This is to certify that the
thesis entitled

IDENTIFICATION OF DROUGHT RESISTANCE IN LARGE
SEEDED COMMON BEAN GENOTYPES

presented by

ESTEBAN FALCONI

has been accepted towards fulfillment
of the requirements for the

M. S. degree in PLANT BREEDING AND GENETICS

James D. Kelly
Major Professor's Signature

Nov 13, 2005
Date

IDENTIFICATION OF DROUGHT RESISTANCE IN LARGE SEEDED COMMON BEAN GENOTYPES

By

Esteban Falconí

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Plant Breeding and Genetics Program – Department of Crop and Soil Sciences

2005

ABSTRACT

IDENTIFICATION OF DROUGHT RESISTANCE IN LARGE SEEDED COMMON BEAN GENOTYPES

By

Esteban Falconí

The bean production areas in Ecuador are subject to intermittent drought and the available irrigation systems do not always provide the minimum water requirements of the bean crop resulting in yield and economic losses. Selection for drought tolerance in common bean (*Phaseolus vulgaris* L.) should be considered as the most practical strategy to help stabilize bean production. The objectives of this study were to: i) evaluate 16 bean genotypes and an inbred backcross line (IBL) population for drought resistance under field conditions in Michigan and Ecuador, ii) compare bean root systems in the greenhouse to identify root traits associated with superior performance under drought stress in the field.

Five genotypes in the IBL population were selected based on high geometric mean (GM) yield in the field, yield under stress, seed weight, and seed quality. The selected genotypes will be further evaluated in Ecuador. Genotypes showing drought resistance and commercial traits were also selected as parents to develop new IBL populations to evaluate under Ecuadorian conditions.

Low correlations were observed between GM yield and root traits measured in 1m-long PVC tubes in the greenhouse. The tube methodology did permit the identification of genetic differences in root traits among genotypes grown under stress conditions.

Dedication:
In memory of my father, Angel Falconí

ACKNOWLEDGMENTS

I want to express my gratitude to Dr. James D. Kelly, my major advisor, for the help, understanding, and knowledge that I received from him during my stay at Michigan State University.

Special thanks to my guidance committee: to Dr. Widders for the time and direction he dedicated to my project, and to Dr. Snapp and Dr. Hancock for their valuables suggestions during my research. My admiration, respect, and appreciation for all of them.

Thanks to the dry bean lab, Halima E. Awale, Veronica Vallejo, Karolyn Terpstra, Ann Armenia, Evan Wright, Shitaye Moges, Norm Blakely, and Brian Long. Thanks for all the assistance, support, and good times.

I wish to thank the Legume Program in Ecuador (PRONALEG) with all its members, Angel Murillo, Mary Batallas , Nelson Mazón, Cristian Subia, Paola Estrella, Juan Ocaña, Marco Rivera, and specially to Ing. Eduardo Peralta and José Pinzón for their friendship and help.

Finally, I wish to thank my beloved family, my father Angel, my mother Yolanda, my brothers Santiago and Pablo, my aunt Maria Augusta, and my cousins Soledad, Johanna, and Juan José. Thank you for all the support, understanding, encouragement, and love.

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KEY OF ABBREVIATIONS

AM	Arithmethic Mean
ANOVA	Analysis of Variance
CBB	Common Bacterial Blight
CIAT	International Center for Tropical Agriculture
CV	Coeficient of Variance
dap	Days after planting
DII	Drought Intensity Index
DS	Desirability Score
GM	Geometric Mean
HI	Harvest Index
IBL	Inbred Backcross Line
INIAP	National Institute of Agricultural Research - Ecuador
LSD	Least Significant Difference
MAS	Marker Assisted Selection
masl	Meters Above Sea Level
NSL	Negro San Luis
PRONALEG	National Legume Program of INIAP-Ecuador
QTL	Quantitative Trait Loci
r	Pearson Correlation Coefficient
RCBD	Randomized Complete Block Design
RIL	Recombinant Inbred Line
SSD	Single Seed Descent
SSI	Stress Susceptibility Index
Xp	Mean yield under non-stress conditions
Xs	Mean yield under moistures stress conditions
Yp	Yield under non-stress conditions
Ys	Yield under moisture stress conditions

INTRODUCTION

From an agricultural perspective, drought is a condition in which water supply is insufficient to meet the needs of the crop. As a result of the reduction in soil moisture, plants suffer water stress and yield is reduced (Subbarao et al., 1995). Two different kinds of drought, intermittent and terminal, can be distinguished. Intermittent drought is due to climatic patterns of sporadic rainfall that cause intervals of drought and can occur at any time during the growing season (Schneider et al., 1997). A similar effect occurs when farmers have the option of irrigation, but water supply is limited. In contrast, terminal drought occurs when plants suffer lack of water during the later stages of development, mainly during reproductive growth (Frahm et al., 2004; Acosta-Gallegos and Kohashi-Shibata, 1989). An example of terminal drought occurs in Central America when common bean is planted toward the end of the first rainy season and water supply is insufficient to support yield.

Lack of water interferes especially with the normal metabolism of plants during flowering and pod-fill, since these are the stages when water deficits cause the greatest yield reduction (Halterlein, 1983; Thung and Rao, 1999). According to Singh (1992) the water requirements for a bean crop is at least 400 mm. In semi-arid production areas that lack adequate amounts of water (< 400 mm) (Thung and Rao, 1999), and have sandy soils with low organic matter content, water holding capacity is limited, so bean yields are reduced further (Acosta and Adams, 1991). Furthermore, drought is intensified by other factors such as high temperatures, presence of root pathogens, and low soil fertility (Singh and White, 1988).

Plant adaptation strategies to drought. Drought adaptation is the ability of plants to thrive and produce more biomass and seed, compared with non-adapted plants growing in the same water-limited environment (Hall, 1993). This adaptation is the result of an evolutionary process that allows specific genotypes to survive in areas with low precipitation. Common bean and plants in general have developed different adaptation strategies in response to the environmental conditions where they grow. These strategies allow plants to be more competitive in terms of water use, utilization of light and/or nutrients, and successful in terms of producing progeny under adverse conditions. In the specific case of environments with water deficits, plants have developed different strategies to perform better than other cultivars or different species. These strategies, according to Ludlow (1989), are recognized as escape, avoidance, and tolerance mechanisms.

Escape strategy. Plants exhibiting this strategy are able to complete their life cycle in shorter periods of time by taking advantage of the available water. With seasonally limited amounts of water, plants maximize water use efficiency and complete seed production early. Ludlow (1989) describes the important characteristics of plants that base their survival on escape as rapid germination after rainfall, fast growth, early flowering and seed production before the water supply is exhausted.

