0.0001), grain size (F=23.05; P<0.0001), grain shape (F=21.98; P<0.0001), glume hairiness (F=10.36; P<0.0015), inflorescence (F=5.21; P<0.0237), grain covering (F=4.73; P<0.0311) and lodicule nerves (F=4.42; P<0.0370) were the characters with greatest discriminatory power in creating the two clusters. The high F-value for stem juiciness reaffirms the suitability of stem juiciness used in the *a priori* selection. The Wilks' lambda (0.08) indicates that the two groups are different (P < 0.0001). Figure 2.5 shows the two cluster of accessions with almost no intermediates.

With Modeclus, the three cluster solution yielded 100 accessions in cluster one, 44 accessions in cluster two and 33 accessions in cluster three. In descending order, grain plumpness (F=79.86; P<0.0001), grain shape (F=26.72; P<0.0001), grain covering (F=19.32; P<0.0001), grain size (F=17.10; P<0.0001), grain color (F=10.95; P<0.0001), glume hairiness (F=8.37; P<0.0003), glume constriction (F=5.82; P<0.0036), and lodicule hairs (F=4.18; P<0.0168) had the greatest contribution in support of the three groups. The Wilks' lambda (0.29) indicates that the three cluster solutions are significantly independent from each other at 0.0001 P-value. Table 2.2 summarizes the Mahalanobis distance, the F-values and their P-values when Modeclus three cluster solution was used as a primary membership criterion. Visual inspection of Figure 2.6 shows that there are three groupings of accessions linked by intermediates, in which more intermediates are seen between clusters 2 and 3 than with cluster 1.

Based on the combined results of the Modeclus three cluster solution and using grain plumpness as a membership criteria (Table 2.3), a botanical key was established for easy classification of the *Sorghum* plants in north Shewa and south Welo regions of Ethiopia:

1) juicy stem . . . . Cluster III
11) non-juicy stem 2
2) dimple grain . . . . Cluster I
22) plump grain . . . . Cluster II

Farmers' classification into landraces (Figure 2.1, Box 4)

The accessions named by the farmers form discrete groups. Midrib color (F=34.27; P<0.0001), grain color (F=15.11; P<0.0001), grain size (F=6.88; P<0.0003), glume color (F=5.51; P<0.0015), glume hairiness (F=3.69; P<0.0131), and grain shape (F=2.65; P<0.05) were the leading discriminant morphological characters in grouping the accessions according to the names given by the farmers. Table 2.4 summarizes the Mahalanobis distance, the F-values and their P-values, when farmers' naming was used as a primary membership criterion. The Wilks' lambda (0.004) as a test of independence of the groupings created by the farmers indicated that the names given to the accessions by the farmers are consistent and highly dissimilar. The Wilks' lambda for farmers' classification was so far the lowest of all the analyses. Figure 2.7 gives the three dimensional representation of the groups of accessions as named by the farmers. The groupings are distinct, different from each other, and the variations explained by the 1st, 2nd and 3rd axes were 58.18%, 25.19% and 12.05%, respectively. Although only five landraces (44 accessions) could be included in this analysis for the reasons mentioned earlier, the evidence in the analyses has led me to generalize that the remaining 55 landraces (133 accessions) identified by the farmers (Appendix 1) in the research area represent 60 different populations in total (Table 2.3b).

DISCUSSION

The foregoing results indicate that the *Sorghum* landraces in north Shewa and south Welo regions of Ethiopia are variable populations grouped into three clusters, and names given to the accessions by the farmers are consistent in representing linguistically and morphologically different *Sorghum* landraces. The variable *Sorghum* landraces which were collected from 457 hectares of farmers' fields represent four of the five cultivated global *Sorghums* as proposed by Harlan and de Wet (1972) and also represent all of the four cultivated *Sorghum* races and one intermediate race as described by Stemler *et. al.,* (1977) within the Ethiopian borders. The representations of the four races and one intermediate race from such a small sample area indicate how farmers in north Shewa and south Welo perceive, select, maintain and disperse the diversity of *Sorghum* landraces using the heterogeneity of the agricultural habitats across the study area.

Overall the analyses suggest the existence of a reasonable degree of consistency between farmers' naming of landraces and the numerical taxonomy used in the clustering of the accessions. Stem juiciness, as provided by the farmers, is the best class criterion in grouping the accessions into two clusters. In the numerical taxonomy, stem juiciness, grain plumpness, grain shape, grain covering, grain size, and grain color had the greatest contribution in supporting the three cluster solution. On the other hand, midrib color, grain color, glume color, glume hairiness, grain size and grain shape is the most important combination of morphological characters used by the farmers to distinguish the *Sorghum* landraces grown on their farmlands. With the exception of midrib color, the list of morphological characters supporting the significant clustering of the landraces as named by the farmers are also subset of the morphological characters supporting the significant clusters created by the Modeclus cluster solution. Thus, midrib color is used as an indicator by farmers of landrace differences.

The pigmentation associated with the morphological characters is perceptually salient to the farmers but has relatively little adaptive significance for the survival of the *Sorghum* plant. For example, midrib color does not have a direct influence on the reproduction and survival of *Sorghum* plants but it is one of the most important field characters used by the farmers to differentiate the grain-forming plant from the juicy sorghum crop stands. The midrib color is also used by the farmers to further distinguish variations within both the juicy and non-juicy sorghum populations. According to Harlan (1975), landraces are the products of human selection for such characteristics as color, flavour, texture and storage quality. The agronomic features mentioned by Harlan (1975) are used by the farmers of north Shewa and south Welo in naming their *Sorghum* landraces.

Unlike the botanical classification, which is mostly hierarchial and purely taxonomic dependent, the folk classification accommodates utilitarian, psychological and linguistic factors along with the taxonomic features (Berlin et al, 1973, 1974; Brush et al, 1981; Hunn, 1982; Martin, 1995). The accessions named by the farmers formed highly significant dissimilar groupings (Figure 2.7) indicating that landraces are distinct plant populations. These populations are maintained by the active selection of the traditional farmers across variable agricultural habitats. If the agronomic importance of each landrace were included in the analysis, the distance between accessions in a grouping would increase and one landrace would be found to be more different from the others than the current analysis indicates. The distinct landrace clusters (Figure 2.7) are indeed products of the selection processes of the farmers (and presumably their forbearers) and reflect the many roles that *Sorghum* plays in their life.

The different groups formed by the various membership class criteria resulted in varying numbers of intermediates between two or more clusters with respect to a single character. These intermediates are naturally occurring taxa due to the fact that major races of sorghum are interfertile and conspecific. *Sorghum bicolor* is both an outbreeding and inbreeding taxon (Doggett, 1957a), in which the inbreeders produce small intra-population variation, while the outbreeding *Sorghum* populations produce wide inter-populational variations. Hybridization and gene flow among the outcrossing and selfing cultivated sorghums, weedy species and wild relatives is free, extensive, and takes place in all possible combinations, increasing variability by producing fertile hybrids and morphologically intermediate individuals as a result of sharing a particular morphological character.

The intermediates are also the result of phenotypic plasticity and ecotypification, and according to Stace (1989), in natural systems, phenotypic plasticity and ecotypification are alternative strategies which are both important in evolution. The presence of some landraces in two or more elevational groupings could be attributed to ecotypification processes making the landrace phenotypically highly plastic and thereby capable of occupying agricultural habitats over larger elevational ranges.

Farmers play an important role in the dynamics of the creation, perpetuation and extinction of crop plants. Farmers make available almost unlimited opportunities for hybridization by bringing together the otherwise geographically and ecologically isolated races to produce fully fertile hybrids and intermediates. Farmers' selection pressures for desirable agronomic traits are the major forces along with natural factors capable of shaping the dynamics of the crop plant population on a farmland. In north Shewa and south Welo, farmers intentionally tolerate the growth of wild relatives and weedy species further facilitating hybridization, gene exchange and creation of new taxa. According to de Wet (1967), Frankel (1974), Harlan (1975), and Hawkes (1983), the intensified and complex morphological variations that we see today are the result of the thousands of years of human activities of isolation, selection and hybridization.

The recognition of intermediates in the dynamics of *Sorghum bicolor* by Harlan (1969), Doggett (1988), De Wet(1978), and Stace(1989) strengthens the findings that the sorghum landraces of north Shewa and south Welo could be grouped correctly into three groupings linked by a few intermediates based on the non *a priori* Modeclus three clusters membership criterion. The combined outcome of the Modeclus three cluster solution and the use of grain plumpness as a membership criterion support the grouping of the landraces into three classes.

A few landraces are found between the clusters. The presence of these landraces between cluster 1 and cluster 2 could be due to altitudinal phenotypic plasticity and localization with respect to adaptability to local microclimatic conditions and human selection pressures.

In cluster 1, three landraces ["Zengada" (1 accession of 19), "Wuncho" (1 accessions of 4) and "Chomogo" (1 of 2 accessions)] were identified in the dimple- grained landrace grouping (Appendix 1). This is because "Zengada" is the most phenotypically plastic landrace grown by most farmers along the vast altitudinal ranges of the research area (i.e. 1,200 - 2,400 m/a/sl). "Wuncho" is only grown specifically by north Shewa farmers in Epheson/Ataye for making beer. "Chomogo" is a landrace with many morphological characters that characterize wild relatives of sorghum. Unlike most of the highly selected landraces, "Chomogo" has long awns and the glumes totally covering its small grains. These characters are typical of the sorghum wild relatives being tolerated by the farmers to grow along with their domesticated landraces. In north Shewa, "Chomogo" is only harvested along with the other sorghums for making local beer and thus is not grown by itself for multipurpose uses. The hairiness, the longer awns and glumes that totally cover the grains, are the main morphological features that make "Chomogo" less attractive to farmers for multipurpose uses.

In cluster 2, eight dimple-grained landraces ["Barchukie" (2 of 3 accessions), "Gubetie" (1 of 3 accessions), "Jemaw" (2 of 5 accessions), "Yekersolatie" (1 of 4 accessions), "Zengada" (1 out of 19 accessions) and "Zeterie" (1 of 2 accessions)] were also identified in the plump-grained landrace grouping (Appendix 1). The misgrouping could be due to the phenotypic plasticity ("Zengada") and the microclimatic conditions ("Jemaw" and "Zeterie") on the north Shewa fields, whereas "Gubete", "Jamuye", "Barchukie", "Wanese" and "Yekersolatie" are grown in Fontenina by farmers from south Welo region of Ethiopia. Jamuye is grown primarily for grain production while the grains from "Gubete", "Barchuke", "Wanese" and "Yekersolatie" are consumed during the fruiting stage as fresh green material ("Eshete") to bridge the farmers between the growing and harvesting seasons. Thus, the stages of growth at which these landraces are utilized, along with the specific locality where they are cultivated, make them different from the other landraces of the same grouping.

A portion of the data set collected for this study was used by Victoria Tunstall (1996) to analyse the risk of genetic erosion for her undergraduate honours thesis indicated that 48 of the landraces with distinct names identified by the farmers are each grown in the four major communities in the study area. Furthermore, the 16 to 24 distinct sorghum landraces identified in some 18 fields (Figure 3.4) demonstrates that each farmer recognizes and identifies each landrace based on a conscious understanding of the biological attributes of the landrace. Besides, according to analysis of the accession allocations by Modeclus (Table 2.3b; Appendix 1) there were only six of the sixty farmer-identified landraces that were grouped between cluster 1 and cluster 2 as a result of their sharing common morphological characters. The above evidence strengthens the case that the sixty farmer-identified landraces in the study area are distinct and that the names given by the farmers to these landraces are consistently applied.

In the three cluster solution (Table 2.3a), the percentage of the intermediate landraces in cluster 1 (1.7%) and cluster 2 (4.5%) are very low compared to the total accession collection correctly classified. The low percentage of the intermediate landraces led me to conclude that the sorghum landraces in the research area could be grouped into three clusters. Intermediates are hybrid derivatives (Harlan and de Wet, 1972), and thus, I believe that eventually through natural and human selection pressures the intermediate could either join one of the well defined clusters of *Sorghum* or evolve into their own distinct taxa.

CONCLUSION

The taxonomic evidence indicates that the *Sorghum* landraces of north Shewa and south Welo regions of Ethiopia are variable and are grouped into three clusters. Nine of the fourteen characters, i.e. stem juiciness, grain plumpness, grain shape, grain covering, grain size, grain color, glume hairiness, glume constriction, and lodicule hairs had the greatest contribution in support of the three groups of *Sorghum* landraces in the research area.

Analyses of the five most common landraces (44 accessions) suggested that the names given to the accessions by the farmers were consistent, representing linguistically and morphologically different *Sorghum* landraces. It is therefore important to document further systematically the folk taxonomy of the study area along with the distribution, richness and equitability of each *Sorghum* landrace to safeguard the rare taxa from displacement by few cosmopolitan cultivated *Sorghums*. It is also important to design complementary *in situ* and *ex situ* conservation strategies so as to ensure the survival and perpetuation of all the _*Sorghum* landraces, including the intermediates, of the research area.

Table 2.1. Fourteen morphological descriptors and their coded characters used in the analyses.

Midrib color	Grey (0) Greyed-Orange (0) Greyed-Purple (0) Dull-Green (1) Dark-Yellow (2) Light-Yellow (2) Yellow (2) Orange-Yellow (3) Brown (4) Moderate-Brown (4) Light-Olive (5) Reddish-Yellow (6) Red (6) White (7)
Stem juiciness	Dry (0) Juicy (1)
Awns	Absent (0) Present (1)
Glume color	Black (0) Purple (1) Yellow (2) Yellow-Orange (3) Orange (4)
Glume constriction	Absent (0) One-sided (1) Two-sided (2)
Glume hairiness	Light (0) Medium (1) Dense (2)
Grain covering	25% (1) 50% (2) 75% (3) Total (4) Glume>Grain (5)
Grain plumpness	Dimple (0) Plump (1)
Grain color	Black (0) Grey (1) Yellow (2) Orange Yellow (3) Brown (4) Red (5) White (6)
Grain size	Small (0) Intermediate (1) Large (2)
Grain shape	Shape I (0) Shape II (1) Shape III (2) Shape IV (3) Shape V (4)
Lodicule hair dist.	No hair (0) One-Sided only (1) Two-Sided only (2) Uniform (3) Dense (4)
Lodicule nerve-setting	Undefined (0) Defined (1) Well-Defined (2)
Inflorescence	DURRA(1), CAUDATUM(2), BICOLOR(3), DURRA-BICOLOR(4), GUINEA(5)

Table 2.2. Mahalanobis distances, F-values and P-values with Modeclus three cluster solution as a group criterion

Clusters (From/To)	Mahalanobis distance	F-value	P-value
Cluster1-Cluster2	7.57	18.06	0.0001
Cluster1-Cluster3	9.75	18.88	0.0001
Cluster2-Cluster3	1.25	1.84	0.0462

Table 2.3a. Summary of accession allocation by Modeclus according to the three cluster solution.

Character	Cluster 1	Cluster 2	Cluster 3
Juicy	0	0	33
Not juicy	108	36	0
Dimple	105	8	10
Plump	3	28	23

Table 2.3b. Summary of number of distinct landrace names given by the farmers and their Categorization in the three cluster solution by Modeclus for the 177 accessions.

	Cluster1	Cluster2	Cluster1+2	Cluster3	Total
Number of landraces	24	11	6	19	60
Number of accessions	105	28	11	33	177

Table 2.4. Mahalanobis distances, F-values and P-values, with farmers' naming of landraces used as group criterion

Landrace (From/To)	Mahalanobis distance	F-value	P-value
Aehyo-Ganseber	44.01	5.56	0.0002
Aehyo-Gedalit	52.06	6.58	0.0001
Aehyo-Wogere	45.71	6.30	0.0001
Aehyo-Zengada	29.24	5.85	0.0001
Ganseber-Gedalit	28.66	3.62	0.0035
Ganseber-Wogere	53.16	7.33	0.0001
Ganseber-Zengada	20.75	4.15	0.0014
Gedalit-Wogere	28.07	3.87	0.0023
Gedalit-Zengada	30.25	6.05	0.0001
Wogere-Zengada	63.92	14.74	0.0001

Figure 2.1. Steps undertaken in the analysis of variability and clustering of *Sorghum* landrace naming by farmers.

CDA =Canonical discriminant analysis.

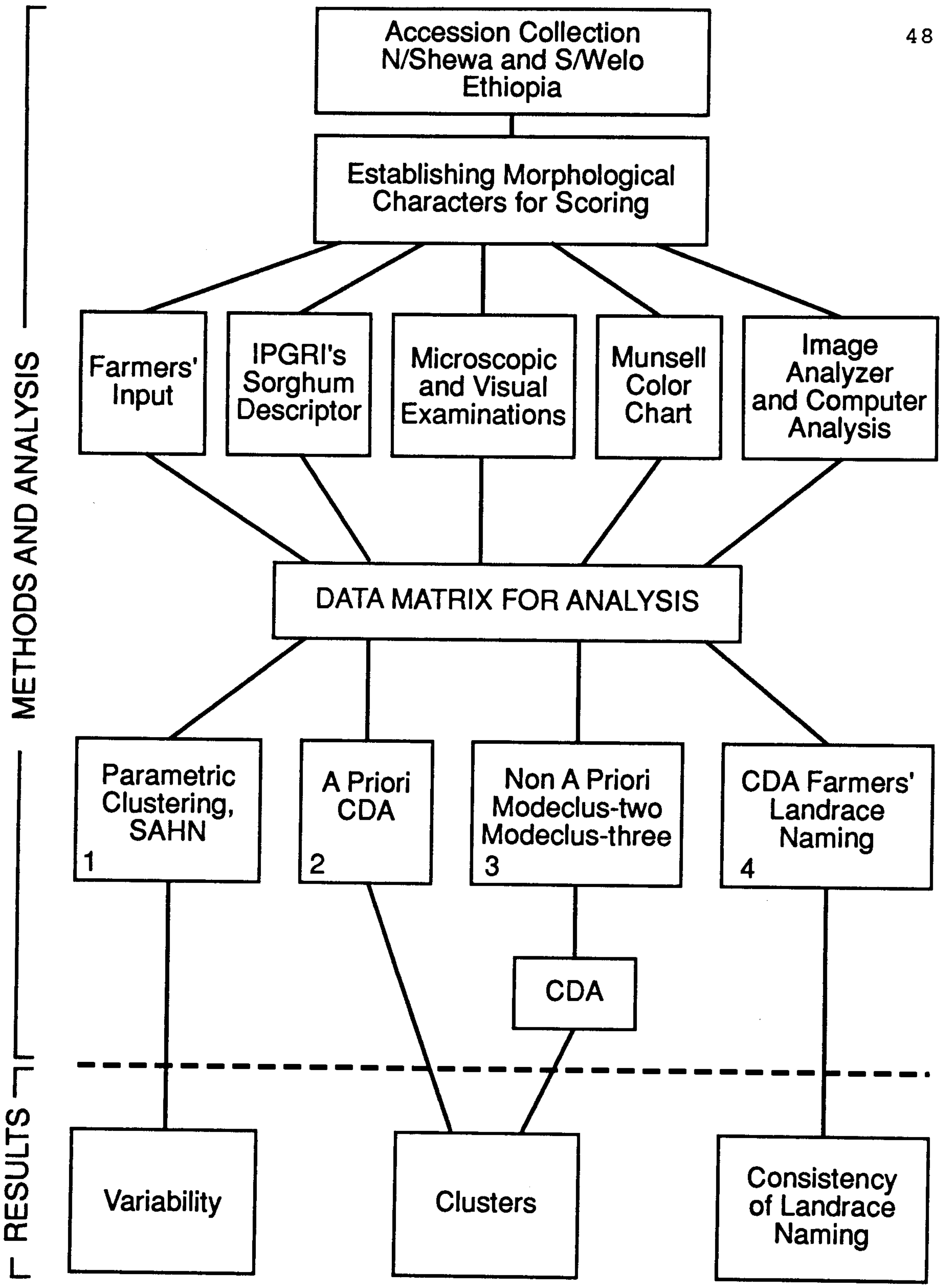

METHODS AND ANALYSIS
RESULTS
Accession Collection N/Shewa and S/Welo Ethiopia
Establishing Morphological Characters for Scoring
Farmers' Input
IPGRI's Sorghum Descriptor
Microscopic and Visual Examinations
Munsell Color Chart
Image Analyzer and Computer Analysis
DATA MATRIX FOR ANALYSIS
Parametric Clustering, SAHN
1
A Priori CDA
2
Non A Priori Modeclus-two Modeclus-three
3
CDA Farmers' Landrace Naming
4
CDA
Variability
Clusters
Consistency of Landrace Naming

Figure 2.2. Generating MODECLUS groupings. Three cluster membership was the first stable area in the curve between K = 9-14. Two cluster is stable with K = 15 - 36. K measures the neighborhoodiness among accessions in forming MODECLUS grouping.