Some annual crops also use this strategy. One example in common bean is the cultivar “Bola 60”, which has a shorter vegetative and reproductive cycle than other common bean cultivars planted in the Andean region. However, this strategy is usually associated with low yields in most cultivars because the shorter vegetative growth period prevents maximum seed production. Subbarao et al. (1995) reported that earliness reduces the potential yield by reducing dry matter before flowering and the number of sites for post-anthesis seed filling. Reduction of potential yield is the penalty for individual early-maturing plants. However, an increase in plant density can be considered as an approach to compensate for the limited productivity of individual plants. Certainly, more plants will be competing for reduced amounts of water, but the efficiency of crop utilization of water may be improved, since less soil surface is available for evaporation. This strategy could be applied to certain crops and deserves further examination. Ludlow (1989) also suggested that some crops, such as pearl millet, show developmental plasticity in dry areas. Plasticity, as defined by Acosta-Gallegos and White (1991), is an adaptative feature to highly variable rainfall at the beginning and during the rainy season in semi-arid regions. Adapted crops have the ability to flower and produce seed after short periods of rain. Acosta-Gallegos and White (1995) identified common bean genotypes such as 'Pinto Villa' from the Mexican highlands that showed phenological plasticity.

Avoidance strategy. Plants that use avoidance strategies maximize water uptake or minimize water loss by different mechanisms (Acosta-Gallegos et al., 1996). Traits associated with avoidance include the development of deep tap roots, stomatal regulation, compact canopies, small leaves, paraheliotropic leaf movements, and thick cuticles. One of the most important water stress avoidance mechanism is deep rooting (White and Castillo, 1989). This allows plants to reach water at depth. This feature has been widely studied and there is evidence that differences exist among common bean genotypes for this trait (Yabba and Foster, 1997). Incorporating this important characteristic into commercial common bean cultivars through breeding appears promising, however, the energy that the plant is investing in the developing deep roots could negatively affect yield. Hence, breeders should consider developing root architecture ideotypes able to reach deeper soil layers without losing the nutrients in the top soil and without wasting energy that should go to seed production.

Stomatal regulation is another feature used by plants to maximize water use efficiency. Once the stomata are open, transpiration occurs and photosynthesis takes place. As a result of photosynthesis, plants accumulate biomass. The risk is that plants can experience excessive water loss during the day and suffer water stress. To prevent the consequences of the stress, plants should maintain internal plant water status above critical threshold levels (Subbarao et al., 1995). Selecting genotypes able to control transpiration in an efficient manner would be useful, provided that adequate variability exists for this trait in common bean germplasm. Aguirre et al. (2002) reported that bean genotypes with larger stomatal index in the abaxial than in the adaxial surface exhibited less gas exchange compared with the variety Bayo Madero, which had the same stomatal index on both leaf surfaces. This study suggests that transpiration could be regulated when fewer stomata are present in the abaxial region. Transpiration could be regulated without reducing yield through biochemical control as well. Itai and Birnbaum (1991) reported that plant hormones production under stress conditions are related with the increase in stomata resistance. Aguirre (1999) studied stomatal response to stress in common bean using a split-root system. This experiment demonstrated that signals originating in the roots under water stress controlled the stomatal aperture in the leaves. The system appears useful for conducting studies designed to select more efficient common bean genotypes with optimum regulation of stomatal opening. Only one cultivar, Cacahuate 72, was used in this study and more bean genotypes would need to be studied to investigate if genetic differences exist among genotypes.

Although White and Castillo (1989) reported that root characteristics of common bean are the major factors responsible for plant response to drought, shoot traits have also been described that confer avoidance capabilities when water is limiting. These characteristics include leaf pubescence, small leaves, a thick cuticle layer, number of stomata, and paraheliotropic movements of the leaves (Aguirre-Medina et al., 2002; Berg and Hsiao, 1986; and Ludlow, 1989). Characteristics such as leaf size, shape and thickness deserve further study, but may be linked to seed size. Large genetic variability in leaves can be found among the common bean germplasm. Characteristics such as leaf pubescence and thick cuticle may not affect yield to the same degree as other traits that demand larger amounts of energy.

Tolerance. This strategy refers to the ability of the plant to maintain metabolic activity under low water availability. Kohashi-Shibata et al. (2002) demonstrated that the cultivar Pinto Villa, identified as drought resistant, is less affected by water stress, and that leaves of Pinto Villa continue to grow faster than those of cultivar Bayo Madero under the same stress conditions. Certain compounds are responsible for maintenance of cell membrane integrity and cell proteins during stress periods. These compounds include the amino acids proline, betaine and glycine (Showalter, 1993). Osmotic adjustment is an additional characteristic that allows certain genotypes to retain water and thus avoid dehydration. When water availability is low, osmotic adjustment aids in the maintenance of turgor by producing organic compounds in the cell that facilitate the uptake of water through differences in osmotic potential. The plant is able to continue normal functions such as carbon acquisition through open stomata, and root growth under stress. Eventually, if conditions allow, the roots will reach deeper soil layers where more moisture is available. According to Ludlow (1989), no particular yield reductions have been identified in plants with tolerance, however, this strategy does not necessarily allow more carbon fixation than the avoidance strategy.

Breeding for drought resistance.- Important drought resistance sources of common bean have been identified in races Durango and Mesoamerica germplasm (Singh, 1995). Unfortunately, single crosses with large-seeded Andean races would result in genotypes with phenotypes lacking commercial characteristics. The Ecuadorian market demands large seeds that differ from the majority of Mesoamerican seed classes. The Inbred backcross has been suggested as a breeding method to recover commercial plant and seed characteristics in crosses between Mesoamerican and Andean beans (Beaver, 1999). Bliss (1993) proposed "The Inbred Backcross Line Method of Breeding" to develop populations with genotypes possessing genes from promising donors in a background of well adapted germplasm. The method seems practical to develop new drought resistance bean cultivars for Ecuador, because the materials obtained, after two or more backcrosses, are phenotypically similar to the recurrent parent while maintaining sufficient variability for the trait being improved since no selection is applied until obtain homozygous lines in the population. Interracial populations should result in progress toward obtaining new cultivars with high levels of drought resistance in Andean plant and seed phenotypes.

Evaluation in the field.- Several studies have been conducted to select for drought resistance in common bean (Frahm et al., 2004, Schneider et al., 1997b, and Singh, 1995). Direct selection in the stress environment characterized by low rainfall is the most common method of selection for drought resistant genotypes. This method consists of selection of the highest yielding genotypes subjected to water stress. The method is considered highly accurate since performance is measured in the stress environment, however, this method exhibits some limitations. One difficulty is the large numbers of accessions that need to be evaluated in the field for drought resistance. If the parameter for selection is yield, the plots must be large enough to get accurate information. In addition, drought periods can be erratic in some locations, so entire tests could be lost when dry periods do not occur. This problem slows breeding progress since the differences in yield of the genotypes evaluated under stress conditions could be masked by seasonal and location interactions (van Ginkel et al., 1998). Ramirez-Vallejo and Kelly (1998) conducted a drought study over two years (1988 and 1990). In 1988 the authors observed significant differences between genotypes in the traits studied, whereas in 1990 no significant differences were observed among treatments. One difficulty in detecting genotypic differences result from variable soil type and moisture conditions that that may affect the results. Moreover, since yield is the selection criteria, yield under stress might be also a function of other cultural management practices that may be interacting with drought stress. For these reasons, spatial and temporal limitations are problems that bean breeders face in direct screening for drought tolerance.

In the field, the most effective method to select drought resistant common bean genotypes is evaluating for yield under stress and non stress conditions. These trials provide information on both potential yield and yield under stress. To estimate the intensity of the stress in individual experiments, the drought intensity index can be calculated (DII) (Ramirez-Vallejo and Kelly, 1998). DII= (1-Xs/Xp), where Xs is the experiment mean under stress conditions, and Xp is the experiment mean under non-stress conditions. Additionally, the DII can be used to compare the stress imposed between two or more experiments conducted in different years or locations. Using data on yield under non-stress and water stress, Ramirez-Vallejo and Kelly (1998) suggested that the most effective selection for drought resistance is based first on those genotypes with high geometric mean (GM) yield followed by the selection of the genotypes with high-yielding individuals with low to moderate levels of drought susceptibility index. Schneider et al. (1997) used a similar breeding strategy, selecting first on high a GM yield followed by selection on yield in stress environment. Geometric mean yield is calculated as the square root of the product of yield under stress and non-stress. (GM= $(YpxYs)^{1/2}$), where, Yp is the potential yield and Ys is the yield under stress conditions of each genotype. Geometric mean yield identifies genotypes with high yield under stress and non-stress conditions without the influence of extreme values since the result is normalized through the use of the square root. The use of the GM yield requires two treatments, one under normal conditions with supplemental irrigation (potential yield) and other under stress conditions. Other selection criteria have been proposed such as the selection based on the mean yield [Yx = (Yp + Ys)/2], or the drought susceptibility index [DSI = [(1 – (Ys/Yp)]/DII] (Fisher and Maurer, 1978). However, Fernandez (1993) showed that mean yield favored the genotypes with high yield potential under non-stress and DSI failed to differentiate drought tolerant genotypes with high and low yield potential.

Indirect evaluations.- Field evaluations under local conditions in production areas are the most accurate source of information on genotypic performance. However, the unpredictable nature of the rainfall has forced breeders to consider alternative ways to evaluate genotypes and, under controlled environments, select for genotypes showing drought resistance. These approaches attempt to identify traits that could confer the drought resistance in plants and reduce the impact of drought on plant performance (Ludlow and Muchow, 1990, van Ginkel et al., 1998).

One plant organ with the greatest influence on drought resistance in common bean is the root system. Root parameters, which are highly correlated with drought resistance (White and Castillo, 1989), have been the subject of many studies. Yabba and Foster (1997) used growth pouches in a growth chamber to study root traits in eight common bean genotypes with different performance under drought stress. In this study, the drought resistant genotype BAT 477 produced less number of lateral roots compared with the other genotypes under study, but a deeper taproot helped to avoid the effect of water stress. The conclusion was supported by the findings of Gregory (1994), who showed that BAT 477 has a deeper taproot than susceptible genotypes under stress conditions. Using the pouch methodology, Frahm et al. (2003) evaluated a population of 81 recombinant inbred lines (RILs), but did not find significant differences between drought resistant and susceptible RILs. Probably, the pouch method did not allow sufficient time for root growth to develop significant differences between genotypes. An indirect method to study roots and the effects under both stress and non-stress conditions in alfalfa (*Medicago sativa* L.), was developed by Pennypacker et al. (1990). Plants were grown in 0.9 m tall by 0.2 m diameter containers. Using tensiometers to monitor and control water availability, the authors were able to impose a gradual drought stress and at the same time collect information on different plant growth parameters. Selection for deep taproots under artificial conditions appeared to be a promising approach to identify drought resistant genotypes.

Caution should be exercised when root parameters. Kramer and Boyer (1995) documented how environmental factors (soil texture, structure, aeration, temperature, competition, and mineral content) can affect root growth. Roots are highly plastic, and morphology can change significantly depending on the substrate and the container used. Such factors could explain the frequent observance low correlations between field and greenhouse results. Researchers must recognize these factors and develop screening systems that are highly correlated with field performance of common beans. Ogbonnaya et al. (2003) used a hydroponics method to select cowpea genotypes for drought resistance. The authors found significant correlations between yield and biomass production, shoot-root ratio, and root growth under well-watered conditions. However, under water stress conditions there were no correlations between these variables. Apparently, the hydroponic low oxygen environment altered normal root growth morphology and distribution.

The use of molecular markers is another indirect option that could be applied in the selection of drought resistant common bean genotypes. Schneider et al. (1997b) found correlations between molecular markers and drought resistance based on high geometric means, for two RILs in Michigan, however, there were no significant correlation between the geometric mean and the markers were not detected in the same population tested in Mexico. Frahm et al. (2003) screened the same markers in a black-seeded bean RIL population but obtained low correlation with yield under stress. A probable reason for low correlation could be that the mechanisms of drought resistance linked to the marker are only effective in specific environments.

Molecular markers that explain a large portion of the phenotypic variation that confers drought resistance in a broad range of semi-arid environments will become a powerful selection tool. The effectiveness of marker assisted selection (MAS) is inversely proportional to the heritability of the trait under consideration (Paterson et al., 1990). Therefore, MAS could facilitate the selection of traits such drought resistance with low to moderate levels of heritability ($h^2 = 0.19$ to 0.59; Scheider et al., 1997b; $h^2 = 0.09$ to 0.80; Acosta-Gallegos et al., 1996).

Babu et al. (2003) observed a QTL in rice which explained a high percentage of the variability in yield under stress conditions. This region of the genome was associated with root traits related to drought resistance in rice. Identification of QTLs is a challenge since the QTLs may be affected by the environment (Collard et al., 2005) since complex analyses and effort are required to identify them (Staub et al., 1996). Once QTL are identified the efficiency of MAS can be greater than through direct selection. To date, there are no new drought resistant cultivars developed using molecular techniques, and more research is needed to enable breeders to effectively utilize molecular approaches. Tuberosa et al. (2002) is optimistic when he stated that QTL analysis that detects morphological and physiological traits related with the adaptation to drought conditions can be integrated in plant breeding programs to develop improved cultivars.

More traits indirectly correlated to drought resistance should be used to select putative resistant genotypes. Ramirez-Vallejo and Kelly (1998) studied yield components, biomass and partitioning traits under stress and non stress conditions. Harvest index (HI) measurement was considered due to the high correlation with yield, but was thought to be no more useful than yield data since HI is a product of yield influenced by the environment. The authors also found a significant correlation between stem diameter and biomass traits ($r=0.707^{**}$). Data were consistent being useful to select putative drought resistant genotypes in future screening tests. The stem diameter can be used without difficulty since it is non destructive and easy to collect in the field. More research is needed to confirm the correlation between stem diameter and drought resistance to generalize the statement for different bean classes.

In greenhouses, several methods have been evaluated and developed. Such methods requiring labor intensive evaluations have not become part of routine breeding programs due to the low correlation with high yield under stress conditions in the field. A practical method, able to overcome the problems observed under field evaluations due to the uncontrolled environmental factors, would help improve efficiency of bean breeders in developing new cultivars with drought resistance.