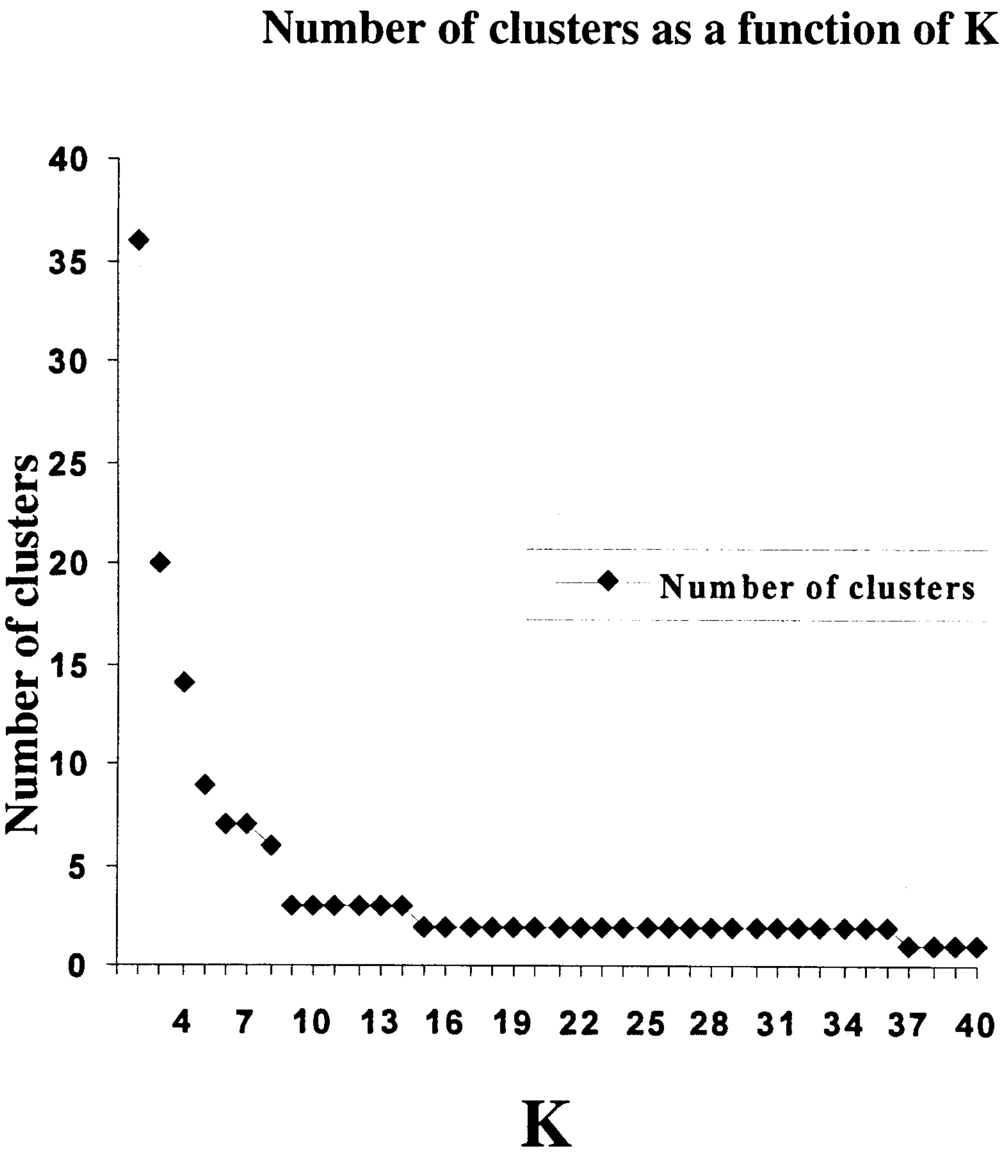

Number of clusters as a function of K
Number of clusters
40
35
30
25
20
15
10
5
0
4
7
10
13
16
19
22
25
28
31
34
37
40
K
Number of clusters

Figure 2.3. *Sorghum* landrace ordination by canonical discriminant analysis, using stem juiciness as group criterion. The juicy (1) and non-juicy (0) groups are partially supported by the other 13 morphological characters which, without the group criterion, by themselves express intermediacy in a number of accessions.

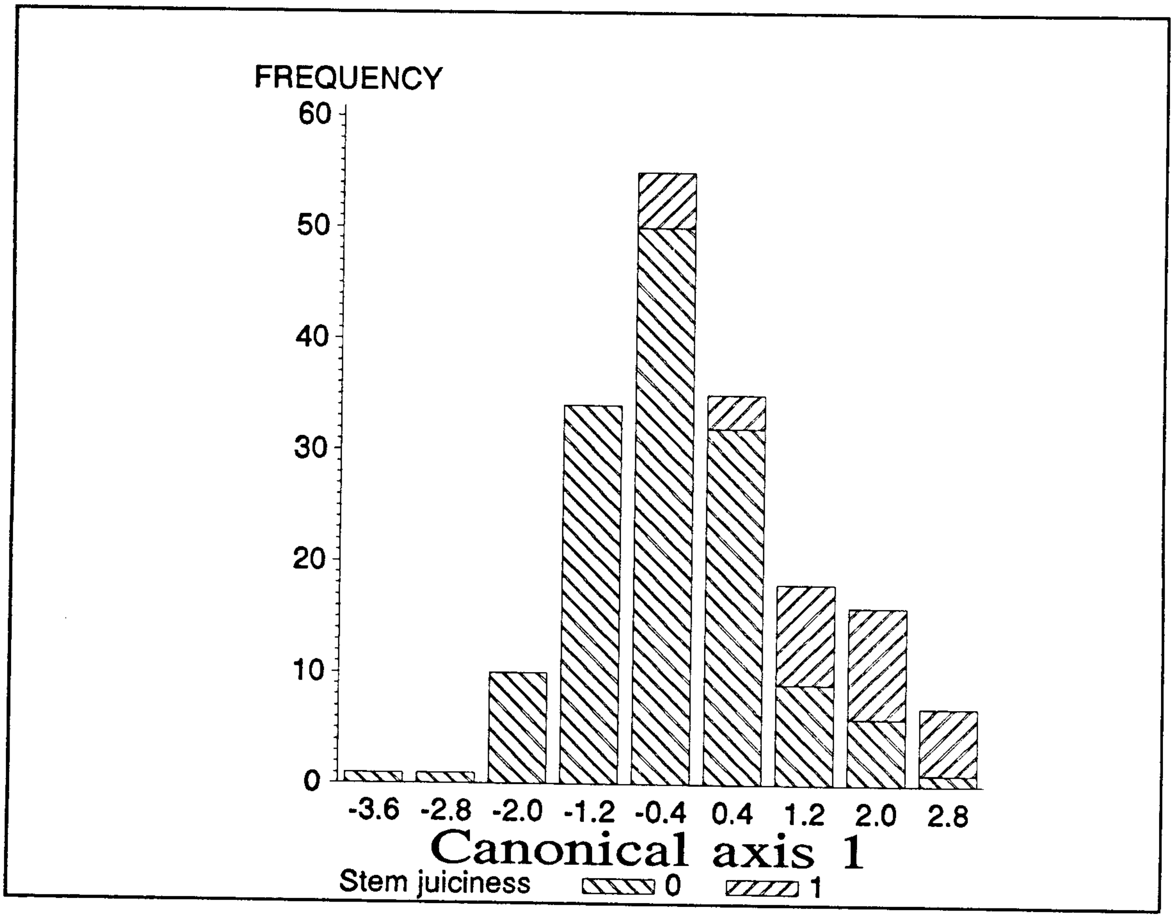

FREQUENCY
60
50
40
30
20
10
0
-3.6
-2.8
-2.0
-1.2
-0.4
0.4
1.2
2.0
2.8
Canonical axis 1
Stem juiciness
0
1

Figure 2.4. *Sorghum* landrace ordination by canonical discriminant analysis, using grain plumpness as group criterion. The dimple (0) and plump (1) groups are partially supported by the other 13 morphological characters which, without the group criterion, by themselves express some intermediacy in a number of accessions.

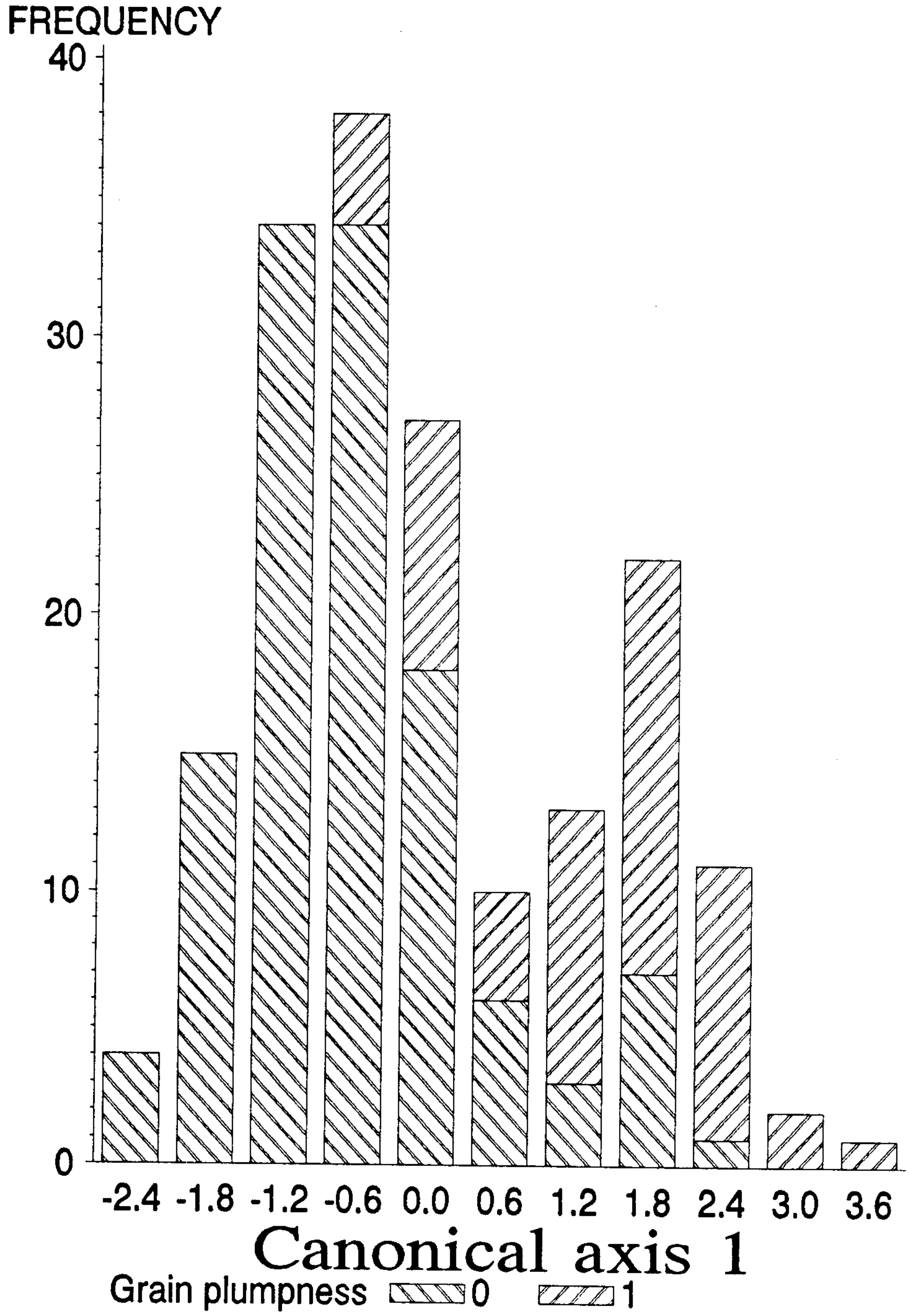

FREQUENCY
40
30
20
10
0
-2.4 -1.8 -1.2 -0.6 0.0 0.6 1.2 1.8 2.4 3.0 3.6
Canonical axis 1
Grain plumpness ▧ 0 ▨ 1

Figure 2.5. *Sorghum* landrace ordination by canonical discriminant analysis, using the two-cluster solution obtained by MODECLUS, as group criterion. The two clusters are almost completely supported by the 14 morphological characters.

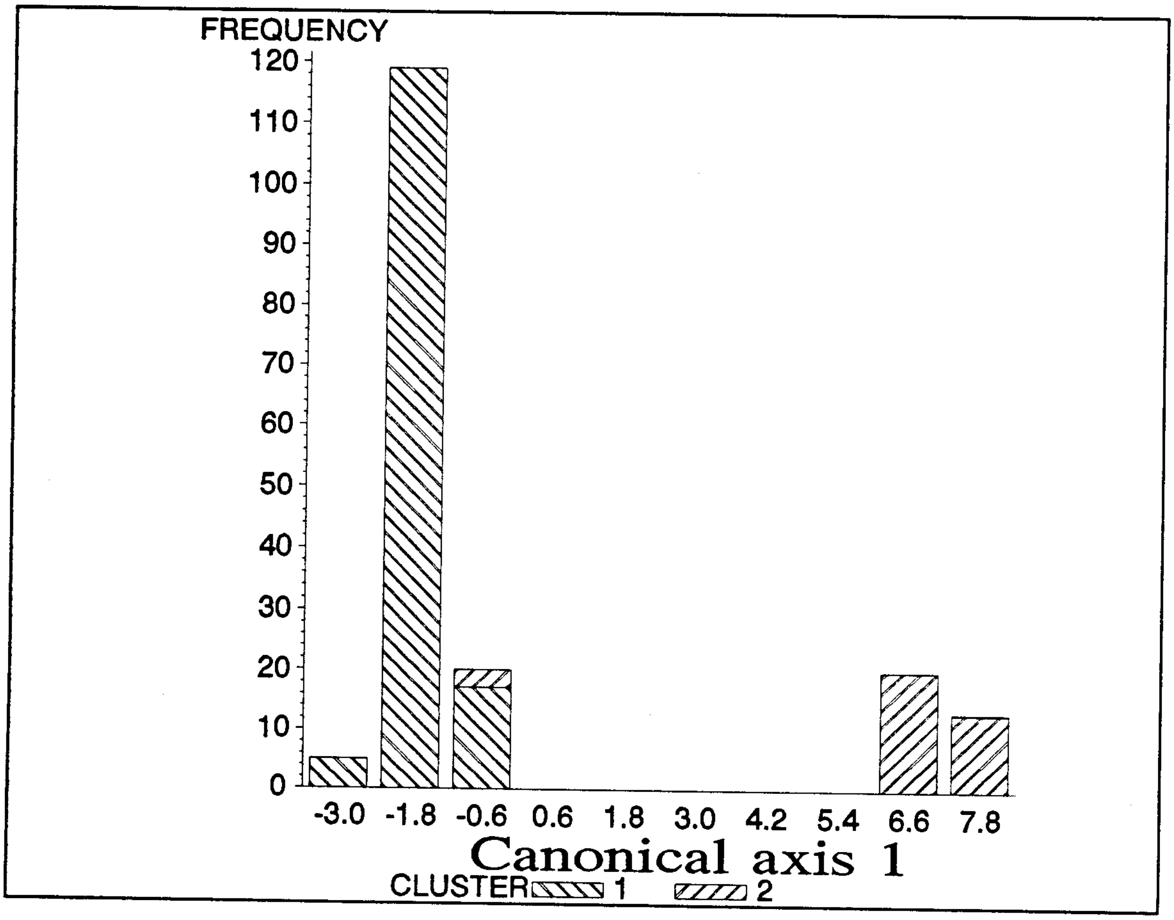

FREQUENCY
120
110
100
90
80
70
60
50
40
30
20
10
0
-3.0
-1.8
-0.6
0.6
1.8
3.0
4.2
5.4
6.6
7.8
Canonical axis 1
CLUSTER
1
2

Figure 2.6. *Sorghum* landrace ordination by canonical discriminant analysis, using the three cluster-solution obtained by MODECLUS, as group criterion. The three clusters are to a degree supported by the 14 morphological characters. Clusters 2 and 3 show more intermediates than with cluster 1.