CONCLUSIONS

From the bean breeding perspective, the selection of drought resistant genotypes should be based on performance under stress and non-stress environments, instead of the selection of genotypes showing tolerance *per se*. Seed production must be the fundamental component to consider. Breeders could focus on yield trials exclusively, or indirectly selecting traits that confer drought resistance followed by field selection. High and stable yields are the ultimate goal. Additionally, breeders who concentrate on selecting traits that confer drought resistance should recognize that the trait must be effective for the specific environment where the new cultivars are to be grown.

The selection of the parents plays an important role, since breeders must take advantage of the opportunities offered by genotypes adapted for dry environments. Utilizing such germplasm will increase the genetic base of Andean beans by introducing novel traits and genes to enhance the current cultivars or to develop new genotypes with superior performance. Such strategies represent a challenge due to the genetic barriers, genetic distance, and lack of commercial traits, but it may provide opportunities. Finally, bean breeders should emphasize work with indirect screening methods and molecular markers. Even though, progress to date has been limited in improving drought resistance, breeders must recognize that new techniques and greater knowledge will be generated and could have potential value in future improvement programs for drought resistance in common bean.

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CHAPTER I

INTRODUCTION

Drought is one of the major constraints limiting world agricultural productivity. Precipitation is erratic and insufficient in a large percentage of the agricultural production regions. Additionally, water for irrigation is becoming less available every year in many parts of the world. According to FAO (2003), drought is the most common cause of severe food shortages. In the developing countries of Latin America, Africa, and Asia, more than 60 % of the area planted to common bean (*Phaseolus vulgaris* L.) is affected by water stress at some stage of crop growth (Singh, 1995). Ecuador is similar to other major common bean production areas in the world where water stress conditions are responsible for the large disparity between potential bean yields and actual yields. Common bean production in Ecuador is concentrated principally in the highlands (Murillo et al., 1996), where low precipitation and lack of irrigation systems constitute a limitation for the small scale producers of this important basic food crop. The Chota and Mira valleys, located in the northern province of Imbabura, are two of the principal bush bean production areas in Ecuador (Peralta et al., 2001). These valleys are located in the dry ecological area "*Monte espinozo Pre-montano*" at 1,500 – 1,600 meters above sea level. The valleys of Chota and Mira receive an average annual precipitation of less than 300 mm (INAMHI, 2004). Common bean, which usually requires more than 400 mm of water to satisfactorily complete the growing cycle (Singh, 1992), is usually sown twice a year in these regions. Thus, according to the temporal rain distribution, farmers face a deficit of natural precipitation. Precipitation approximates 100 mm in the first planting season from March through July, whereas the second planting season from September through January averages 200 mm (Fig. 1). Therefore, the producers in this region need an additional water supply to irrigate their crops and avoid or reduce the effect of the intermittent drought of the region (Maggio, 1989). Unfortunately, water canals for furrow irrigation are not available to all farmers and, in the majority of the cases, those farmers that possess water canals do not always have an adequate water supply. To help alleviate this problem, the most practical approach would be to develop bean cultivars adapted to drought conditions, based on the breeder's understanding of the traits involved in drought resistance for this specific environment.

The development of new drought resistant cultivars is a more feasible approach than providing additional expensive irrigation systems. Identifying sources of drought resistance, and developing bean germplasm that combines drought resistance with desirable commercial traits, could help alleviate the drought effect in bean production areas in Ecuador. The objectives of this study were to: (i) identify common bean genotypes possessing resistance to drought conditions in Michigan and Ecuador; (ii) evaluate drought resistance in an inbred backcross population to identify inbred lines possessing drought resistance and commercial seed traits; and (iii) develop Inbred Backcross Lines (IBL) bean populations from genotypes identified as drought resistant with genotypes possessing commercial seed and plant traits.

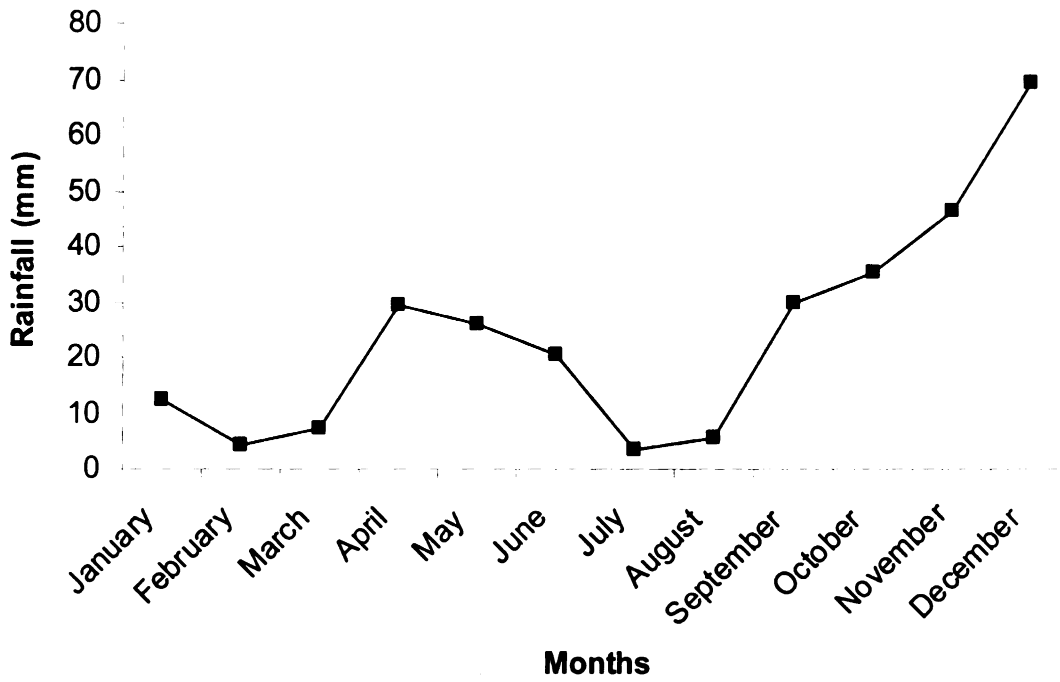

Figure 1. Annual rainfall distribution in Chota's and Mira valley. Meteorological Station of Salinas, Imbabura, Ecuador. (1982 – 2002).

MATERIALS AND METHODS

Plant Material and Population Development.- A population of 26 common bean inbred backcross lines (IBLs) (Table 1) and a group of 16 common bean genotypes (SGT) (Table 2) were used to study drought resistance under field and greenhouse conditions. The IBL population derived from the cross of line C97407*2/'Negro San Luis' (NSL) using the inbred backcross method described by Bliss (1993). The recurrent parent was C97407 and the donor for drought resistance was NSL. The line C97407 is a race Nueva Granada large cranberry seed-type (Taylor Hort/Cardinal) with growth habit type I from the Andean gene pool. The cultivar 'NSL', identified as a drought resistant genotype from the Durango race (Middle American gene pool) (Roman-Aviles and Kelly, 2005), is a medium-sized black seeded landrace that possesses a type III growth habit. C97407 possesses a shallow root system with limited branching, whereas 'NSL' tends to have many adventitious roots and a dominant tap root system (Roman-Aviles et al. 2004). Two backcrosses were performed with the recurrent parent C97407. The population was advanced by the single seed descendant method to the $BC_2F_{4:5}$ generation without selection (Roman-Aviles and Kelly, 2005). In Michigan, only the recurrent parent (C97407) of the IBLs was planted. NSL was not included in the experiments because the genotype is photo-period sensitive and does not flower under long-day conditions. The check cultivars planted in Michigan were B98311, L88-63, identified as drought tolerant (Frahm et al., 2004), and Taylor Hort, while Mil Uno, and L88-63 were planted in Ecuador. Each IBL experiment consisted of 30 entries.

Table 1. Characteristics of 30 Genotypes evaluated for drought in Michigan, U.S. and Tumbaco, Ecuador. 2004-2005.

Genotype	Pedigree	Growth habit	100 seed weight (g)	Days to flower	Days to maturity
IBLs					
C03102	C97407*2/NSL	III	49	38	86
C03104	C97407*2/NSL	I	50	39	82
C03108	C97407*2/NSL	I	51	38	85
C03110	C97407*2/NSL	I	58	38	86
C03117	C97407*2/NSL	I	46	38	79
C03119	C97407*2/NSL	III	50	41	88
C03121	C97407*2/NSL	I	53	41	86
C03122	C97407*2/NSL	I	48	39	85
C03123	C97407*2/NSL	I	48	39	85
C03125	C97407*2/NSL	I	45	40	86
C03127	C97407*2/NSL	I	45	39	83
C03129	C97407*2/NSL	I	55	39	82
C03131	C97407*2/NSL	I	53	39	85
C03143	C97407*2/NSL	I	51	40	82
C03147	C97407*2/NSL	III	43	46	85
C03148	C97407*2/NSL	I	43	38	81
C03149	C97407*2/NSL	III	36	42	90
C03150	C97407*2/NSL	III	51	47	90
C03151	C97407*2/NSL	III	51	42	90
C03154	C97407*2/NSL	I	34	39	86
C03155	C97407*2/NSL	I	50	39	85
C03156	C97407*2/NSL	III	45	47	89
C03157	C97407*2/NSL	III	56	44	86
C03160	C97407*2/NSL	III	48	41	88
C03161	C97407*2/NSL	III	38	38	90
C03163	C97407*2/NSL	I	42	38	90
Parents					
NSL*	Landrace	III	38	40	100
C97407	C92167/Taylor Hort.	I	58	55	95
Checks					
B98311**	X98102/Raven	III	24	18	95
L88-63	B98311/TLP-19	III	26	16	95
Taylor Hort***		I	54	58	95
Mil Uno+	Landrace	I	65	44	95

* NSL is photo-period sensitive and was planted only in Ecuador.
** B98311 is a drought resistant line used instead of NSL in Michigan experiments to complete 30 entries.
*** Taylor Hort was used as local check in Michigan, US.
+ Mil Uno was used as local check in Tumbaco, Ecuador.

The 16 genotypes of the standard test included several landraces and inbred lines from different origins and different research programs (Table 2). The test included drought resistant lines such as L88-63 (Frahm et al., 2004), SEQ 1016 (Programa Nacional de Leguminosas, 1995), AFR 476 (Programa Nacional de Leguminosas, 1995), RAB 651 and RAB 655 (CIAT, 2002), drought resistant cultivars such as Paragachi (Programa Nacional de Leguminosas, 1995), and commercial cultivars such as Mil Uno, were included as checks. The members of this heterogeneous group were selected to increase the likelihood of finding well-adapted, high-performance genotypes under water stress and non-stress conditions.

Table 2. Genotypes from the standard test evaluated in Tumbaco, Ecuador. 2005.

Genotype	Pedigree	Class	100 seed weight (g)	Growth habit	Trait of interest	Origin
Inbred						
Yunguilla	G13922//G21721/ G6474	Red mottled	50	I	Comercial seed	INIAP[1]
ACE 1	CAP 9/Canario Bola	Yellow	50	I	Comercial seed	INIAP
ACE 2	CAP 9/Canario Bola	Yellow	50	I	Comercial seed	INIAP
ABE 4	SUG 55/INIAP 417	White	55	I	Comercial seed	INIAP
POA 10	AND 688//AFR 606/AND 390	Red mottled	53	I	Comercial seed	CIAT[2]
AFR 476	G24512/BAT 37	Red	29	I	Drought resistant	CIAT
YxAs7	Yunguilla/ AFR 612	Red mottled	50	I	Comercial seed	INIAP
SEQ 1016	-	Yellow	48	II	Drought resistant	CIAT
L88-63	B98311/ TLP-19	Black	16	II	Drought resistant	MSU[3]
RAB 651	XAN 309/Orgulloso// Tio Canela 75/XAN 309	Red	27	II	Drought resistant	CIAT
RAB 655	VAX 3/MAM 38	Red	27	II	Drougtht resistant	CIAT
C97407	C92167/ T.Hort	Cranberry	58	I	Commercial seed	MSU
ARME 2	AND 1005 / Paragachi	Red mottled	45	II	Commercial seed	INIAP
Paragachi	BAT1274// Pompaduour Mocana/Guanajua	Red mottled	45	II	Drought resistant and Commercial seed	CIAT
Landraces						
Mil Uno	Collection 1996	Purple mottled	62	I	Commercial seed	Ecuador
Cocacho	Collection 1979	Canario	42	I	Commercial seed	Ecuador

[1] INIAP = National Institute of Agricultural Research from Ecuador
[2] CIAT =International Center for Tropical Agriculture
[3] MSU = Michigan State University

Montcalm, MI 2004, 2005

A total of 30 genotypes were studied during the summers of 2004 and 2005 in the Montcalm Research Farm (MRF) near Entrican, Michigan (43°20′N; 85°01′W). The soil type is an alfisol soil (Montcalm/McBride loamy sand), which is prone to drought in dry years. The genotypes included a population of 26 IBLs (C97407*2/'NSL') with the recurrent parent (C97407) and three check genotypes: a commercial variety ('Taylor Hort') and two drought resistant genotypes (L88-63 and B98311). The genotypes were evaluated under water stress and non-stress conditions. The two water treatments were arranged in a randomized complete block design (RCBD) of 30 genotypes with three replications. The plots consisted of two rows 6.0 m long and 0.5 m wide. Eighty seeds per row were machine-planted. The edges were trimmed before harvest and only 4.6 m of row were harvested.