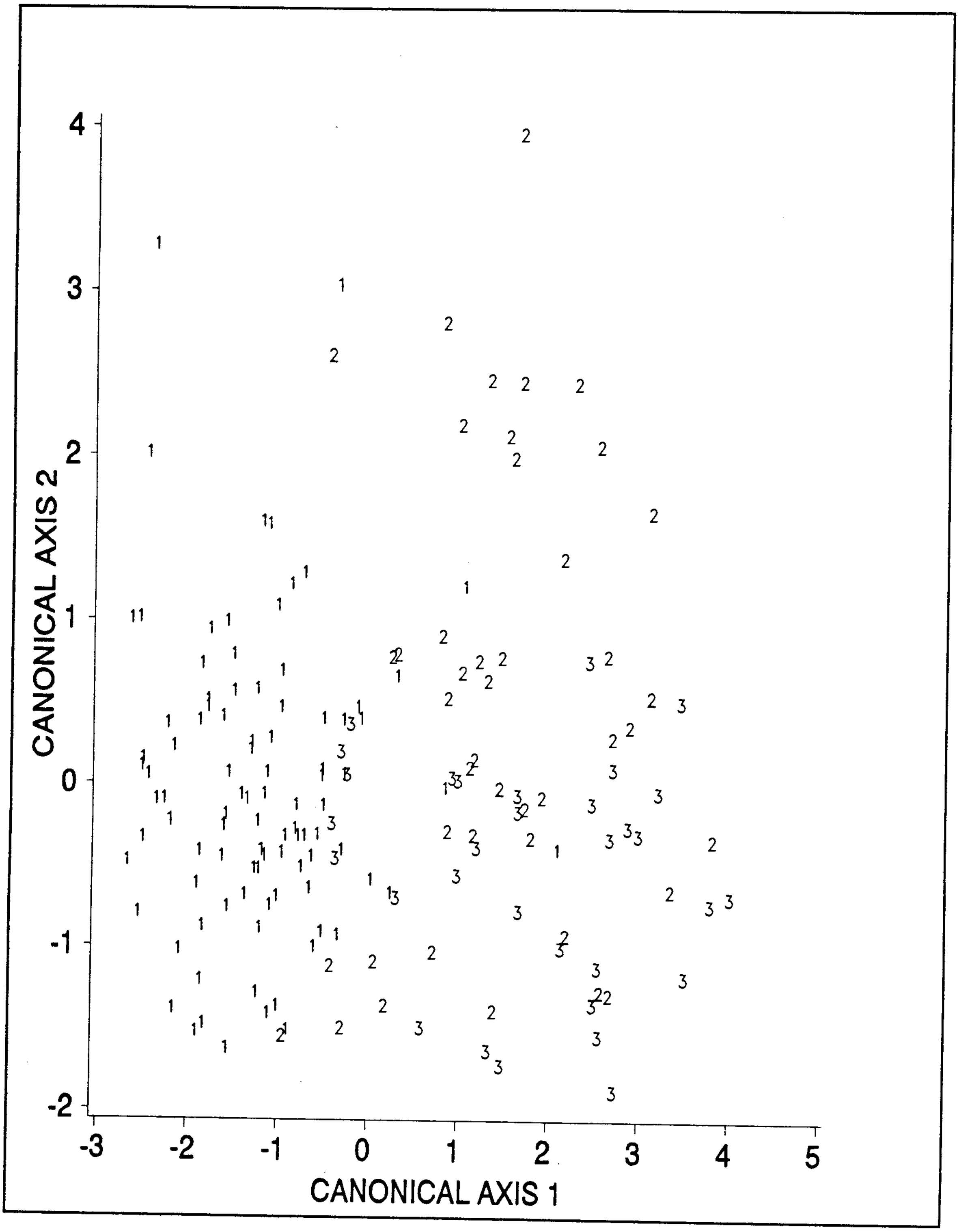
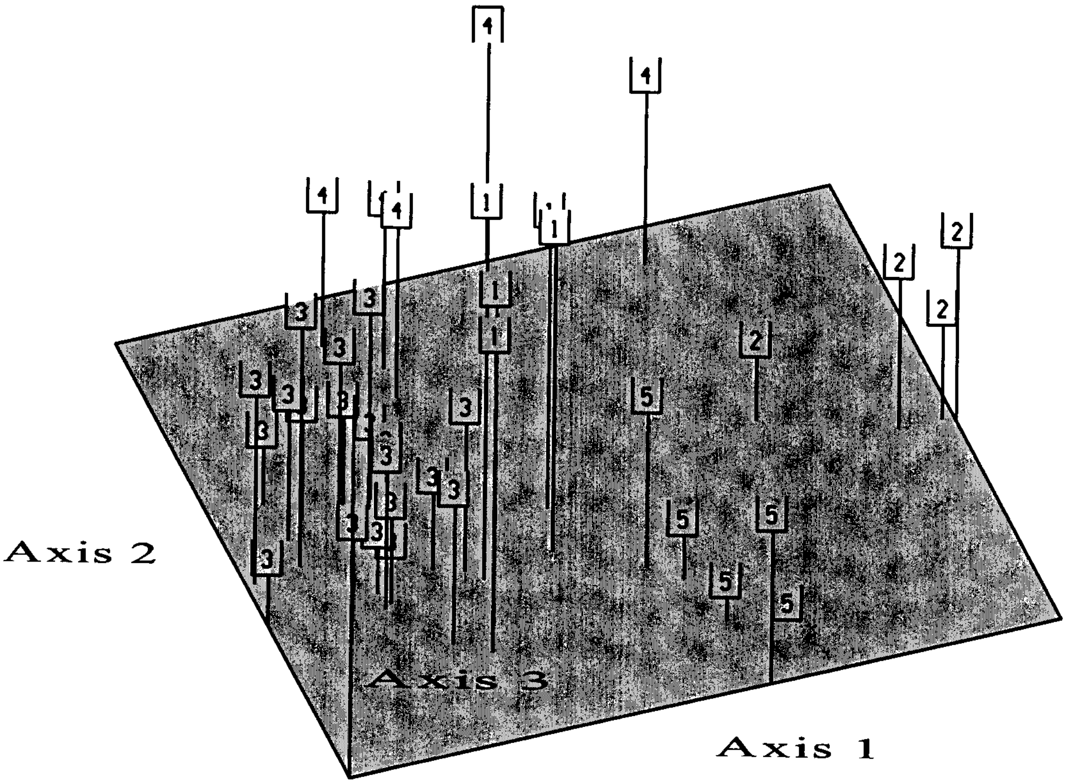

CANONICAL AXIS 2
4
3
2
1
0
-1
-2
-3
-2
-1
0
1
2
3
4
5
CANONICAL AXIS 1

Figure 2.7. *Sorghum* landrace ordination by canonical discriminant analysis, using farmers' naming of *Sorghum* accessions as group criterion. The landraces named by the farmers are supported by the 14 morphological characters and form distinct groups on the ordination plot as well as in the analysis. Variation explained by axes 1, 2, and 3 were 58.18%, 25.19%, and 12.05%, respectively.


Axis 2
Axis 3
Axis 1
1
2
3
4
5

CHAPTER THREE

NATURAL FACTORS AND THE MAINTENANCE OF SORGHUM [*Sorghum bicolor(L.) Moench*] LANDRACE DIVERSITY BY FARMERS' SELECTION IN ETHIOPIA.

INTRODUCTION

Biological diversity provides humans with the wide array of materials needed for food, fibre, medicine and industry. It is essential that scientists understand the factors involved in the generation and maintenance of diversity in order to reduce the risk of degradation of diversity and extinction of genetic resources.

In natural systems, the main factors that ecologists have identified as determinants of species richness in natural systems include: latitude (Fischer, 1960; Whittaker, 1967; Harper, 1977; Ricklefs, 1983; Huston, 1994), habitat heterogeneity (Antonovics, 1971), disturbance (Huston, 1979, 1994; Ricklefs, 1983), productivity (Rosenzweig et al, 1993), energy supply and balance (Currie, 1991; Wright et al, 1993; Wright, 1983), and the size and isolation of islands (MacArthur, 1965; MacArthur and Wilson, 1967; Simberliff, 1976; Smith et al, 1989).

Agricultural scientists, primarily Vavilov (1926, 1951) and Harlan (1975), have conducted phytogeographical research to describe the origin, domestication, cultivation, evolution, dispersion and diversification of crop plants around the world. Both Vavilov and Harlan employed large scales and showed that spatial differentiation of diverse cultivated taxa at the macro- and meso-geographical levels was due to human activities.

Human selection pressures were inherent to the establishment of agriculture 10,000 - 12,000 years ago (Hawkes, 1983). Since then, traditional farmers have played a deterministic role in the generation and maintenance of populations of variable and adapted landraces as well as wild- and weedy-relatives of crop plants (Frankel, 1974, 1976; Harlan, 1971, 1975; Vavilov, 1926, 1951). Traditional agroecosystems represent accumulated experience of generations of their farmers interacting with the environment (Altieri and Merrick, 1987).

The association between farmers and the maintenance of crop varieties has been shown for: potatoes in the Andes (Bellon, 1991; Brush et al, 1981, 1992, 1995); maize in the Americas (Wilkes, 1989; Galinat, 1992; Bellon et al, 1994); and beans in central Africa (Martin et al, 1987; Voss, 1992). These studies emphasized the roles of traditional farmers in the maintenance of genetically diverse traditional varieties (landraces), along with the roles of environmental factors. Landraces, which result from cultural and environmental interactions with the plant genome (Frankel, 1974), are recognizable morphologically. Farmers can distinguish the various landraces (Harlan, 1975), and each landrace named by the farmer can be considered a distinct cultivated taxon (Harlan et. al., 1972; Brush et al 1995; Berlin et al, 1973).

Since the beginning of this century, landraces have been used to develop high yielding varieties (HYVs) (Frankel, 1974) which have been bred to meet the increasing food demands of the ever-growing human population. These HYVs are now causing genetic erosion by displacing the highly variable landrace populations in the centers of origin and diversification of cultivated plants (Frankel, 1974; Harlan, 1975; Hawkes, 1983; Brush et al, 1988, 1992; Altieri, 1995; Oldfield and Alcorn, 1987). According to Chambers (1983), HYVs are also causing the loss of traditional knowledge of cropping patterns and management practices and the ecological rationale behind them.

The HYVs are genetically uniform and, as a consequence vulnerable to a host of environmental risks, such as disease, pests, and extreme weather conditions. The risks associated with monoculture farming, which is what agriculture based on HYVs represents, are evident from the Irish potato famine (Fowler and Mooney, 1990), the southern corn leaf blight, and the Californian barley yellow dwarf virus (Adams et al, 1971; Brown, 1983; Wilson, 1985). The barley yellow dwarf virus was controlled by a single gene from the Ethiopian barley collections (Qualset, 1975). These and other experiences of the vulnerability of HYVs to diseases and pests are the main reasons for rising global interest in the maintenance of genetic variation of cultivated plants, because, in the absence of genetic diversity, world agriculture may not continue to meet the high demands of yield and quality, particularly in dynamic environments that demand equally dynamic adaptations to edaphic and climatic processes, and disease and pest resistance. The Vavilovian gene centers, of which Ethiopia is one, are the sources of genetic diversity for world agriculture (Harlan, 1975; Frankel, 1974; Vavilov, 1926, 1951).

An important step in conserving genetic diversity is to determine the role of environmental factors and farmers' selection in generating crop diversity. Several studies give full descriptive accounts of how farmers' knowledge and land use practices are related to crop diversity (Wilkes, 1989; Brush et al, 1981, 1992, 1995; Martin et al, 1987; Voss, 1992). The relationship between crop diversity and farmers' selection criteria on a field has not been quantified, but should be in order to test the role of humans, in addition to other environmental variables of the agroecosystem.

In this chapter I quantitatively examined the relationships between sorghum landrace diversity at the field level and environmental factors and farmers' selection criteria in north Shewa and south Welo regions of Ethiopia. Environmental factors are included in the study in order to statistically control for their effects and thereby determine the unique role of farmers' selection practices on sorghum diversity. The environmental variables included field size, altitude, soil texture (sand, silt, and clay), soil organic matter content, and soil pH. The farmers' role was measured as the number of selection criteria that a farmer used in choosing the landrace(s) growing on his/her field. I hypothesized that sorghum landrace diversity at the field level would increase as the number of farmers' selection criteria increases.

MATERIALS AND METHODS

Sorghum landrace diversity for this research is defined as the number of distinct sorghum plant populations grown on a field, as named by the farmers. Testing against numerical taxonomy, determined that farmers' identification and naming of sorghum landraces was consistent (Chapter two). Brush et al, (1992), Boster (1983) and Zimmer and Douches (1991) also conducted research using crop plants as identified and named by farmers. In other investigations, farmers' identification and naming of crop plants has consistently been found to approximate the standard scientific taxonomic approaches (Berlin et al, 1973; Quiros et al, 1990).

MEASURING ENVIRONMENTAL VARIABLES AND FARMERS' SELECTION CRITERIA

Information was collected from 260 randomly selected farmers' fields in north Shewa and south Welo regions of Ethiopia. The altitude and size of each field were recorded. Sorghum plants at 5 meter intervals along transect lines spaced 10 meters apart over the whole of each field were identified by the farmers (Figure 3.1). Based on the geomorphological similarities within each field soil samples ranging from 3 to 5 per field were also collected from all of the chosen fields for pH determination (Jackson, 1967) and sand, silt and clay content measurement by the falling drop method (Moum, 1965). The owner of each field was asked why she/he decided to grow each landrace identified.

STATISTICAL APPROACH.

Simple and polynomial regressions (SAS, 1992) were first carried out to examine the relationship between each individual variable (field size; altitude; percents of sand, silt, clay, and soil organic matter content; soil pH; and number of farmers' selection criteria) and sorghum diversity on each field. Sorghum diversity was measured as the number of sorghum landraces identified during the sampling procedure on each field. The individual predictor variables, including significant higher order polynomial terms, were then included in a step-wise multiple regression analysis (SAS, 1992) which generated the best model for predicting sorghum diversity. The response variable was square root transformed in order to meet the assumptions of analysis of variance. An alpha value of 0.05 was set for all statistical tests. Type III sums of squares were used in the significance tests so that the effect of each variable is examined after accounting for the effects of all the other variables in the model.

RESULTS

The mean, standard deviation, and minimum and maximum values for each explanatory variable (Table 3.1) indicate that farmers' fields in the study area are heterogeneous. For example, the approximate coefficients of variation for each soil textural fraction, i.e., clay (3:1), silt (4:1), and sand (2:1) demonstrate the heterogeneity of the soil resources among the farmers' fields. Relationships among the environmental variables include the negative correlations with soil pH and soil organic matter (Table 3.2) which suggest that the soil fertility, and hence the suitability for sorghum, decreases with increasing altitude. It is also notable that the number of farmers' selection criteria was positively correlated with field size and soil organic matter content, and negatively correlated with altitude (Table 3.2).

Based on single variable regressions, sorghum landrace diversity at the field level showed significant relationships with Altitude (Figure 3.2), Field size (Figure 3.3), and the Number of farmers' selection criteria (Figures 3.4, 3.5). The selection criteria identified by farmers were grain yield, biological yield, insect/pest resistance, market value, beverages, milling quality, maturity level, drought resistance, threshability, and bird resistance. The total number of these selection criteria applied to individual landraces ranged from one to six, and the number of selection criteria used per field ranged from two to nine.

The multiple regression analysis (Table 3.3) shows that sorghum landrace diversity at the field level had significant relationships with pH(-) and clay(-), along with the terms that were significant in the linear and polynomial regressions (selection criteria, altitude and field size).

DISCUSSION

The results clearly indicate that sorghum landrace diversity at the field level is influenced by many factors. Discussion ensues on their individual functional relationships and how they may interact.

ENVIRONMENTAL VARIABLES

Altitude

Altitude is a measure of position of the field relative to sea level. Altitude per se does not influence plant growth and diversity (Huston, 1994; Ricklefs, 1983; Whittaker, 1967, 1977; Whittaker et al., 1975), but a series of environmental factors which change with altitude do influence plant growth and diversity (Whittaker et al, 1975; Norman et al., 1984). These factors include precipitation, temperature, seasonality, growing season, crop types, farmers' selection criteria and intensity of cropping activities.

In the north Shewa and south Welo study area, the greatest sorghum landrace diversity is found at approximately 1,500 - 1,700 meters, with the diversity decreasing towards both higher and lower elevations (Figure 3.2). Thus, at lower and higher elevations diversity decreases as a result of the influence of temperature, precipitation, growing seasons and farmers' selection pressures.

Temperatures decrease by 6° C for every 1000 meter rise in elevation (Whittaker, 1967) and consequently, sorghum growth is slower at higher altitudes because it is a cold-sensitive tropical crop (C_4) that experiences increased photorespiration and increased membrane impairment during photosynthesis as temperature decreases, and the seed of which fail to germinate below about 12° C (Taiz et al., 1991; Norman et al., 1984). The poor adaptation of sorghum to growing in cool conditions is the main reason why sorghum landrace diversity decreases towards higher elevation (above 1600m). The few sorghum landraces such as "Zengada" (Chapter two), recorded at high elevation are presumably among those few that are adapted to cooler temperatures as described by Harlan (1975). While the cooler temperatures at higher altitudes disadvantage sorghum, they are advantageous for cold-resistant crops (C_3) such as wheat, barley, and oat (Taiz et al, 1991; Norman et al, 1984). These crops show photorespiration and membrane impairment below 4°C and their seeds show germination failure below 4°C (Norman et al., 1984; Taiz et al., 1991). The availability of cold-resistant crops more adapted to the higher elevations exposes sorghum to additional negative selection pressure by farmers who plant cold-resistant small grains, beans, field peas and other *Phaseolus* that mature more quickly. This farmer response to the availability of more adapted crops further reduces sorghum landrace diversity at higher elevations.

The decrease in sorghum landrace diversity below about 1500m is most probably explained by precipitation decrease which makes the lowland areas more susceptible to dry spells and drought (Tilman and El Haddi, 1992). Thus, at lower altitude, the main sorghum landraces grown will be those reputed for their resistance to dry spells and drought, which would account for the decreased sorghum landrace diversity observed. Whittaker and Niering (1975) and Whittaker (1977) also found that increasing drought at lower elevations in the natural systems is accompanied by decreases in overall biomass production and biotic diversity. If the limiting factor of drought at low elevation is alleviated by farmer intervention, through irrigation and water conservation measures, biomass production can be amplified by growing 2-3 crops in a year and biological diversity may be increased.