The plots received supplemental irrigation using overhead sprinkler irrigation. In 2004, plots under non-stress received a total of 285 mm of water, while the plots under water stress received a total of 216 mm of water. In 2005, plots under non-stress received 365 mm and plots under stress received 315 mm of water. In 2004 and 2005, the plots were fertilized at planting with 191 kg/ha of 19-19-19 and after 30 days with 25 kg/ha of 46-0-0. Pests and diseases were controlled. Weeds were controlled with pre-plant incorporated herbicide. The field data recorded included days to flower, stem thickness at maturity, desirable score (DS); (scale 1-9, where 1 corresponds to the worst and 9 the best), number of pods per four plants, and number of seeds per ten pods. Yield, biomass, and 100 seed weight were recorded at harvest. Yield data were used to calculate geometric mean yield, drought susceptibility index {[(1 – (Ys/Yp)]/DII} and drought intensity index [1-(Xs/Xp)]. The severity of common bacterial blight was evaluated in 2005 since there was severe pressure in the nursery. The scale utilized to score the severity of the disease was the 1 – 5 scale (scale 1-5, where 1 indicates plants without symptoms, and 5 indicates plants totally infected with the disease).

Tumbaco, Ecuador 2005

Two common bean trials were evaluated under water stress and non-stress conditions during 2005. The experiments were conducted in Ecuador at Tumbaco Research Farm (TRF) of the National Autonomous Institute of Agricultural Research (INIAP) located in Tumbaco parish, province of Pichincha (0°12´S; 78°24´W) in collaboration with the Programa Nacional de Leguminosas (PRONALEG). The first trial included 30 genotypes (Table 1), the 26 IBLs previously described with the parents (C97407 and 'NSL'), and two checks, the drought resistant genotype (L88-63) and an Ecuadorian commercial cultivar ('Mil Uno'). The second trial included 16 bean genotypes (Table 2). The experiments were arranged in an RCBD with three replications each under stress and non-stress conditions.

Plots consisted of two rows 5.0 m long and 0.6 m wide. Plots were trimmed to 4.5 m before harvest. Eighty seeds per row were planted by hand and thinned to 65 plants at third trifoliate-leaf stage. Rows were hilled for furrow irrigation. Weeds were controlled using a pre-plant incorporation (ppi) herbicide combination of 3 L/ha Lasso (alaclor) and 1L/ha Afalon (linuron) and manually after emergence. *Agrotis* sp. were controlled by an application of 1 L/ha Endosulfan (endosulfan) at 15 days after planting. Empoasca were controlled by an application of 1.5 L/ha Suko (lambdacihalotrina) at 23 days after planting (dap). Baycor (bitertanol) was applied at the rate of 1.5 L/ha at 35 and 73 dap to control bean rust (*Uromyces appendiculatus*). Bacterial diseases were controlled by an application of Phyton (copper sulfate) 73 dap. Fertilizer (10-30-10) was applied 2 dap at the rate of 90 kg/ha and foliar fertilization was applied before flowering. The precipitation during the growing season totaled 294 mm. The IBL nursery under non-stress conditions received a total of 359 mm of water, whereas plots under stress conditions received 309 mm. In the SGT experiment, the plots under non-stress conditions received a total of 348 mm of water, while plots under stress conditions received 304 mm. Field data collected included days to emergence, days to flower, maturity, plant height, stem thickness, lodging, resistance to root rot, desirable score. Yield, biomass, and 100 seed weight were recorded at harvest. Yield data were used to calculate geometric means, harvest index, drought susceptibility index and drought intensity index.

Statistical analyses

Analyses of variance (ANOVA) were calculated for each experiment. The data were analyzed as a randomized complete block design (RCBD) using INFOSTAT 2.0 (INFOSTAT, 2002) and SAS (SAS Institute INC., 2000). ANOVAs were calculated for every variable in each water treatment. Combined ANOVAs were calculated to compare results between genotypes in different water treatments and to compare genotypes from the experiments MC 2004 with MC 2005. LSD values in sources of variation showing significant differences and CV (%) were calculated for every variable. The correlation between variables was calculated using the Pearson coefficient values (r).

RESULTS

Four field studies were conducted over two years (2004 – 2005) in MRF-Michigan and TRF-Ecuador. Two experiments were conducted in MRF in 2004 and 2005, and two experiments were conducted in TRF in 2005. The experiments evaluated in MRF included the IBL population and, the experiments evaluated in TRF included the IBL population and the SGT. All the experiments included water stress and non stress treatments. The experiments showed significant differences in performance when comparing non-stress and water stress treatments and genotypic differences were also detected.

MC2004

Significant differences in yield were detected for treatment effect ($p < 0.0001$) and for genotype ($p < 0.0001$), whereas the G x E interaction was not significant. The overall yield mean of the experiment was 2502 kg/ha. The mean yield under non-stress conditions was 2887 kg/ha, while the mean yield under stress conditions was 2117 kg/ha. The drought intensity index (DII = 0.27) showed a moderate water stress in the experiment. Lower CV was observed under non-stress conditions compared with stress conditions. Significant genetic differences for yield among genotypes under non-stress conditions were not detected, whereas significant genetic differences among genotypes were detected under water stress conditions ($p < 0.01$). Yield of genotypes under non-stress conditions ranged from 2346 to 3356 kg/ha, whereas yield of genotypes under water stress conditions ranged from 1369 to 2709 kg/ha. The top yielding genotype under stress conditions was C03121 with 2709 kg/ha, while the lowest yielding genotype was the entry C03149 with 1369 kg/ha. The similar performance of the IBLs under non-stress conditions, and the different performance of the genotypes under stress conditions indicate that the genotypes placed in the top groups under stress are better adapted to drought conditions as a result of and the genetic resistance. The top yielding genotype C03121 had a GM yield = 2916 kg/ha. Genotypes C03108, C03151, and C03122 exhibited favorable performance under the two water treatments. However, genotypes C03108 and C03122 showed severe leaf deformities which would affect their commercialization.

Table 3. Geometric mean (GM) yield, yield under stress conditions, yield under non-stress conditions, and stress susceptibility index of the IBL population evaluated in Michigan, US. 2004.

Genotype	GM[1]	Stress	Non-stress	DSI[2]
	Kg/ha			
IBLs				
C03121	2916	2709	3140	0.51
C03108	2845	2412	3356	1.05
C03151	2829	2409	3322	1.03
C03122	2805	2422	3250	0.95
C03110	2766	2377	3220	0.98
C03104	2760	2427	3139	0.85
C03102	2757	2389	3181	0.93
C03129	2677	2293	3125	1.00
C03147	2610	2113	3223	1.29
C03163	2539	2203	2928	0.93
C03157	2526	2289	2787	0.67
C03131	2501	2177	2873	0.91
C03143	2472	2311	2644	0.47
C03155	2460	2321	2607	0.41
C03119	2429	2259	2612	0.51
C03161	2407	2297	2523	0.34
C03125	2313	1795	2981	1.49
C03156	2306	1959	2714	1.04
C03148	2253	1740	2917	1.51
C03127	2199	1880	2572	1.01
C03160	2190	1624	2954	1.69
C03150	2153	1640	2827	1.57
C03123	2122	1760	2558	1.17
C03154	2008	1484	2717	1.70
C03149	1965	1369	2820	1.93
C03117	1839	1441	2346	1.44
Parent				
C97407	2374	2127	2650	0.74
Checks				
B98311	2563	2268	2895	0.81
L88-63	2890	2592	3221	0.73
Taylor Hort.	2462	2429	2496	0.10
Overall mean	2465	2117	2887	
LSD (0.05)		665	678	
CV (%)		19.2	14.4	
DII[3]				0.27

[1]GM= $(Ys \times Yp)^{1/2}$

[2]DSI= $[(1 - (Ys/Yp)]/DII$

[3]DII= $1-(Xs/Xp)$

Significant differences were detected in 100 seed weight for water treatment ($p < 0.0001$), genotype ($p < 0.0001$) and the G x E interaction ($p < 0.001$). The overall mean of seed weight in the IBL population in MC2004 was 53 g/100 seeds. The mean seed weight under non-stress conditions was 55 g/100 seeds, whereas the seed weight mean under water stress conditions was 51 g/100 seeds. Genotypes C03123 (68 g/100 seeds), C03121 (67 g/100 seeds) produced the largest seeds, while the resistant controls L88-63 (22 g/100 seeds) and B98311 (24 g/100 seeds) produced the smallest seeds. The mean for the recurrent parent (C97407) was 56 g. The 100 seed weight ranged from 22 to 68 g/ 100 seeds in the combined analysis.