Field size

Field size plays a significant role in the amount of sorghum landrace diversity on individual fields in north Shewa and south Welo regions of Ethiopia. The sorghum landrace diversity-field size curve (Figure 3.3) indicates that over most of the field size range diversity increases as field size increases. This may be because larger fields have a greater diversity of microhabitats (Williams, 1943) in which the farmers choose to grow a greater diversity of intraspecific sorghum landraces. Interestingly, the diversity field-size curve also rises for the smallest fields relative to those of intermediate size. This arises because fewer of the small than of the intermediate fields have low diversity, most probably because of their proximity to settlement areas, which lead to their receiving more attention and more inputs of organic residues than fields located more distant from the home. It may also be that those farmers who, because of fragmentation of land holdings through the generations, have only small land holdings are forced to satisfy their range of requirements for sorghum on their small holdings.

Soil parameters

Sorghum landrace diversity at the field level showed negative relationships with soil pH and the percentages of clay particles (Table 3.3).

The pH range of 5.7 to 7.5 encountered in the study area is in the middle of the 4.3 - 8.7 range of tolerance for Sorghum bicolor indicated by Duke (1978) and, with sorghum being a semi-arid region crop, one would expect it to be best adapted to the upper end of its pH range of tolerance. The interplay of pH with altitude, whereby the highest pH occurs at low elevation where there is drought stress, may explain the negative pH - diversity correlation.

Clay-rich soils are usually considered quite fertile due to the presence of high cation exchange capacity which retains nutrient elements and their ability to retain relatively large amounts of available moisture which make them less susceptible to drought than coarse soils. Clay-rich soils may, however, pose operational constraints to subsistence farmers when they become sticky, waterlogged and untrafficable in wet seasons and firm and hard to cultivate during the dry season. My field observations indicate that, where Vertisols (Clay-rich soils) predominate, most farmers plant quick-maturing sorghum landraces in late June and early July (Table1.1). These utilize the high soil moisture residuals and are ready for harvest at the same time as the longer-season landraces planted in February and March. By planting late on these soils, the farmers avoid the need to plough these heavy-textured soils during either dry or wet seasons and consequently are restricted to growing only the fast-maturing landraces, thereby limiting the diversity in these fields.

FARMERS' SELECTION CRITERIA

In the north Shewa and south Welo study area my analyses have demonstrated that as the number of farmers' selection criteria increases diversity in their fields increases (Figure 3.4). This effect is not a result of the correlations between selection criteria and environmental factors (Table 3.2), because the influence of the farmers' selection criteria is significant after statistically correcting for the effects of the chosen environmental variables (Table 3.3; Figure 3.5).

The fields where the landraces are grown are heterogeneous with respect to their topographic, biotic, edaphic and climatic resources. It was clear during the field survey with the farmers that they recognized this heterogeneity and that they took it into consideration when deciding which landraces to plant in specific fields. This is consistent with Brush (1995) who states for potato farmers in Peru that the farmer matches the strengths of each landrace to the environmental heterogeneity of each field so as to benefit at harvest time from each of the different selection criteria.

The farmers know the attributes of the various landraces and the appropriate range of intraspecfic sorghum landraces to meet their varied social, cultural, economic and ecological needs. In risk-prone situations the farmers were aware that growing a range of sorghum landraces in a field increased the security of obtaining a satisfactory harvest. In agreement with the observations of Clawson (1985) and Altieri (1995), these traditional farmers were consciously applying a range of selection criteria and a range of landraces that met these criteria. The employing of more selection criteria by a farmer increases the number of morphologically different sorghum landraces that are planted.

In north Shewa and south Welo regions of Ethiopia, farmers use both time and space strategically to maintain the genetic integrity of the crop plants they grow. Farmers plant different sorghum landraces at different times, or may use separation of fields by distance or elevation, to minimize the chances of undesired pollen exchange at the time of flowering, and to enable the specific landraces to retain their integrity with regard to the intended selection criteria. At the same time, the farmers tolerated the presence of weedy relatives of sorghum on or around their fields to allow some interpollination which could lead to beneficial characteristics being attained by the cultivated landraces. These farmers are acting according to the same principles that Harlan (1975), Dogget (1988) and Altieri (1995) have observed traditional farmers growing different cultivated crops, including sorghum, in different places. Farmers with more than two holdings located at different elevations plant their fields with different combinations of sorghum landraces, using the distance between the two fields as an isolating mechanism against undesired gene exchange during flowering time.

The multiple selection criteria employed by farmers are shaped by both the environment in which they live and centuries of accumulated knowledge passed from generation to generation (Harlan, 1975). Farmers' selection practices are integral to generating and maintaining and thereby reducing the risk of homogenization that can come about due to the continual replacement of a highly diverse set of landraces, by a single dominant crop genotype. The present study establishes the central role of farmers' selection criteria in the generation and maintenance of sorghum landrace diversity in north Shewa and south Welo regions of Ethiopia. The selection criteria associated with each landrace could be used to identify what is useful to the farmers and to identify valuable characters in the sorghum landrace germplasm for the development of new varieties. Thus, scientists and policy makers should place explicit value on maintenance of the knowledge base of the traditional farmers.

Table 3.1. Statistics Summary on the Explanatory Variables (N=260). Select (Number of Selection Criteria/Field); Size (Hectares); Altitude (Meters above sea level of each field); Soil pH; Per Cent of Soil Organic Matter Content, Sand, Silt and Clay Particles in the Soil Samples Collected From Each Field.

	Mean	Std Dev	Minimum	Maximum
Select	5.24	1.55	2.0	9.0
Size	2.14	1.28	0.4	8.1
Altitude	1716	261.10	1290	2390
Soil pH	6.54	0.33	5.7	7.5
Organic Matter	4.98	1.66	1.18	9.27
Sand	28.96	14.85	0	73.6
Silt	50.34	12.33	5.77	84.56
Clay	18.87	6.52	0	36.3

Table 3.2 Pearson Correlations among the independent variables. Strong Correlations were observed among the soil textural classes, and between altitude and farmers' selection criteria.

	Select	Size	Altitude	Soil pH	Organic Matter	Sand	Silt	Clay
Select	-----	0.17**	-0.32***	0.08	0.17**	-0.009	0.05	-0.04
Size		-----	0.09	0.13*	0.02	-0.05	0.05	0.01
Altitude			-----	-0.12*	-0.15*	-0.04	0.03	0.03
Soil pH				-----	0.22***	-0.15*	0.17**	0.04
Organic Matter					-----	-0.49***	0.37***	0.34***
Sand						-----	-0.88***	-0.63***
Silt							-----	0.24***
Clay								-----

*$p < 0.05$ **$p < 0.01$ ***$p < 0.001$ N=260

Table 3.3. Model resulting from step-wise multiple regression analysis. Response variable is square root (Sorghum Landrace Diversity). [Sample size=260; $R^2=0.635$; $P<0.0001$]. Select=Number of selection criteria, Size=field size, pH=soil pH, Altitude=position of each field from sea level, Clay=percentages of clay particles in the soil sample.

MODEL TERM	df	Type III SS	P	Coefficient
Altitude	1	613.98	0.0001	+0.77
Altitude^2	1	578.23	0.0001	-0.00042
Altitude^3	1	526.16	0.0001	+0.0000001
Size	1	321.50	0.0001	+0.148
pH	1	69.21	0.0072	-1.63
Clay	1	39.61	0.0414	-0.06
Select	1	92.80	0.0019	+0.42

Figure 3.1. Random identification and measuring of sorghum plants at 5 meters interval along transect lines spaced 10 meters apart over the whole field.

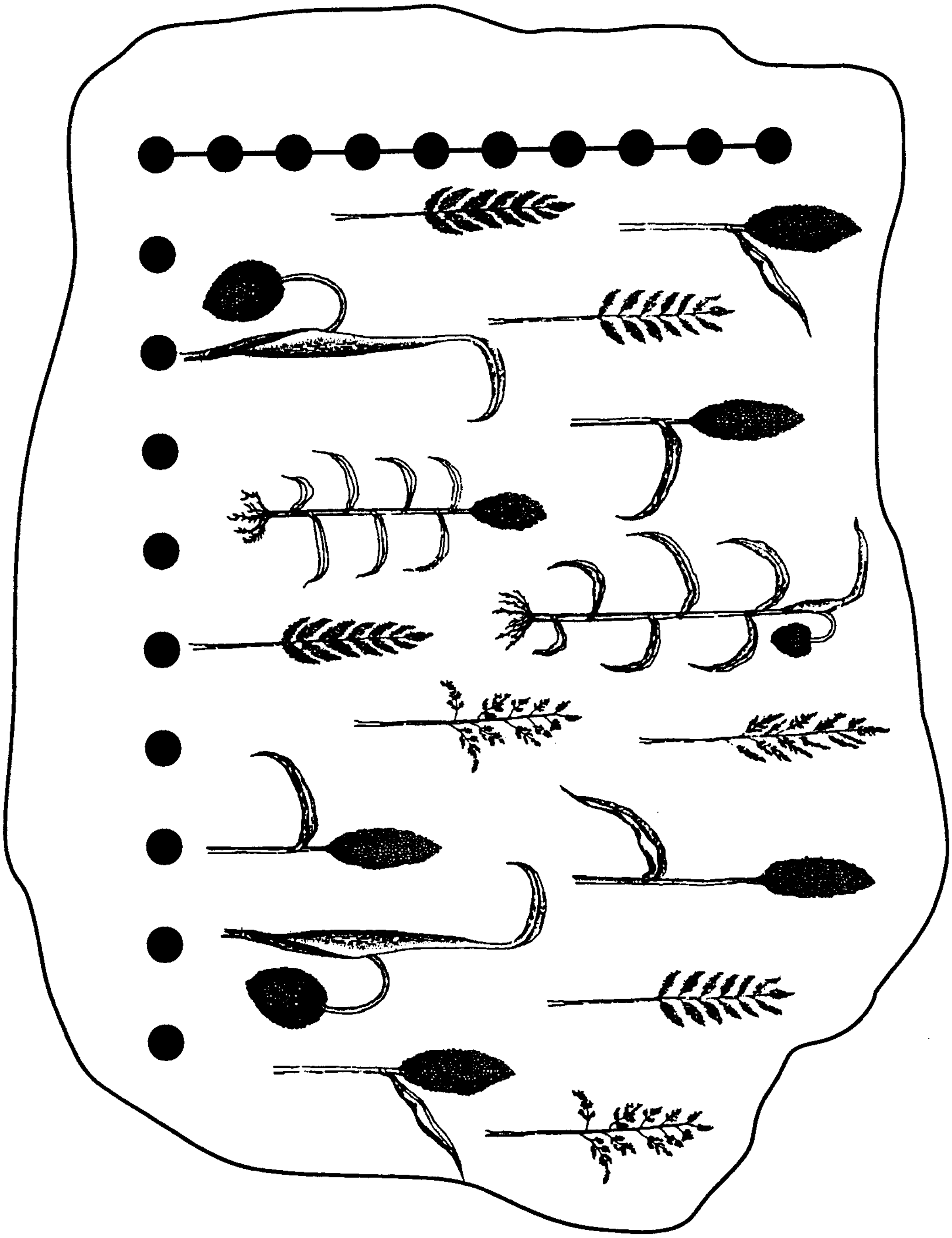


Figure 3.2. Relationship between Altitude and sorghum landrace diversity based on polynomial regression analysis ($R^2 = 0.63$; $P < 0.0001$).

Sqrt diversity = $0.13\text{Alt} - 0.000069\text{Alt}^2 + 0.0000001\text{Alt}^3 - 75.74$

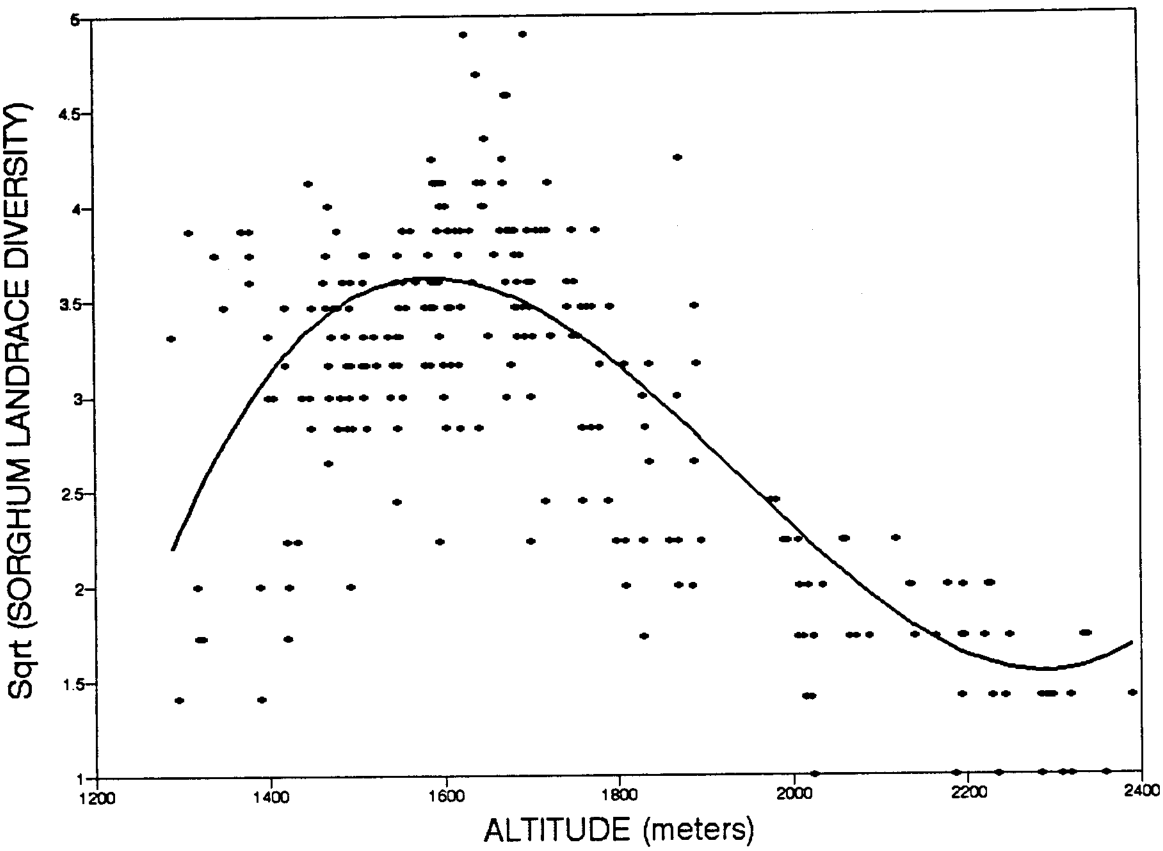

Sqrt (SORGHUM LANDRACE DIVERSITY)
5
4.5
4
3.5
3
2.5
2
1.5
1
1200
1400
1600
1800
2000
2200
2400
ALTITUDE (meters)

Figure 3.3. Relationship between Field size and sorghum landrace diversity based on polynomial regression analysis ($R^2 = 0.075$; $P < 0.0002$) Sqrt diversity = $-0.36\text{Size} + 0.046\text{Size}^2 - 0.0014\text{Size}^3 + 3.73$

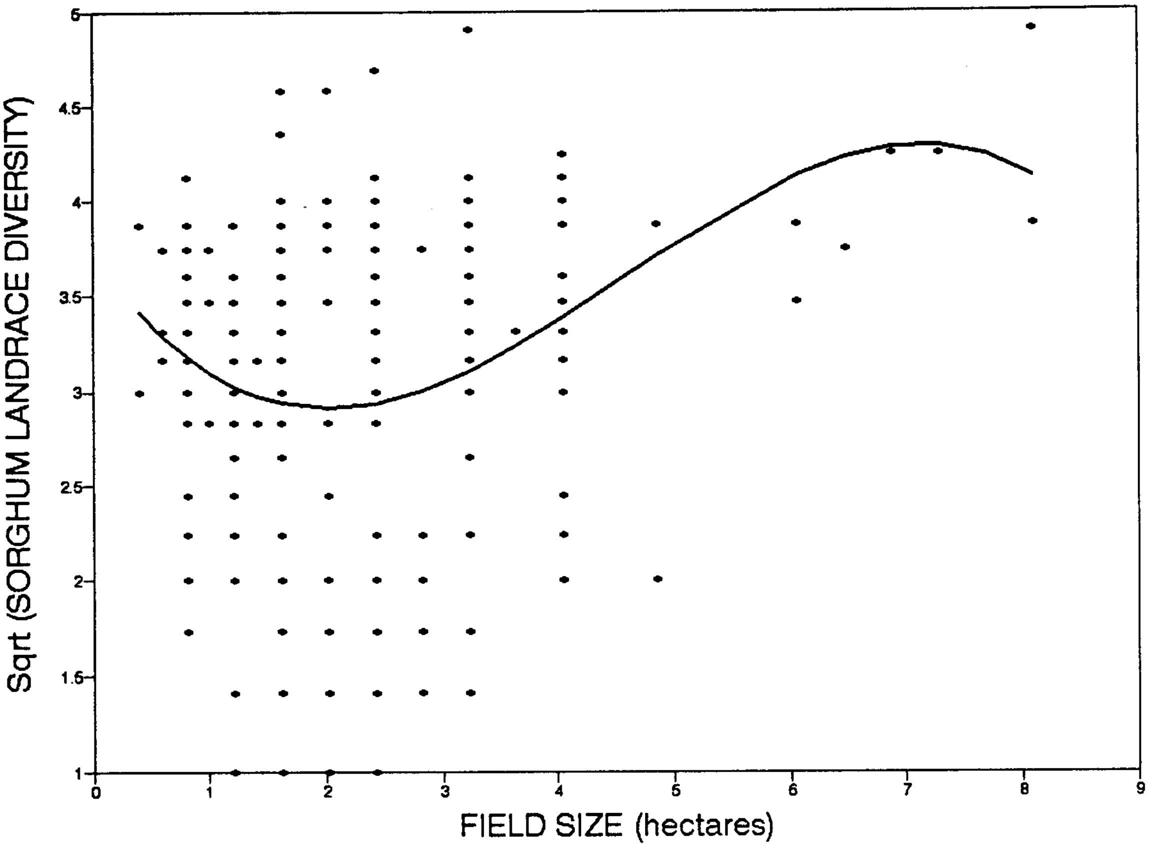

Sqrt (SORGHUM LANDRACE DIVERSITY)
5
4.5
4
3.5
3
2.5
2
1.5
1
0
1
2
3
4
5
6
7
8
9
FIELD SIZE (hectares)

Figure 3.4. Relationship between the number of farmers' selection criteria and sorghum landrace diversity based on polynomial regression analysis. ($R^2 = 0.21$; $P < 0.0001$)