Significant differences in HI were detected for treatment effect ($p < 0.05$), genotype ($p < 0.0001$), and the G x E interaction ($p < 0.001$). The overall mean for HI was 0.48. The HI under non-stress conditions was 0.49, whereas under water stress conditions the HI was 0.47. The harvest index ranged from 0.32 to 0.6. There was no correlation between yield and harvest index. Less water in plots under stress conditions caused a greater reduction in seed production than for biomass production. The consequence was a very small reduction in HI under stress conditions (0.49 vs. 0.47).

Table 4. Analysis of variance for the IBLs experiment for yield, 100 seed weight (g), and harvest index under non-stress and stress conditions of the IBLs evaluated in Michigan, US. 2004.

	non-stress								
	Yield (kg/ha)			100 seed weight (g)			Harvest index		
Source	DF	MS	F test	DF	MS	F test	DF	MS	F test
block	2	417545	1.21	2	27	2.4	2	0.01	5.2*
genotype	29	6882629	1.38^{ns}	29	9828	49.4****	29	0.01	7.2****
error	58	9978121		58	398		58	0.001	
grand mean			2887			55.3			0.49
LSD (0.05)			ns			4.3			0.07
CV (%)			14.4			4.7			8.5
	Stress								
Source	DF	MS	F test	DF	MS	F test	DF	MS	F test
Block	2	1591425	9.6***	2	24.0	2.2	2	0.06	18****
genotype	29	11234045	2.3**	29	290	26.7****	29	0.02	6.7****
Error	58	9593138		58	10.6		58	0.001	
grand mean			2117			51.1			0.47
LSD (0.05)			665			5.3			0.09
CV (%)			19.2			6.4			11.9

*P<.05; **P<.01; ***P<.001; ****P<.0001; ^{ns}Non significant

Significant differences in number of pods per plant were detected for treatment effect ($p < 0.0001$) and genotype ($p < 0.0001$), while no significance was detected for G x E interaction. The mean under non-stress conditions was 10.4 pods/plant and the mean under stress conditions was 9.2 pods/plant. The number of pods per plant in the genotypes ranged from 8.0 to 17.2. The genotype with the largest number pods per plant was B98311 (17.2 pods/plant). C97407 was placed in a second group with 11.4 pods/plant, along with L88-63 (13.0 pods/plant), C03155 (11.9 pods/plant), and C03121 (11.6 pods/plant).

Significant differences in number of seeds per pod were detected for treatment effect ($p< 0.05$) and genotype ($p < 0.0001$), while no significance was detected for G x E interaction. The overall mean was 4.3 pods/plant. The mean under non stress conditions was 4.4 pods/plant and the mean under stress conditions was 4.2 pods/plant. The genotypic means ranged from 2.8 to 5.3 pods/plant. Genotypes C03123 (2.8 pods/plant) and C03121 (3.3 pods/plant) were the genotypes with the smaller number of seeds per pod. The genotypes showing the largest number of seeds per pod were L88-63 (5.3 pods/plant), C03149 (5.1 pods/plant), B98311 (5.0 pods/plant), C03147 (4.9 pods/plant), and C03161 (4.7 pods/plant).

Table 5. Yield, biomass, 100 seeds weight, harvest index (HI), number of pods per plant, and number of seeds per pod across treatments of the IBL population evaluated in Montcalm, US. 2004.

Genotypes	Growth habit	Yield (kg/ha)	Biomass (kg/ha)	HI	100 seeds weight (g)	No. pods/plant	No. seeds/pod
IBLs							
C03121	I	2924	6193	0.48	67	11.6	3.3
C03108	I	2884	4799	0.6	53	8.2	4.5
C03151	I	2866	5633	0.5	57	9.5	4.3
C03122	I	2836	5555	0.51	58	9.3	3.9
C03110	I	2798	5358	0.53	64	9.5	4.1
C03102	III	2785	5002	0.56	59	8	4
C03104	I	2783	4946	0.56	55	9.1	3.8
C03129	I	2709	5441	0.5	55	10.5	4.2
C03147	III	2668	5739	0.47	57	8	4.9
C03163	I	2565	4936	0.52	60	8.5	4.2
C03157	III	2538	6716	0.38	62	8.2	4.4
C03131	I	2525	4519	0.56	54	9.6	4.3
C03143	I	2478	5285	0.47	52	8.8	4.1
C03155	I	2464	4956	0.5	57	11.9	4.1
C03119	III	2435	4835	0.5	60	8.2	4.4
C03161	III	2410	5837	0.41	45	9.1	4.7
C03125	I	2388	4807	0.49	47	9.2	4.5
C03156	III	2337	5733	0.41	52	9.6	4.2
C03148	I	2329	6196	0.37	53	9.7	4.2
C03160	III	2289	6346	0.36	52	9.7	4.5
C03150	III	2234	5513	0.41	56	9.8	4.2
C03127	I	2226	4679	0.48	50	9.3	4.4
C03123	I	2159	5896	0.38	68	10.1	2.8
C03154	I	2100	4315	0.49	47	9.5	4.6
C03149	III	2095	6565	0.32	45	9.4	5.1
C03117	I	1894	3416	0.55	49	9.6	4.1
Parent							
C97407	I	2389	4303	0.56	56	11.4	4.4
Checks							
Taylor Hort.	I	2463	4276	0.58	60	8.2	4.3
L88-63	II	2907	6446	0.47	22	13.0	5.3
B98311	II	2582	6132	0.43	24	17.2	5.0
MEAN		2502	5346	0.48	53	9.8	4.3
LSD (0.05)		474	1010	0.06	3	2.3	0.6
CV (%)		16.4	16.4	10.3	5.6	20.2	12.1

MC2005

Significant differences in yield were detected for treatment ($p< 0.001$) and genotype ($p < 0.0001$) effect, and no significance was detected for G x E interaction. The overall mean yield of the experiment was 1669 kg/ha. Yield under non-stress condition was 1808 kg/ha and yield under stress conditions was 1529 kg/ha. The drought intensity of the experiment was 0.2. The top yielding genotypes based on GM were C03157, C03143, C03110, C03151, C03131, and C03147. Genotypes C03121 and C03122 were identified as the lowest yielding genotypes in MC2005.