Sqrt diversity = 0.69Select - 0.043Select^2 + 0.73

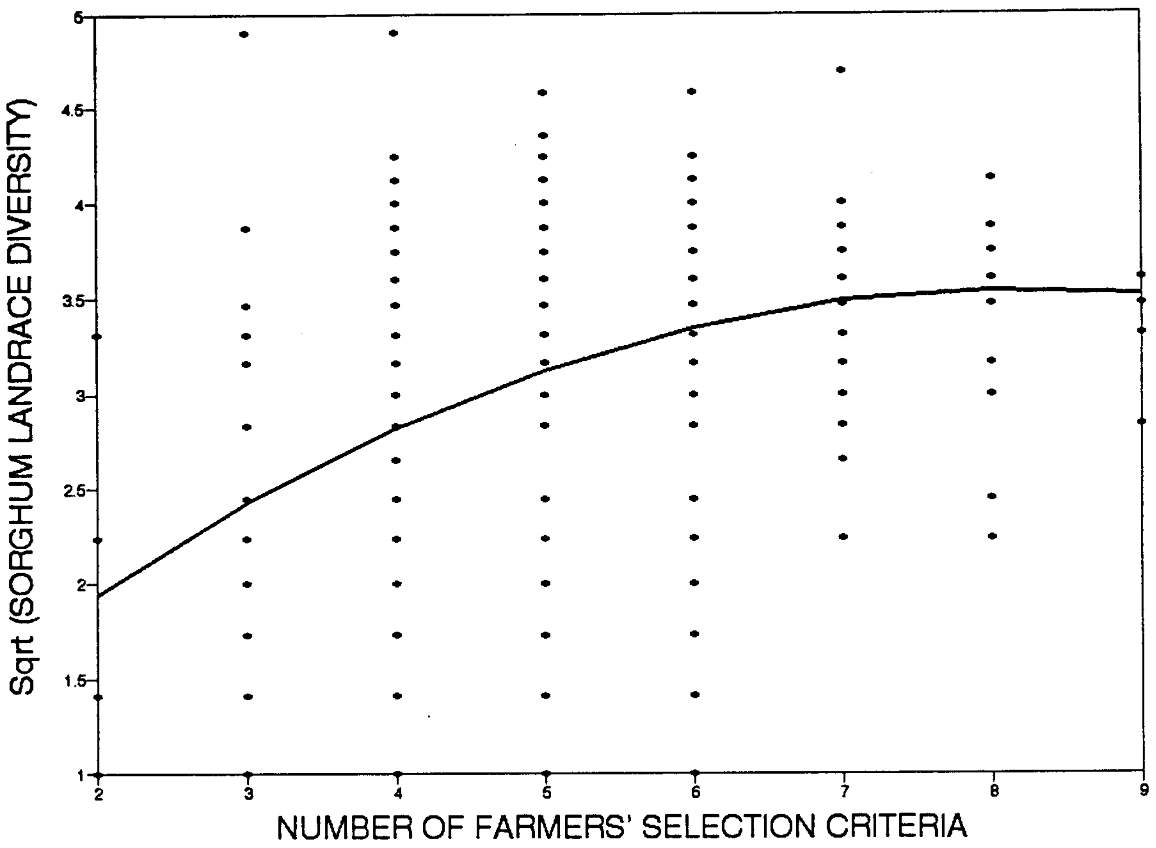
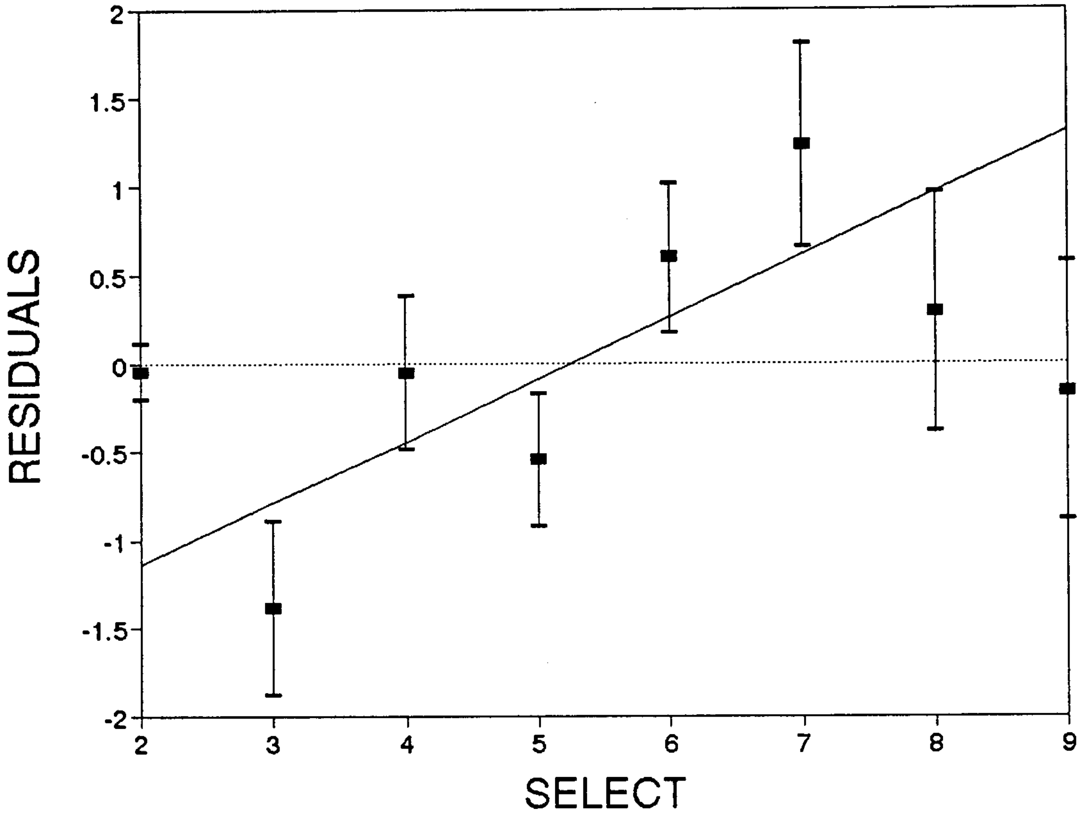

Sqrt (SORGHUM LANDRACE DIVERSITY)
5
4.5
4
3.5
3
2.5
2
1.5
1
2
3
4
5
6
7
8
9
NUMBER OF FARMERS' SELECTION CRITERIA

Figure 3.5. Relationship between the number of Farmers' selection criteria and the residual of the regression of Sqrt (landrace diversity on Alt, Alt^2, Alt^3, pH, and Clay particles ($P < 0.0043$; $N=260$). Standard error bars are shown.


RESIDUALS
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
2
3
4
5
6
7
8
9
SELECT

CHAPTER FOUR

TRADITIONAL FARMERS' KNOWLEDGE OF SORGHUM [*Sorghum bicolor (L.) Moench*] LANDRACE STORABILITY IN ETHIOPIA: COMPARISON OF CONSENSUS KNOWLEDGE WITH LABORATORY EVALUATION OF SUSCEPTIBILITIES TO RICE WEEVILS (*Sitophilus oryzae*)

Order:Coleoptra

Family:Curculionidae

INTRODUCTION

Post harvest losses of agricultural produce to stored grain insects are a global problem. The rice weevil [*Sitophilus oryzae* (L.)], a stored grain insect with world wide distribution, causes millions of dollars of grain losses annually (Sinha and Watters, 1985). *S.oryzae* is the smallest of three grain weevils, and like its relative the maize weevil *S.oryzae* M., may cause severe infestations of grain prior to harvest and in storage (Halstead, 1963; Kuschel, 1961). Losses are particularly problematic in the tropical developing countries where environmental factors are conducive for the perpetuation of insect pests, and where storage facilities are reported to be inadequate. Storage losses of sorghum in Africa were estimated frequently to be greater than 30% (IDRC, 1976).

Sorghum, which was domesticated and diversified in Ethiopia (Vavilov, 1926, 1951; Harlan, 1969, Doggett, 1988), is the fourth most important cereal in the world, only surpassed in acreage production by maize, rice and wheat (FAO, 1993; Purseglove, 1972). Sorghum is consumed in many tropical and subtropical countries. In Ethiopia one third of the cereal diet comes from sorghum (Dendy, 1995), and 90% of the sorghum grain produced in Ethiopia is directly utilized as staple food (roasted, boiled or processed to make "injera"/bread and porridge) and 10% in making home beverages

(ICRISAT, 1982).

Sorghum cultivars have been reported to be highly susceptible to insect pests during storage (Dendy, 1995; Doggett, 1988), particularly to infestation by *Sitotroga cerealella* (Oliver) and *S.oryzae* (L.) (Shazali and Smith, 1985; Doggett, 1957, 1958) which are the most common insect pests of stored sorghum in Ethiopia (Tebebu and Tessema, 1986; Anonymous, 1986).

It would be more realistic, more affordable and safer to use non-chemical means of protecting sorghum grains at the farm level, than to use insecticides. Such non-chemical protection could come from the genetic diversity of crop landraces grown by the farmers themselves. Nutritional, physical and non-nutritive factors are the main resistance mechanisms used by different crop plants to fight against stored-product insect pests (Dobie, 1984).

Some landraces of different cultivars are reported to possess excellent resistance to pest damage, including insects (Jotwani, 1981; Dobie, 1974, 1987; Doggett, 1957, 1958; Fortier et al, 1982, Arnason et al., 1993). The farmers who grow landraces are also reported to be knowledgeable of the agronomic qualities of their crops, including pest resistances (Doggett, 1957, 1958; Adams, 1977). To the extent that this is correct, farmers' knowledge of crop-pest interactions may give scientists the lead to extract, analyze and study the resistance factors embodied in the genetic constitution of the landraces.

Because grain losses are so important to small farmers and because insect damage is easily observable, I hypothesize that traditional knowledge of insect resistance in landraces of *Sorghum* is highly accurate. To test farmers' knowledge of sorghum landrace storability I compared consensus resistance value scored by farmers with the resistance levels to *S.oryzae* (L.) as measured in the laboratory for sixteen Ethiopian stored-sorghum landraces.

The main objectives are to:

1. measure in the laboratory an index of susceptibility to infestation by the weevil, *S.oryzae* (L.), for 16 Ethiopian sorghum landraces using five susceptibility parameters;
2. document farmers' knowledge of the resistance of Ethiopian sorghum landraces to the storage pest, *S.oryzae* (L.);
3. determine the correlations between the laboratory findings and farmers' evaluation of the resistance of Ethiopian stored-sorghum landraces to the storage pest, *S.oryzae* (L.),.

MATERIALS AND METHODS

Grain from 16 stored-sorghum landraces was collected from farmers' fields in the 1993-94 cropping seasons, shipped to Canada and refrigerated until May, 1995 when the susceptibility experiment commenced.

Sixteen stored landraces were collected for the laboratory investigation of weevil susceptibility. While collecting sorghum germplasm samples in Shewa and Welo regions of Ethiopia, at elevations between 1,200 and 2,400 meters above sea level, I asked the farmers what they knew about weevils and their effects on post-harvest storage of sorghum landraces. I also asked the farmers to categorize the landraces they were growing as stored landraces or non-stored landraces, and to further classify the duration of storability of the stored landraces, if exposed to *S.oryzae* infestation, as long, medium or short.

A stored-sorghum landrace is defined as one that is harvested and stored, for later use, for at least one cropping season. The non-stored sorghum landrace is harvested, consumed and/or sold during the same harvest season.

When farmers rank the storability of a landrace as short, medium, or long, they mean that the grain harvest stays fresh for consumption and viable for planting for less than one growing season, less than two growing seasons, and for more than two growing seasons, respectively. Thus, numerical values of 4, 2, and 1 were assigned accordingly for long, medium, and short duration of sorghum landrace storability in order to calculate Consensus Index (C.I.) for each landrace tested in the laboratory using the following formula.

$$C.I. = \frac{4(L) + 2(M) + 1(S)}{L + M + S}$$

Where:

C.I. = Consensus Index for a stored-sorghum landrace,

L = Number of farmers who responded that the stored landrace has a long duration of storability (i.e.greater than two growing seasons),

M = Number of farmers who responded that the stored landrace has a medium duration of storability (i.e.less than two growing seasons),

S = Number of farmers who responded that the stored landrace has a short duration of storability (i.e. less than one growing season),

L+M+S = Total number of farmer respondents who ranked the duration of storability of the stored landrace as Long, Medium, or Short.

Prior to exposure to weevils, the stored-sorghum landraces were conditioned and kept at 27°C and 70% relative humidity for three weeks in a growth chamber. The average moisture content of each landrace was determined by weighing 10 grams of randomly selected grain from all the mason jars before and after drying them at 45°C for 48 hours.

S.oryzae (L.) populations were obtained from established stock cultures of the Agriculture Canada Research Center in

Winnipeg, Manitoba, Canada and were multiplied for several generations on a susceptible soft white wheat at the University of Ottawa (70% r.h, 27°C). As part of the weevil conditioning process the weevils were multiplied for two further generations on the grain of susceptible sorghum landraces brought from Ethiopia. This final step in the propagation process was deemed essential to avoid any short-term changes in the insect behaviour or biology associated with the change of the host grain (Dobie, 1974).

The infestation process consisted of introducing 25 seven-day-old unsexed weevils into 25 grams of each stored landrace. There was one gram of sorghum per adult weevil, and the use of 25 weevils exceeded the minimum of 20 required to avoid the need for sex determination (Dobie, 1977). Eight replicates (four to count oviposition and four to measure emergence), were conducted for each of the 16 stored-sorghum landraces. All cultures were maintained in a growth chamber, at 27°C and 70% relative humidity, for seven days. The light in the growth chamber was on for 12 consecutive hours in each 24 hours period.

After seven days of infestation and incubation the adult insects introduced to each container were removed by sieving from both the emergence and oviposition replicates. The oviposition replicates were transferred to a refrigerator, from which the replicates were taken one at a time, soaked in berberine chloride (20 ppm in water), and the eggs which fluoresce yellow under ultra-violet light were counted under a magnifying glass (Milner et al, 1950).

The emergence replicates were returned to the growth chamber for three more weeks to allow for F_1 hatching and emergence. The first weevil emergence counting was started at the end of the fourth week after infestation, and counting continued every other day for three weeks, at which time the experiment was terminated to exclude F_2 generation progeny (Dobie, 1974). The emergence count enabled calculation of the Dobie Index (D.I.) of susceptibility using the following formula:

D.I= [ln (progeny)]/median development period X 100%

With a slight modification of Dobie's (1977) assignments of values to resistance classes, the **D.I.** values for each stored-sorghum landrace in this research were designated as: 0-5 indicating the landrace was resistant; >5-10 moderately susceptible; >10-13 susceptible; and above 13 highly susceptible.

At the end of the emergence count, each emergence replicate was sieved to remove the powder and re-weighed to measure how much of the initial 25 gram grain sample was lost to weevil infestation. Dobie Index, F_1 emergence, median development period, oviposition and weight loss were measured for each of the sixteen stored-sorghum landraces to determine whether the landraces were resistant, moderately susceptible, susceptible or highly susceptible.

The Statistical Analysis System (SAS) package for computer data analysis (SAS Institute, 1992) was used to conduct Pearson correlation among the five susceptibility parameters, and to test for significant differences using ANOVA (LSD) multiple range test among the means of F_1 emergence and oviposition from the 16 Ethiopian stored-sorghum landraces. Curve-fit function on CA-Cricket Graph III (1992) version 1.1.5 was used to determine if there is a significant correlation between the laboratory findings for each of the five susceptibility parameters and the calculated Consensus Index (C.I.) representing farmers' evaluation of the storability of each of these 16 Ethiopian stored-sorghum landraces. The coefficient of determination (r^2) from the curve-fit was used to show the total variation explained by the relationship between farmers' consensus index and the five susceptibility parameters.

RESULTS

The mean values for each of the five susceptibility parameters as measured for each of the 16 stored-sorghum landraces are presented in ascending order in Table 4.1. All of the susceptibility parameters, except development period, are significantly correlated with farmers' consensus index (Table 4.2). Highly significant positive correlations occurred between the mean number of oviposited seeds and the mean F_1 emergence ($r=0.95$, $p<0.0001$); and between the Dobie Index of susceptibility and both the mean F_1 emergence ($r=0.94$, $p<0.0001$) and the mean oviposited seeds ($r=0.92$, $p<0.0001$). The median Developmental Period (DEVP) is negatively correlated with both the mean F_1 emergence ($r=-0.55$, $p<0.05$) and the mean oviposited seeds ($r= -0.58$, $p<0.01$).

The mean numbers of adults emerging from each replicate varied from 0.50 (Mokakie and Subahan) to 37 (Cherekit) and 39.50 (Merabete), an almost 80 times difference. The ANOVA (LSD) multiple range test (Table 4.3) for F_1 emergence shows that the mean total number of adult emergence is significantly different among the 16 Ethiopian stored-sorghum landraces ($P<0.05$) ($T=2.01$, $df=48$, $MSE=8.98$, $LSD=4.26$). In Table 4.3, the 16 Ethiopian stored-sorghum landraces are categorized into 10 classes based on the mean number of adult emergence, showing an overlap among the groupings.

The mean number of eggs laid per 25 insects varied from 160 (Merabete) to 16 (Subahan) [Table 4.1]. The extremes of preference for oviposition by *S.oryzae* were 10% preference (90% non-preference) for Subahan and 90% preference (10% non-preference) for Merabete, the most susceptible landrace. The ANOVA (LSD) multiple range test for oviposition (Table 4.3) shows that the mean number of oviposition varies significantly among the 16 Ethiopian stored-sorghum landraces ($P<0.05$) ($T=2.01$, $df=48$, $MSE=186.87$, $LSD=19.44$). In Table 4.3, the 16 stored-sorghum landraces are categorized into 13 classes according to the mean number of oviposited eggs, showing an overlap among the groupings.

The developmental periods for *S.oryzae* in the stored-sorghum landraces (Table 4.1) suggest that one effect of increased resistance is a prolongation of the developmental period. The most susceptible stored-sorghum landraces, Merabete and Cherekit, had approximately 10-day shorter developmental periods for the mean F_1 emergence than the most resistant landraces.

The weight loss susceptibility parameter (Table 4.1) indicates that the most susceptible stored sorghum landraces had lost almost four grams of grain to the *S.oryzae* infestations, whereas the most resistant landraces did not show significant weight loss.

The Dobie Index of susceptibility ranges from 1.65 to 15.34. Based on the values of D.I., the Ethiopian stored-sorghum landraces are classified as follows: resistant(3) - Mokakie, Subahan and Tuba; moderately susceptible(5) - Tenglaye, Abula gorad, Key jamuye, Nech jamuye and Wofe aybelash; susceptible(6) - Aehyo, Goronjo, Wogere, Zengada, Enat gorad and Jiru, and highly susceptible(2) - Merabete and Cherekit.

Table 4.4 summarizes the calculated Consensus Index (C.I.) and the number of farmers who evaluated the duration of storability of each of the 16 Ethiopian stored-sorghum landraces as long, medium, or short.

The relationships between the five susceptibility parameters and farmers consensus index (Figures 4.1, 4.2, and 4.3) indicate the reliability of farmers' prediction on the storability of sorghum landraces. Farmers' consensus index is inversely related with the susceptibility parameters of F_1 emergence ($r^2=0.90$), oviposition ($r^2=0.87$), weight loss ($r^2=0.85$), and Dobie Index ($r^2=0.96$); and directly, but much less strongly, related with the susceptibility parameter of the median development period ($r^2=0.40$).

DISCUSSION

The significant correlations between farmers' consensus knowledge of *Sorghum* landrace storability and the laboratory evaluation of the resistance of 16 Ethiopian stored-sorghum landraces to the storage pest, *S.oryzae*, indicate clearly that farmers know the duration of storability of their germplasm. The accuracy of their predictions is remarkable considering that r^2 value greater than 0.85 were found for several parameters.

Fewer F_1 adults emerged from the resistant Ethiopian stored landraces (Mokakie, Subahan and Tuba) than the most susceptible landraces (Cherekit and Merabete). The large F_1 difference between the resistant and susceptible Ethiopian stored landraces is important and should be used more in the management of *S.oryzae* and other pests of stored sorghum. This is because the difference in the total number of emerging adult rice weevil progeny is an adequate measure for comparing damage among sorghum varieties (Davey, 1965).

Adetunji (1988) reported a significant difference in the numbers of emergent adults within Nigerian and Tanzanian sorghum cultivars, indicating that there were more adults emerged from the most susceptible sorghums than from the least susceptible ones. Doggett (1957, 1958), using different methodology, reported that there were more weevils emerging from the most susceptible sorghum varieties than from the resistant ones. Arnason et al (1993) and Dobie (1974), using the same methodology of susceptibility as the present study but a different insect pest *S.zeamais* on corn cultivars, reported that there were more F_1 emergents from the most susceptible corn varieties than from the resistant ones. A considerable difference between the total number of F_1 adults hatched from the most susceptible and resistant cultivars was also reported by Shazali and Smith (1985), and Russell (1962).

The considerable ovipositional differences between the most susceptible and most resistant Ethiopian stored-sorghum landraces are similar to the ovipositional differences reported by Adetunji (1988), Davey (1965), Russell (1962, 1966), and Shazali and Smith (1985). Russell (1966), using *S.zeamais*, reported a twenty-two-fold ovipositional difference among the rice cultivars. In this experiment there was a ten-fold ovipositional differences between the most susceptible stored sorghum landrace and the most resistant stored landrace. Dobie (1974) and Arnason et el (1993) reported no significant differences in the number of oviposited seeds among the cultivars of maize they tested against *S.zeamais*. They suggested factors operating after oviposition were solely responsible for the differences in the numbers of emerging F_1 weevils, which implied that non-preference as a resistance mechanism might be less important in maize.

The weight loss due to *S.oryzae* infestation ranges from zero, for the most resistant landraces (Mokakie, Subahan and Tuba), to 15.8% for Merabete and Cherekit, the most susceptible stored landraces. Doggett (1957, 1958) reported the mean percentage grain loss by weevils ranging from 6.8 - 32.7% (1957), and 18 - 47.9% (1958). Russell (1966) reported a range of 30% to 39.7% of weight losses due to weevil damage. Weight loss due to adult *S.zeamais* weevil populations after weeks of infestation indicated significant differences among maize landraces tested in the experiment (Serratos et al, 1987).

The most susceptible Ethiopian stored-sorghum landraces produced weevils with a shorter median development period (DEVP) than the most resistant stored landraces. The DEVP for this study ranges from 33 to 43.75 days. Adetunji (1988) reported longer DEVP in the resistant Nigerian and Tanzanian sorghum varieties. The average DEVP for the Nigerian and Tanzanian sorghum varieties was 35.24 (Adetunji, 1988), while the average DEVP for the Ethiopian stored-sorghum landraces in this experiment was 41 days. Shazali and Smith (1985), and Russell (1966) reported 29.5 days and 27.5 days, respectively, as the mean development period in their experiments.

Farmers are reported to be knowledgeable about a large number of crop pests, including insects (Mohammed et al, 1989). Farmers are also known to use a range of techniques to control agricultural pests. These techniques include mechanical killing of insects, selection of growing season, dates of planting and harvesting. Incidental controls involving different cultural practices based on the strategies of intercropping, terracing, microclimate regulation, genetic diversity and sanitation both in the field and in the storage sites are also used (Altieri, 1995; Mohammed et al, 1989). In Zambia, Adams (1977) observed farmers selecting uninfested tight-husked cobs to place in store while selling off the larger cobs which were more susceptible to insect attack. Unsuitable cultivars for storage and the unsold ones were kept on drying platforms for immediate consumption.

Doggett (1957, 1958) found the reputation for weevil resistance of different sorghum varieties among local people were reasonably consistent with his results. In the current research, the consistency of the laboratory susceptibility indices (D.I.) with the raw data of resistance survey (Table 4.4) indicates that farmers have reliable knowledge on the storability of *Sorghum* landraces in north Shewa and south Welo regions of Ethiopia. Regardless of the location of their farmlands, most of the respondent farmers agreed that Cherekit (97.9% farmer respondents) and Merabete (96% of farmer respondents) were the most susceptible of the Ethiopian stored-sorghum landraces studied. The percentages of farmer responses indicating short lifetime for both Merabete (96%) and Cherekit (97.9%) correspond very well with the laboratory findings of the susceptibility indices (D.I.) for the two stored landraces, 15.34 and 15.14, respectively.

On the other end of the susceptibility spectrum, almost 94% and 96% of farmer respondents from the research area suggested that Mokakie and Subahan were the most resistant Ethiopian stored-sorghum landraces. Their susceptibility indices were indicated by Dobie Index as 1.65 and 1.82, respectively. There are, however, some differences among the farmer respondents in classifying the Ethiopian stored-sorghum landraces based on the duration of storability as long, medium or short. The calculated Consensus Index (C.I.) has been employed in creating a common ground for the discrepancies observed in the raw data of farmers' responses by accommodating the perceptions of all individual farmers who participated in the survey across the research area.

Some of the difference in farmer assessment of storability could be due to the climatic factors prevailing at the altitudinal locations where the farmers store their grain harvests. Environmental factors, including relative humidity and temperature, have been reported to influence the rates of weevil reproduction (Shazali and Smith, 1985; Russell, 1966). Temperatures below 18°C and drier conditions were reported to extend the average weevil development period to more than 100 days (Sinha and Watters, 1985) compared to 28 days when relative humidity and temperature are at 70% and 27°C, respectively. As a consequence, a resistant stored-sorghum landrace for the farmers in the highland could be susceptible at lower altitudes where moisture and temperatures are conducive for faster weevil multiplication.

In all, the storage life of the stored sorghum landraces is dependent on the managerial skills of the farmers, the inherent biological factors emboided in each landrace, and on the environmental conditions under which the landraces are harvested and stored. The variations among the values of the five suscepribility parameters indicated that the landraces have different inherent susceptibilities to infestation and/or damage by the storage pest, S.oryzae. The environmental conditions, particularly relative humidity and temperatures influence both the inherent resistance of the landraces and the farmers' storability management practices.

"Zengada" is a good case example to explain farmers' storability evaluation and the influences of environmental factors associated with elevation. "Zengada" (Chapter two), the most highly plastic sorghum landrace, was grown across the full altitudinal range of the study area (1,200 - 2,400 m/a/s/l). The storability of Zengada was evaluated as long by the 8 highland farmers, as medium by the 31 farmers from intermediate elevations, and as short by the 18 lowland farmers. The Dobie Index of susceptibility for Zengada was 10.43. This does not mean that the highlanders were wrong; instead they evaluated the duration of the storability of Zengada, and presumably their other stored sorghum landraces, from their experience as dictated by the environmental factors at the location where they are growing, harvesting, and storing their sorghum grain products. Thus, the remarkable accuracy of farmers' predictions clearly demonstrated that farmers know which landraces are resistant and storable or susceptible and non-storable, and accordingly take the necessary storage measures to prevent losses that may occur due to both environmental and biotic influences.

CONCLUSION

The farmers who grow *Sorghum* landraces in north Shewa and south Welo regions of Ethiopia know with considerable accuracy the duration of storability of their *Sorghum* germplasm when infested by the storage pest, *S.oryzae*. Integrated pest management strategies, therefore, should recognize and incorporate farmer knowledge into new systems of protecting *Sorghum* grains at the farm level in the research area. The local storability knowledge may give scientists an important lead to extract, analyze and study the resistance factors from the identified resistant *Sorghum* landraces in developing elite *Sorghum* varieties that are resistant to *S.oryzae* infestations.

Table 4.1. Mean values for the susceptibility parameters of F_1 Emergence, Oviposition, Weight loss, Developmental Period. Dobie Index and Farmers' consensus index as measured for each of the sixteen Ethiopian stored-sorghum landraces.

LANDRACE	F_1 Emergence (#/replicate)	Oviposition (eggs/replicate)	Weight Loss (g)	Development Period (days)	Dobie Index	Consensus Index
Mokakie	0.50	24	0.00	42.00	1.65	3.88
Subahan	0.50	16	0.00	38.00	1.82	3.91
Tuba	1.00	29	0.00	42.00	3.30	3.80
Abula Gorad	4.38	36	0.21	39.40	7.30	2.55
Key Jamuye	5.81	40	1.52	42.36	7.42	2.29
Nech Jamuye	7.31	48	2.00	43.00	7.81	2.10
Tenglaye	12.00	58	2.21	43.75	8.84	2.13
Wofe Aybelash	16.44	69	2.69	43.00	9.73	1.78
Enat Gorad	17.13	72	2.79	42.00	10.06	2.00
Jiru	18.44	76	2.80	42.70	10.07	2.01
Zengada	22.56	110	3.01	43.00	10.47	1.96
Aehyo	22.31	87	3.01	43.00	10.44	1.81
Goronjo	20.75	85	3.30	42.00	10.52	1.76
Wogere	23.31	98	3.30	43.00	10.55	1.88
Cherekit	37.00	152	3.88	33.00	15.14	1.02
Merabete	39.50	160	3.95	33.00	15.34	1.04

Table 4.2. Pearson Correlation Coefficients among the susceptibility parameters of F_1 Emergence, Oviposition, Weight loss, Development period, and Dobie Index, and Consensus Index.

	F_1	OVIP	Weight Loss	DEVP	Dobie Index	Consensus Index
F_1	-----	0.95***	0.92***	-0.55*	0.94***	-0.88***
OVIP		-----	0.82***	-0.58**	0.87***	-0.80***
Weight Loss			-----	-0.26	0.94***	-0.93***
DEVP				-----	-0.41	0.29
Dobie Index					-----	-0.98***
Consensus Index						-----

*p < 0.05 **p < 0.01 ***p < 0.001 N=16

Table 4.3. Mean F_1 Emergence and Ovipositions from sixteen Ethiopian stored-sorghum landraces.

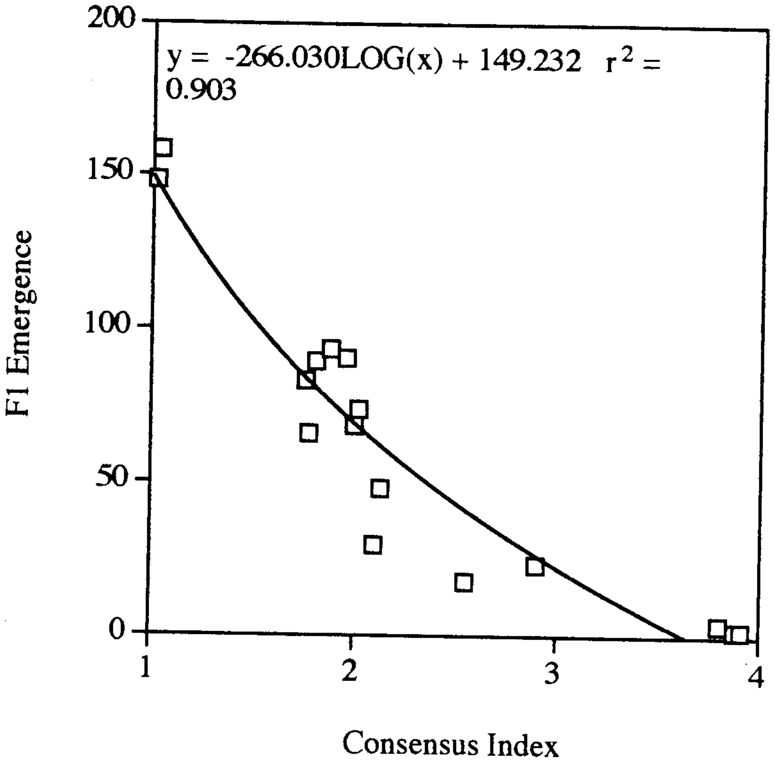
LANDRACE	*F_1 ± S.E	*OVIP ± S.E
Mokakie	0.5 ± 0.289 g	24 ± 3.342 j-k
Subahan	0.5 ± 0.289 g	15.5 ± 1.500 k
Tuba	1.000 ± 0.408 g	29 ± 1.291 i-k
Abula Gorad	4.375 ± 0.357 f-g	36 ± 3.67 h-j
Key Jamuye	5.813 ± 0.066 f	40 ± 4.41 f-h
Nech Jamuye	7.313 ± 1.328 f	48 ± 7.382 g-i
Tenglaye	12.000 ± 1.354 e	58 ± 2.160 e-g
Wofe Aeybelah	16.44 ± 2.115 d	69 ± 5.583 d-f
Enat Gorad	17.125 ± 1.264 d	72.75 ± 4.308 i-k
Jiru	18.438 ± 2.117 c-d	76 ± 6.831 d-e
Zengada	22.563 ± 0.439 b-c	110 ± 2.198 b
Aehyo	22.313 ± 3.350 b-c	87 ± 9.883 b-c
Goronjo	20.750 ± 2.136 b-d	85 ± 3.559 c-d
Wogere	23.313 ± 1.924 b	98 ± 9.883 b-c
Cherekit	37.000 ± 0.408 a	152 ± 14.124 a
Merabete	39.500 ± 1.190 a	160 ± 11.965 a

* Means followed by different letters are significantly different based on ANOVA (LSD) multiple range test ($P<0.05$)

Table 4.4. Consensus Index (C.I.) and number of Farmers who evaluated the duration of sixteen Ethiopian Sorghum landraces as Long, Medium, and Short.

	--- Number of Farmers ---			
LANDRACE	Long	Medium	Short	Consensus Index
Cherekit	0	1	46	1.02
Merabete	0	2	48	1.04
Mokakie	31	2	0	3.88
Zengada	8	31	18	1.96
Subahan	21	1	0	3.91
Tuba	18	2	0	3.80
Abula gorad	15	40	0	2.55
Enat gorad	3	55	6	2.00
Key jamuye	2	12	0	2.29
Nech jamuye	1	8	1	2.10
Tenglaye	10	75	8	2.13
Wofe aeybelash	1	35	13	1.78
Jiru	2	63	3	2.01
Aehyo	0	29	7	1.81
Wogere	0	14	2	1.88
Goronjo	0	22	7	1.76

Figure 4.1. Relationships between Farmers' Consensus Index (C.I.) and the susceptibility parameters of F_1 Emergence ($R^2 = 0.903$), and Development Period ($R^2 = 0.402$).


y = -266.030LOG(x) + 149.232 r^2 = 0.903
F1 Emergence
Consensus Index
200
150
100
50
0
1
2
3
4

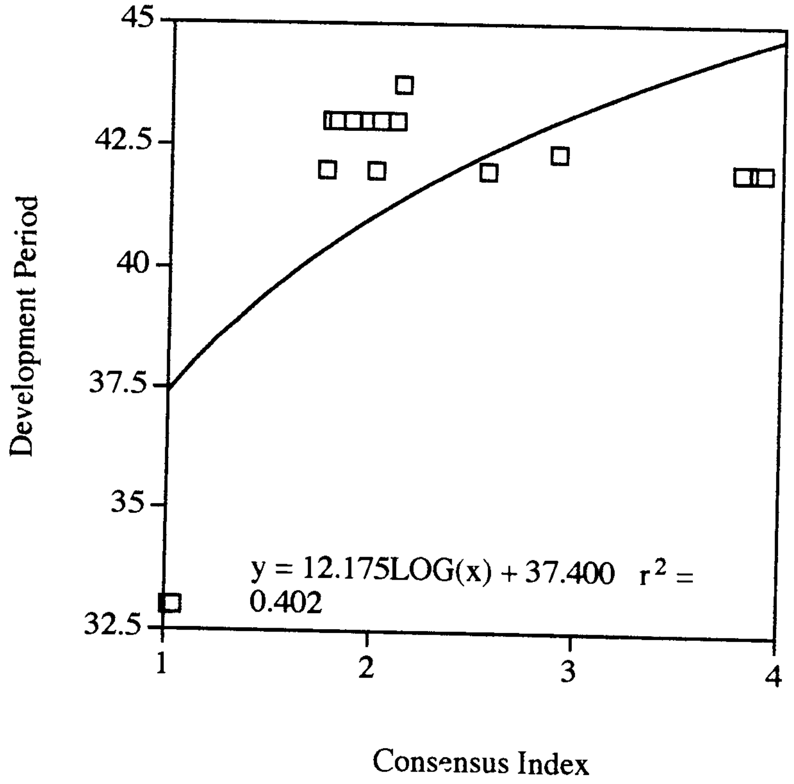
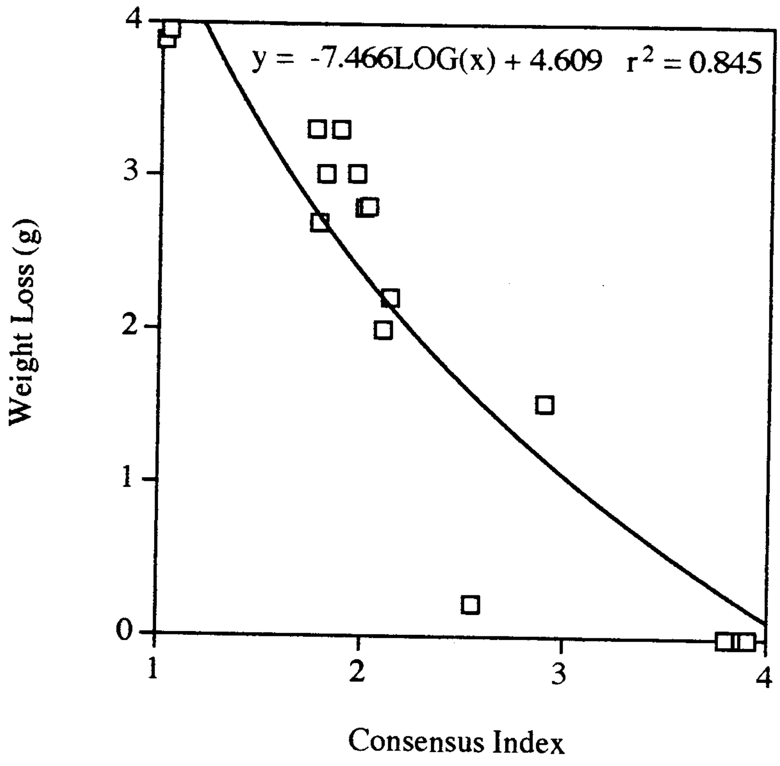

y = 12.175LOG(x) + 37.400 r^2 = 0.402
Development Period
Consensus Index
45
42.5
40
37.5
35
32.5
1
2
3
4

Figure 4.2. Relationships between Farmers' Consensus Index (C.I.) and the susceptibility parameters of Weight loss ($R^2 = 0.845$), and Ovipositions ($R^2 = 0.87$)


y = -7.466LOG(x) + 4.609 $r^2 = 0.845$
Weight Loss (g)
4
3
2
1
0
1
2
3
4
Consensus Index

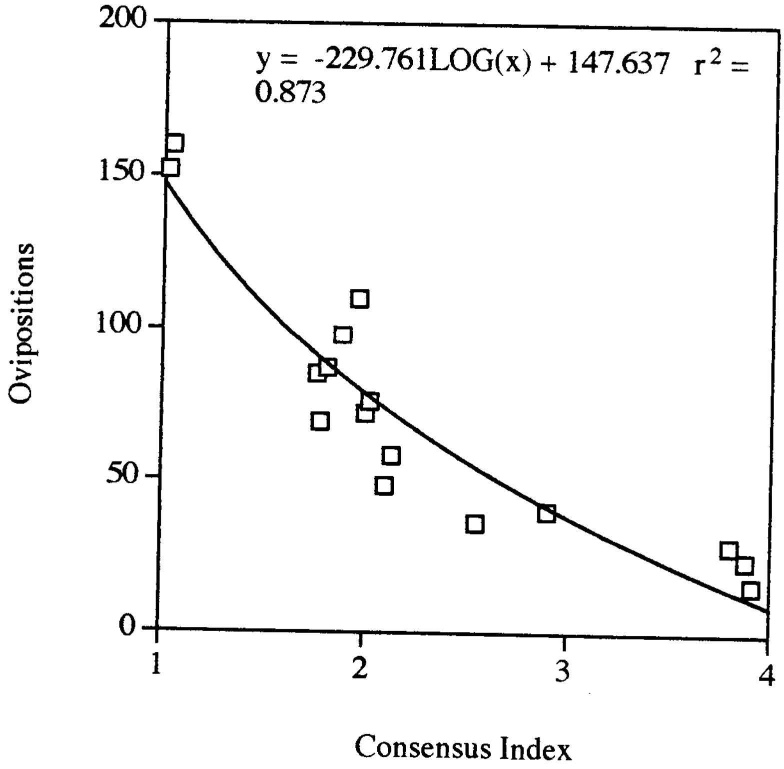
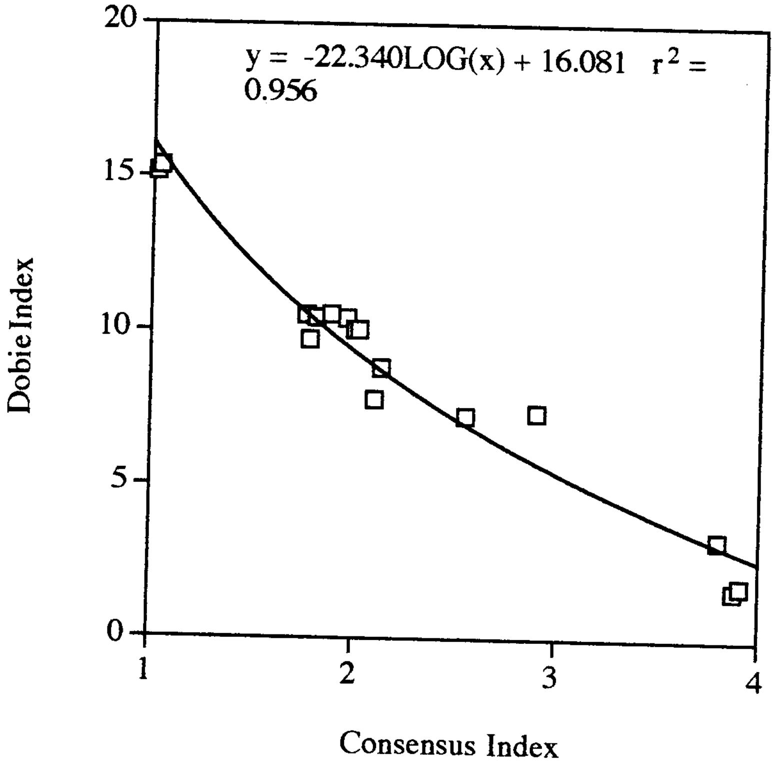

y = -229.761LOG(x) + 147.637 $r^2 =$ 0.873
Ovipositions
200
150
100
50
0
1
2
3
4
Consensus Index

Figure 4.3. Relationship between Farmers' Consensus Index (C.I.) and the susceptibility parameter of the Dobie Index ($R^2 = 0.96$).


y = -22.340LOG(x) + 16.081 r² = 0.956
Dobie Index
Consensus Index
20
15
10
5
0
1
2
3
4

CHAPTER FIVE

GENERAL DISCUSSION

DISCUSSION

This thesis began with a concept of a study within the broad context of the conservation of genetic resources, most specifically in the context of the role of the traditional farmers in generation and maintenance of the various landraces. The field study necessitated collection of information on the landrace attributes, on the farming systems and on the farmers' decision-making processes. The results of specific aspects of these studies, in particular - sorghum landrace variability and classification in north Shewa and south Welo, Ethiopia; environmental factors and the maintenance of sorghum landrace diversity by farmers' selection in Ethiopia; and traditional farmers' knowledge of sorghum landrace storability in Ethiopia: comparison of consensus knowledge with laboratory evaluation of susceptibilities to rice weevils - have been presented, in paper format, in Chapters 2, 3, and 4, respectively. This final chapter presents a broader reflection on the whole study and discusses the results in the context of the importance of the genetic resources present in landraces and the knowledge of traditional farmers to attaining agricultural sustainability.

The schematic diagram (Figure 5.1) outlines the interactions of human and environmental factors contributing to the generation and maintenance of genetic diversity of sorghum landraces in the study area. The environmental, human and biological entities of the agroecosystem of the study area interact and affect each other through different feedback mechanisms creating modalities of co-evolutionary relationship between the crop and farmers. It is clear that farmer selection has influenced the evolution of *Sorghum* landraces and the maintenance and management of these varieties has clearly influenced human culture through the development of sophisticated farming practices. Based on time-tested experiential knowledge and keen observations, farmers use the environmental and biological heterogeneity to meet their varied and often dynamic social, cultural, economic and ecological needs.

Natural Factors, Farmers' Knowledge, and Genetic Diversity

Farmers are creators, managers and primary users of the biological diversity generated on their fields. They have extensive knowledge of their agricultural production systems. Farmers employ multiple strategies to generate and maintain genetic diversity. The generation and maintenance of the immense diversity that we see in the field (Figure 5.1) is not a random occurrence, instead the farmers play a substantial role by applying their understanding of the elements and interactions of the agroecosystem, guided by a relatively sophisticated folk taxonomic classification (Chapter 2, Figure

2.7) , and farming practices and selection criteria (Chapter 3, Figures 3.3, 3.4). One aspect of traditional knowledge - storability (Chapter 4, Figures 4.1, 4.2, 4.3) was remarkably precise in predicting observed insect resistance. This has been done in a manner that is generally consistent with protecting the resource bases of the agricultural fields from irreversible degradative processes.

The subsistence agricultural fields are the production units where crops are grown. These fields provide heterogeneous edaphic, altitude, topographic and climatic resources (Chapter 1; Chapter 3, Table 3.1) which create natural selection pressures in the generation and maintenance of biological diversity. The traditional farmers, who do not have either the external inputs or scientific backing to homogenize the heterogeneity of their fields, use instead the multiple microhabitats to grow a variety of crops. Over the generations they have learned how to meet their varied needs and how to reduce the risks of crop failures. Part of this strategy is the recognized need to maintain a broad genetic base across time and space by using the diversity of the germplasm available. Consequently, the deliberate human selection process is superimposed on the natural pressures and has a substantial role in generating the intraspecific sorghum diversity observed in the fields.

A single landrace does not possess all the attributes needed to meet the requirements of individual farmers, and hence all farmers plant more than one landrace and use a range of the selection criteria appropriate to their requirements when deciding which landraces to grow (Chapter 3). During planting season, farmers select, based on acute observation and experiential learning, the best grains from heads they selected for seed during the previous year's harvest. They either mix and broadcast several landraces in their fields or intentionally sow each landrace in a chosen portion of each field. The farmers' choices during the planting season are determined by the combination of the knowledge they possess of the range of microenvironments, which are variable in terms of soil, water, temperature, altitude, slope, and fertility status, and the criteria which they desire the harvest to satisfy. The genetic diversity resulting from such mixed planting apparently provides the farmers with some degree of protection from the risks of diseases, pests, dry spells, drought and other environmental stresses.

Although farmers have an appreciation for mixtures, the selection of landrace mixtures is conducted according to the desires of individual cultivators. Farmers are interested in individual landrace type, and consequently, selection, exchange and maintenance of sorghum for seed is done at a landrace level rather than as bulk mixtures. Markets are the primary mode for seed exchange among households, villages and regions and break the physical barriers to genetic exchange created by rugged mountains and river valleys.

The seeds obtained from farmer selection and exchange networks become part of the sources of the evolutionary processes of hybridization, gene flow, mutation, and recombination occurring in the field between the crops and their wild and weedy relatives. The natural selection pressure is accelerated and intensified by farming practices which act to increase the variability and genetic diversity available to the farmers. Intercropping, staggered planting, non-clean cultivation, and relaxed weeding are the major farming practices by which farmers intentionally tolerate wild and weedy relatives of sorghum, including *S.aethiopicum* and *S.arundinacium*, to encourage gene flow, to enhance organic matter accumulation, soil conservation and nutrient cycling, and to increase and preserve the natural enemies of the cultivated crop pests. The crops and their wild and weedy relatives coexisted and co-evolved over a long period of time with each other and with the farming practices. Through introgression this has enhanced the adaptive range of the cultivated crops in the field. Consequently, the sorghum population in the field consists of mixtures of genetic lines reasonably adapted to the region in which they are grown.

The landraces differ in their resistances to different races of pathogens (Harlan, 1975b), and to insect pests such as the rice weevils (Chapter 4). Farmers' knowledge of storability is used to reduce the risk of loss of a major food supply as well as of genetic diversity due to storage pest infestations. If the farmers do not know which landraces are resistant and storable or susceptible and non-storable and do not take the necessary storage measures to prevent losses (eg storage of susceptible seeds in roof rafters that receive smoke from cooking fires), there may be serious loss of germplasm and a lesser diversity returned to the fields in the next planting season. Thus, farmers' storability knowledge is part of the process of maintaining genetic variability by knowing which landraces have built-in insurance against the storage pests and other biological stresses and which require special protective measures.

Farmers, through mass selection, grow and use the germplasm for next planting season responsible for most of the biological processes taking place in the fields. Modern plant breeders mimic the traditional farmers' breeding practices except that they follow a single line instead of mass selection and breed in a more deliberate and controlled environment. These traditional farmers can indeed be called farmer-breeders (Harlan, 1975). When farmers select for one agronomic value, they also select simultaneously for other attributes. For example, if a landrace is selected primarily for its yield, then the farmer also looks for associated important features including larger heads, larger seeds, more seeds, better seed set, ease of threshing, and quick maturation before destructive rains set in. Such conscious selection conducted by the farmer increases the statistical chances of survival and perpetuation of a given genotype in the field. For example, a landrace selected for its milling quality (i.e. for making injera) or for making beer survives in the field only if disadvantages it may have in terms of susceptibility to negative natural selection factors are balanced by positive human selection factors, including the activities of transplanting and the use of backup seeds for replanting during poor crop performance. The survival of such a landrace in the heterogeneous agricultural habitats is heavily dependent on farmers' selection pressure and manipulations. Thus, the phenotypic diversity shown in Figure 5.1 represents the interaction of natural factors and the very-long-term application of the conscious multiple selection criteria used by the farmers (Chapter 3, Figure 3.4).

Farmers in north Shewa and south Welo regions of Ethiopia have their own classification system for sorghum landraces. This folk taxonomy is consistent and has apparent utility for making distinction among the sorghum landraces grown by the farmers. There are identifiable agronomic characters incorporated into the folk taxonomy that could be used as a key to understand the driving forces influencing crop evolution (Table 5.1). The folk taxonomy is based on inflorescence, cultivation, palatability, processing, and agronomic quality of each landrace. Both the naming system and selection criteria employed in the folk taxonomy are frequently based on the morphological appearances and agronomic importance of each sorghum landrace grown in the field. The agronomic and nutritive value of each landrace may require laboratory analysis to scientifically confirm the experiential knowledge. For example, out of the world sorghum collection at ICRISAT (1985), a landrace named by the Ethiopian farmers as "wotet begunchie"/"milk in my mouth" has been analyzed to contain high lysine content (Table 5.1), an amino acid that is deficient in most cereal crops. The morphological characters used by the farmers in their folk taxonomy are easily recognizable and their presence does not have destructive effects on the cultivation, yield or use of the landrace (Chapter 2).

The folk taxonomy allows farmers to accurately separate landraces. Confirmation of the value of the folk taxonomy comes from the basing of crop germplasm collections of sorghum for national and international gene banks on the naming systems used by the farmers in their sorghum landrace folk taxonomy. As is the case with farmers in other Vavilovian gene centers, farmers in the study area have subsidized international commercial agriculture through the supply of genes for pest and disease resistance and other characteristics. Unfortunately, the farmers' efforts in developing and maintaining genetic diversity receive little recognition internationally and go unrewarded (IPGRI, 1993; Fowler and Mooney, 1991).

Implications to Agricultural Sustainability, Food Security, and Biodiversity

We are living in a generation where our striving for high agricultural sustainablity makes a higher demand on plant genetic resources. Agricultural sustainability has different goals in traditional agriculture and in the modern so-called "green revolution" (Altieri, 1995; Beets, 1990; Ruthenberg, 1980). Sustainability in traditional agriculture, such as in my study area: has stable yields; grows mixtures instead of monocultures, for reasons of harvest security (Clawson, 1985); uses genetic resistance and integrated pest management (IPM) to control pests rather than using chemicals; and is being practised in heterogeneous and often marginal environments in order to keep food production sufficient for the fast-growing local population. Sustainability in commercial agriculture involves the growing of monocultures (wheat, maize and rice) in homogenized prime agricultural fields with the use of agrochemical inputs for increased yields intended for global markets. The features of agricultural sustainability in the traditional farming systems underline the focus of modern commercial agriculture on using HYVs and modern varieties in optimal and the neglect of marginal and heterogeneous environments (IPGRI, 1995; Frankel et al., 1995), and also for paying less attention to marginal but nutritionally and locally important crop plant species such as legumes and oil seeds. The agricultural sustainability promoted today, however, could benefit from the establishment of a collaborative link between these important systems for the better service of this and the coming generations.

The farmers in north Shewa and south Welo regions of Ethiopia grow a diversity of crops with both intraspecific and interspecific variations (Chapter 1, Table 1.2), in marginal and heterogeneous environments. This strategy, evolved over generations, acts to minimize risk, stabilize yields over a long period of time, and maximize returns in the absence of external purchased inputs. The conservation and use of the intraspecific diversity (Figure 5.1; Appendix 1) is the primary concern of IPGRI (1993). IPGRI's concern is based on the conviction that intraspecific variations, such as within sorghum, are the key to the reproduction, survival, and adaptation of a cultivated species in the ecological dynamics of pests and diseases, edaphic and climatic processes.

The farming systems that conserve high levels of genetic diversity are, however, subject to pressures for change stemming from demographics, agricultural policies, extension services, commercial interests, and national and international research programs. This change has resulted in a global loss of the genetic diversity maintained by the farmers. According to IPGRI (1995) genetic erosion remains an actual and potential threat in all farming systems, and, with changing social and economic structures and the loss of genetic diversity, the farmers' knowledge which has developed and maintained the diversity may not be passed on, and will be lost forever.

In light of the current food production and environmental degradation challenge facing world agriculture, concern about loss of biological diversity is well founded. Reasons for the concern and approaches to conservation of diversity, however, vary considerably. The modern cultivars, particularly the HYVs, are primarily blamed for the losses of biodiversity in the traditional agricultural systems by displacing these systems entirely or the traditional varieties within these systems (Frankel, 1974; Frankel et al., 1995). *In situ* (i.e. conservation of cultivated plants in an environment where they originated, evolved, and diversified) and *ex situ* (i.e. conservation of cultivated plants in an environment other than those in which they originated, evolved, and diversified) conservation strategies are designed to conserve and use the biological diversity in the traditional agricultural systems around the world.

In the *ex situ* conservation strategy, the landraces that contribute to genetic diversity should be conserved in botanical gardens, and national and international gene banks to be used as essential raw material for plant breeding in industrial agriculture (Frankel and Soul, 1981; Plucknett et al., 1987). The *ex situ* conservation approach is interested in the genetic information encoded in the DNA of the landraces and pay no attention to the knowledge, farming practices, and traditional systems that generated and maintained over generations the biological diversity.

Contrary to this approach, diversity in the traditional farming systems is considered as part of the livelihood of the traditional farmers and thus should be conserved in an *in situ* conservation strategy as valuable sources of agronomic, social, and cultural benefits for the local farmers (Brush, 1991, 1995). In this view, *in situ* conservation can be used not only as a back up to *ex situ* conservation, but also to study crop evolution and its direction, forces of selection, crop ancestry, and the genetic structures, compositions, and functions of the existing crops in the field. Such *in situ* conservation efforts should be linked to rural development by taking into account the ethnobotanical knowledge of the farmers (Altieri et al., 1987).

Conservation efforts, therefore, should not only preserve the genetic information encoded in the DNA of the landraces but should also retain the knowledge of nutrient cycling, soil conservation, natural pest control, selection, cultivation, storage, seed saving, taxonomy and usage of the crop plants along with their weedy and wild relatives and the cultural values embodied in them. The quantified empirical evidence in this research demonstrates clearly that: as the number of farmers' selection criteria increases diversity increases; farmers understand the adaptation of their crops to the heterogeneous environmental factors of the agricultural fields; farmers have a highly reliable knowledge of germplasm storability, and their folk taxonomy is consistent with the modern numerical taxonomy. Based on my results, I call for increased recognition of traditional farmers' role in genetic diversity. Their knowledge adds to the knowledge of the scientific community, particularly as to how farmers generate, select, and maintain diversity in their fields. This traditional knowledge has distinct benefits for present and future generations. Furthermore, substantial efforts should be made to recognize, test, preserve, and make available, where it is applicable, the traditional knowledge in order to develop dynamic and appropriate agricultural strategies which are sensitive to the complexities of biophysical and socioeconomic processes and tailored to the challenges of today's agricultural sustainability, food security and biodiversity at the local and regional levels. The recognition of their roles and self-interest in the generation and maintenance of crop genetic resources may encourage traditional farmers to continue to diversify, maximize and stabilize production in the highly marginal and heterogeneous agricultural habitats. It may also allow modern commercial agriculture to become less dependent on harmful and expensive agricultural inputs and boost its yield on a sustainable basis by using the genetic variations generated and maintained by the traditional farming systems. The link and collaboration between traditional and modern systems may help address the issues of agricultural sustainability, food security and biological diversity at all of the local, regional and global levels.

Table 5.1. Examples of Vernacular Names of Some *Sorghum* Landraces and Their Translations.

Vernacular Name	Translations and Remarks
Aeyfere	"fearless"..to drought and other environmental stresses.
Afeso	Bumper crop, High yielding
Bakelo	Like beans; has big grains like horse beans (*Phaseolus)*
Betenie	Loose panicle, difficult for birds to land and eat the grain
Ganseber	"Pot breaker"; ferments very well to make good beer
Gubetie	Liver appearance and texture
Marchukie/Barchkie	Tastes like honey; oozing honey
Mognayakish	"Fool can not identify you"; is a juicy sorghum with confusing morphological similarities with a grain-producing sorghum landrace
Wofe aeybelash	Bird resistant, due to its big grain size, bitter taste, and total glume cover
Wotet begunchie	"Milk in my mouth"; high lysine content***

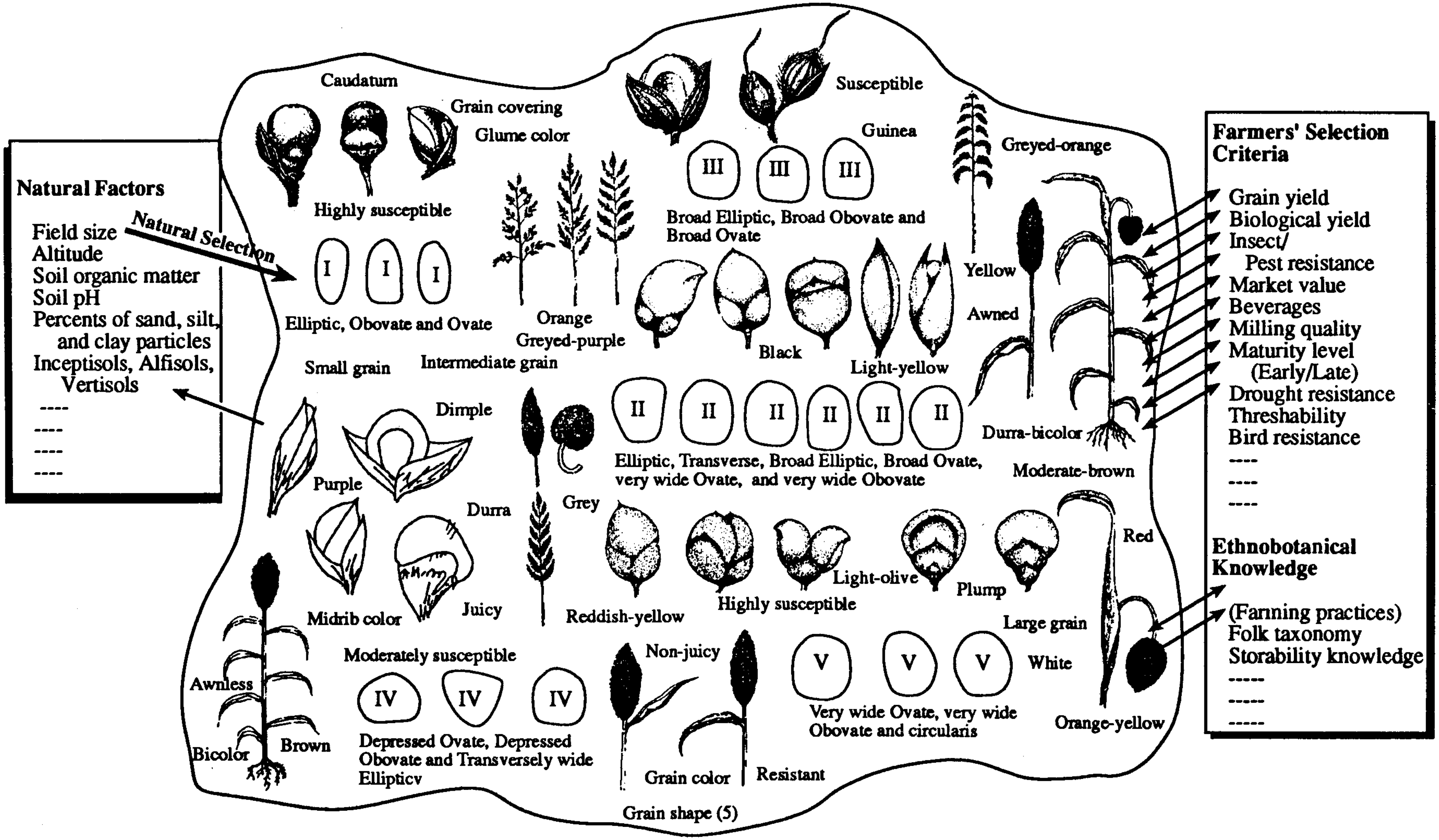
****High lysine content has been analyzed by ICRISAT (1985)

Table 5.1. continued. Examples of Vernacular Names of Some *Sorghum* Landraces and Their Translations.

Vernacular Name	Translations and Remarks
Yegenfo ehil	Porridge grain; super processing and palatability of porridge for pregnant, and lactating mothers and children
Yekermendaye	"Never mind about my wage"; because of the irresistible taste, one will compromise to trade his/her wage for this genotype. It is eaten fresh green
Yekersolatie	"Never mind about the prayer"; a Moslem will give up his/her prayer to enjoy this particular genotype. It is eaten fresh green.
Yeshet ehil	A landrace grown for green consumption, to bridge between the growing and harvesting season of the grain-forming landrace

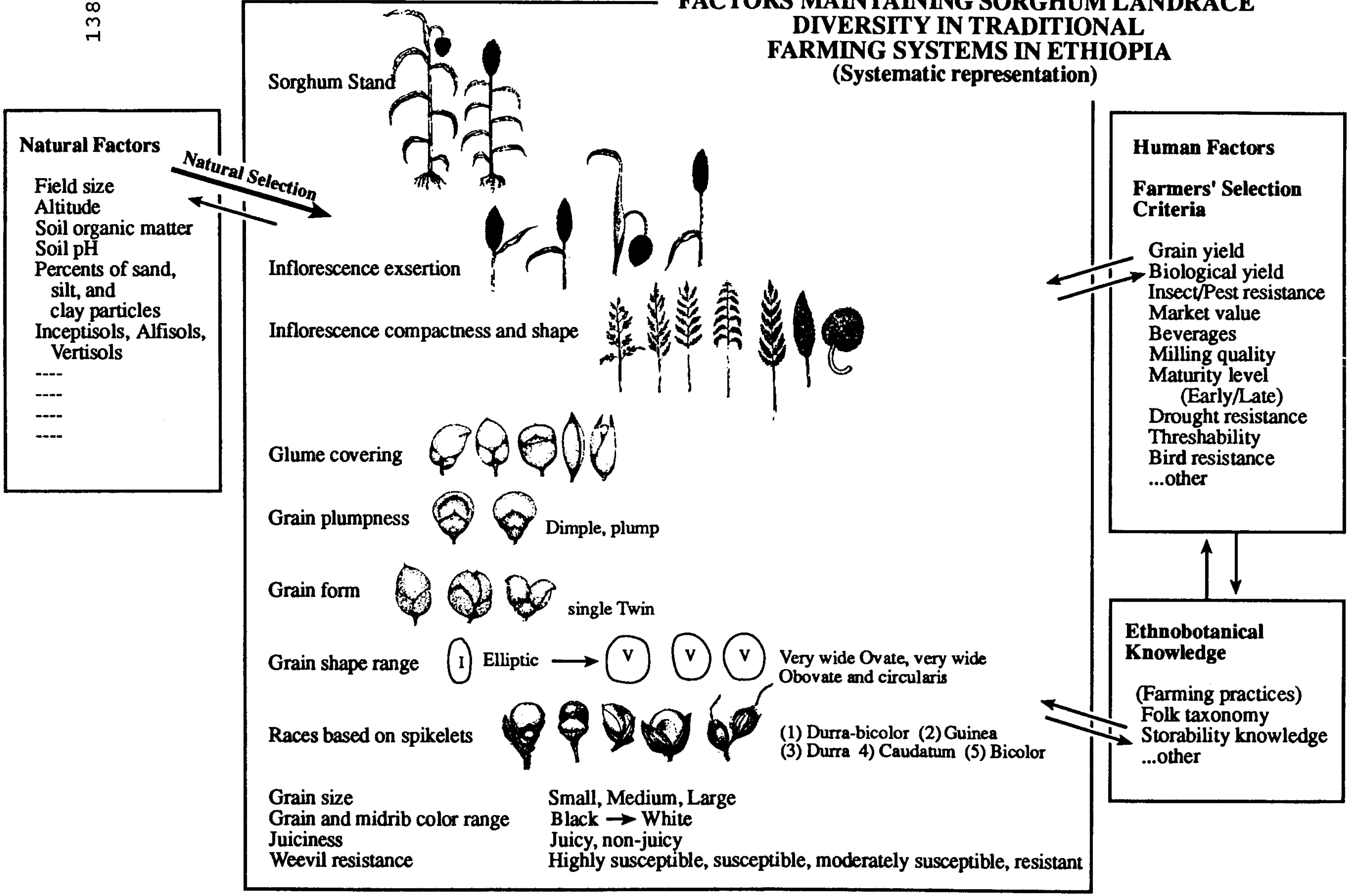
Figure 5.1a and 5.1b. Factors Maintaining Sorghum [*Sorghum bicolor (L.) Moench]* Landrace Diversity in north Shewa and south Welo regions of Ethiopia. The interaction of natural and human factors are shown how they generate and interact with biological diversity in the study area.

FACTORS MAINTAINING SORGHUM [Sorghum bicolor(L). Moench]LANDRACE DIVERSITY IN ETHIOPIA (Field diversity simulation)



FACTORS MAINTAINING SORGHUM LANDRACE DIVERSITY IN TRADITIONAL FARMING SYSTEMS IN ETHIOPIA

(Systematic representation)



Appendix 1. Allocation of *Sorghum* landraces by Modeclus into three clusters according to stem juiciness and grain plumpness membership criteria.

	NON-JUICY LANDRACES		JUICY LANDRACES			
	Cluster 1		Cluster 2		Cluster 3	
Landrace accessions	Dimple	Plump	Dimple	Plump	Dimple	Plump
Abaerie	x					
Abaerie	x					
Adow				x		
Aehyo	x					
Aehyo	x					
Aehyo	x					
Aehyo	x					
Aehyo	x					
Aeyfere	x					
Afeso	x					
Afeso	x					
Afeso	x					
Afeso	x					
Amelsi						x
Bakelo	x					
Barchukie	x					
Brachukie			x			
Barchukie	x					
Basohe					x	

Appendix 1...continued. Allocation of *Sorghum* landraces by Modeclus into three clusters according to stem juiciness and grain plumpness membership criteria.

	NON-JUICY LANDRACES		JUICY LANDRACES			
	Cluster 1		Cluster 2		Cluster 3	
Landrace accessions	Dimple	Plump	Dimple	Plump	Dimple	Plump
Betenie						x
Borie	x					
Borie	x					
Borie	x					
Buskie	x					
Buskie	x					
Cherekit				x		
Cherekit				x		
Cherekit				x		
Chomogo	x					
Chomogo		x				
Delgome				x		
Delgome				x		
Delgome				x		
Dekussie						x
Dekussie						x
Dobie	x					
Dobie	x					
Dobie	x					

Appendix 1... continued. Allocation of *Sorghum* landraces by Modeclus into three clusters according to stem juiciness and grain plumpness membership criteria.

	NON-JUICY LANDRACES		JUICY LANDRACES			
	Cluster 1		Cluster 2		Cluster 3	
Landrace accessions	Dimple	Plump	Dimple	Plump	Dimple	Plump
Ganseber	x					
Ganseber	x					
Ganseber	x					
Ganseber				x		
Ganseber				x		
Gedalit	x					
Gedalit	x					
Gedalit	x					
Gedalit	x					
Gedalit	x					
Gorade	x					
Gorade	x					
Gorade	x					
Gorade	x					
Goronjo	x					
Goronjo	x					
Goronjo	x					
Goronjo	x					
Gubete	x					

Appendix 1. ..continued. Allocation of *Sorghum* landraces by Modeclus into three clusters according to stem juiciness and grain plumpness membership criteria.

	NON-JUICY LANDRACES		JUICY LANDRACES			
	Cluster 1		Cluster 2		Cluster 3	
Landrace accessions	Dimple	Plump	Dimple	Plump	Dimple	Plump
Gubete			x			
Gubete	x					
Jamuye	x					
Jamuye	x					
Jegretie	x					
Jemaw	x					
Jemaw	x					
Jemaw			x			
Jemaw			x			
Jemaw	x					
Jiru	x					
Jiru	x					
Jiru	x					
Jiru	x					
Jiru	x					
Jiru tk						x
Jofa tk						x
Jofa tk						x
Jofa tk						x

Appendix 1...continued. Allocation of *Sorghum* landraces by Modeclus into three clusters according to stem juiciness and grain plumpness membership criteria.

	NON-JUICY LANDRACES		JUICY LANDRACES			
	Cluster 1		Cluster 2		Cluster 3	
Landrace accessions	Dimple	Plump	Dimple	Plump	Dimple	Plump
Keyo tk						x
Keyo tk						x
Kumie	x					
Keteto				x		
Keteto				x		
Kilo				x		
Kilo				x		
Kilo				x		
Kilo				x		
Mali tk						x
Megali tk						x
Meltae	x					
Meltae	x					
Meltae	x					
Merabete				x		
Merabete				x		
Merabete				x		
Mogayefere	x					
Mognayakish						x

Appendix 1...continued. Allocation of *Sorghum* landraces by Modeclus into three clusters according to stem juiciness and grain plumpness membership criteria.

	NON-JUICY LANDRACES		JUICY LANDRACES			
	Cluster 1		Cluster 2		Cluster 3	
Landrace accessions	Dimple	Plump	Dimple	Plump	Dimple	Plump
Mognayakish						x
Mognayakish						x
Mognayakish						x
Mokakie	x					
Mokakie	x					
Mokakie	x					
Mokakie	x					
Motie					x	
Motie					x	
Motie					x	
Motie						x
Necho tk						x
Necho tk						x
Necho tk					x	
Necho tk					x	
Nchero				x		
Nchero				x		
Nchero				x		
Nchero				x		

Appendix 1...continued. Allocation of *Sorghum* landraces by Modeclus into three clusters according to stem juiciness and grain plumpness membership criteria.

	NON-JUICY LANDRACES		JUICY LANDRACES			
	Cluster 1		Cluster 2		Cluster 3	
Landrace accessions	Dimple	Plump	Dimple	Plump	Dimple	Plump
Rayo	x					
Senklie	x					
Serergie						x
Serergie						x
Tenglaye	x					
Tenglaye	x					
Tenglaye	x					
Tenglaye	x					
Tuba	x					
Tuba	x					
Tuba tk						x
W/aeyblash	x					
W/aeyblash	x					
W/aeyblash	x					
W/aeyblash				x		
Wanesie			x			
Wanesie			x			
Wanesie			x			
Watigela	x					

Appendix 1...continued. Allocation of *Sorghum* landraces by Modeclus into three clusters according to stem juiciness and grain plumpness membership criteria.

	NON-JUICY LANDRACES		JUICY LANDRACES			
	Cluster 1		Cluster 2		Cluster 3	
Landrace accessions	Dimple	Plump	Dimple	Plump	Dimple	Plump
Watigela	x					
Watigela	x					
Wogere	x					
Wogere	x					
Wogere	x					
Wogere	x					
Wogere	x					
Wogere tk						x
Wuncho	x					
Wuncho	x					
Wuncho	x					
Wuncho		x				
Yegenfoehel				x		
Yekermendaye	x					
Yekermendaye	x					
Yekermendaye	x					
Yekermendaye				x		
Yekersolatie				x		
Yekersolatie			x			

Appendix 1. Continued. Allocation of *Sorghum* landraces by Modeclus into three clusters according to stem juiciness and grain plumpness membership criteria.

	NON-JUICY LANDRACES		JUICY LANDRACES			
	Cluster 1		Cluster 2		Cluster 3	
Landrace accessions	Dimple	Plump	Dimple	Plump	Dimple	Plump
Yekersolatie	x					
Yekersolatie	x					
Zengada	x					
Zengada	x					
Zengada	x					
Zengada	x					
Zengada	x					
Zengada	x					
Zengada	x					
Zengada		x				
Zengada tk						x
Zengada tk						x
Zengada	x					
Zengada	x					
Zengada	x					
Zengada	x					
Zengada	x					
Zengada	x					
Zengada	x					

Appendix 1...continued. Allocation of *Sorghum* landraces by Modeclus into three clusters according to stem juiciness and grain plumpness membership criteria.

	NON-JUICY LANDRACES		JUICY LANDRACES			
	Cluster 1		Cluster 2		Cluster 3	
Landrace accessions	Dimple	Plump	Dimple	Plump	Dimple	Plump
Zengada	x					
Zengada	x					
Zengada	x					
Zengada			x			
Zeterie				x		
Zeterie			x			

tk="Tinkish"=Sweet stalk

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