Table 6. Geometric mean (GM) yield, yield under stress conditions, and yield under non-stress conditions of the IBL population evaluated in Michigan, US. 2005.

Genotypes	GM[1]	Stress	Non-stress	DSI[2]
	Kg/ha			
IBLs				
C03157	2357	2218	2506	0.57
C03143	2175	1807	2618	1.55
C03110	2105	1821	2433	1.26
C03151	2048	1885	2225	0.76
C03131	2028	1635	2514	1.75
C03147	2006	2122	1896	-0.60
C03154	1909	1507	2418	1.88
C03163	1862	1930	1797	-0.37
C03155	1848	1717	1990	0.69
C03127	1761	1519	2041	1.28
C03156	1708	1512	1929	1.08
C03125	1707	1522	1914	1.02
C03119	1646	1724	1571	-0.49
C03129	1615	1799	1449	-1.21
C03104	1607	1256	2056	1.95
C03108	1557	1238	1958	1.84
C03123	1532	1295	1812	1.43
C03150	1508	1426	1596	0.53
C03117	1507	1518	1497	-0.07
C03102	1484	1247	1766	1.47
C03160	1464	1351	1585	0.74
C03149	1329	1117	1581	1.47
C03148	1273	1094	1481	1.31
C03161	1179	1218	1142	-0.33
C03122	1070	1085	1055	-0.14
C03121	757	957	598	-3.00
Parent				
C97407	1859	1720	2009	0.72
Checks				
Taylor Hort	1196	1074	1332	0.97
L88-63	1792	1892	1698	-0.57
B98311	1725	1672	1778	0.30
MEAN	1654	1529	1808	
LSD (0.05)		629	589	
CV (%)		27.7	24.0	
DII[3]				0.2

[1] $GM = (Ys \times Yp)^{1/2}$
[2] $DSI = [(1 - (Ys/Yp)]/DII$
[3] $DII = 1-(Xs/Xp)$

The plots in MC2005 experiment were seriously affected by common bacterial blight. The overall mean registered in the plots was 3.6 based on a scale of 1 – 5. The score in the genotypes ranged from 2.0 to 5.0. The genotypes with the highest values were C03127 (5.0), C03151 (4.75), C03155 (4.5), C03121 (4.5), C03119 (4.5), and C03149 (4.25), while the genotypes with the lowest scores were C03154 (2.0), C97407 (2.25), C03110 (2.5), and C03104 (2.5). The controls Taylor Hort. (3.0) and L88-63 (3.5) had intermediate scores.

Significant differences in biomass for treatment ($p < 0.01$) and genotype ($p < 0.0001$) effect was detected, while no significance was detected for G x E interaction. The overall mean was 6874 kg/ha. The mean biomass under non-stress conditions was 6631 kg/ha, whereas the mean biomass under stress conditions was 7117 kg/ha. The biomass ranged from 4397 to 10425 kg/ha. Genotypes C03150, C03157, and C03160 produced the largest biomass.

Significant differences in HI for treatment effect ($p < 0.0001$) and genotype ($p < 0.0001$) were detected, and no significance for G x E interaction. The overall mean of HI was 0.24. The HI under non-stress conditions was 0.25, whereas the HI under stress conditions was 0.22. The HI ranged from 0.13 to 0.33. Genotypes C03131, C03143, C03154, and C03110, along with the parent C97407 and the drought resistant controls L88-63 and B98311 showed the largest HI. No data were collected on pods/plant and seed/pod in 2005

Table 7. Yield, biomass, harvest Index (HI), common bacterial blight reaction (CBB), and desirability score (DS) across treatments of the IBL population evaluated in Michigan, US. 2005.

Genotypes	Yield	Biomass	HI	CBB	DS (1-9)
	kg/ha				
IBLs					
C03157	2362	9371	0.25	3.75	4.2
C03143	2213	7922	0.28	3.75	4.2
C03110	2127	7543	0.28	2.55	5.2
C03131	2075	5652	0.33	3.25	4.0
C03151	2055	7971	0.26	4.75	3.0
C03147	2009	8103	0.25	3.75	3.5
C03154	1963	4397	0.28	2.00	4.2
C03163	1864	6703	0.24	3.25	4.0
C03155	1854	7049	0.25	4.50	4.0
C03127	1780	6950	0.26	5.00	3.5
C03156	1721	8300	0.21	3.20	3.7
C03125	1718	6884	0.24	3.70	4.0
C03104	1656	5534	0.27	2.50	4.2
C03119	1648	6835	0.24	4.50	3.0
C03129	1624	6752	0.24	3.00	5.0
C03108	1598	6522	0.24	3.00	4.2
C03123	1554	7197	0.19	4.00	3.5
C03150	1511	10425	0.15	4.00	3.5
C03117	1508	5089	0.27	3.00	4.2
C03102	1507	5418	0.25	3.50	4.0
C03160	1468	9305	0.16	3.50	3.7
C03149	1349	7164	0.19	4.25	3.7
C03148	1288	6752	0.18	3.75	3.5
C03161	1180	6752	0.18	4.00	3.7
C03122	1070	5517	0.19	3.25	4.5
C03121	778	6209	0.13	4.50	3.0
Parent					
C97407	1865	6785	0.27	2.28	5.0
Checks					
Taylor Hort.	1203	4661	0.25	3.03	4.7
L88-63	1795	6324	0.28	3.53	4.2
B98311	1725	6127	0.28	3.28	4.2
Mean	1669	6874	0.24	3.57	4.0
LSD (0.05)	492	1333	0.04		
CV (%)	25.6	16.8	15.8		

Significant differences in yield were detected for treatment effect ($p < 0.0001$), year ($p < 0.0001$), genotype ($p < 0.0001$), treatment x year interaction effect ($p < 0.0001$), and genotype x year interaction effect ($p < 0.0001$). The overall mean over two years (2004 and 2005) in MRF was 1974 kg/ha. The mean yield in MC2004 was 2502 kg/ha, while the mean yield in MC2005 was 1669 kg/ha. The top yielding genotypes over two years under two water regimes were C03151, C03110, C03157, C03147, C03143, C03108, C03129, and C03104. The drought resistant checks, the black beans L88-63 and B98311 were also among the top yielding genotypes.

Table 8. Analysis of variance for yield (kg/ha) for 30 genotypes grown under stress and non-stress conditions over two years in Montcalm, MI 2004, 2005.

Source	DF	MS	F Test
Year	1	100373856	629.98****
Water trt.	1	17443805	109.48****
Year x Water trt.	1	9752550	61.21****
Genotype	29	619287	3.89****
Genotype x Year	29	460081	2.89****
Genotype x Water trt	29	168790	1.06^{ns}
Genotype x Year x Water trt.	29	167811	1.05^{ns}
Repetitions	2	843489.94	5.29**
Error	238	159329	
Grand mean (kg/ha)			1974
CV (%)			20.2

**P<.01; ****P<.0001; ^{ns}Non significant

Tumbaco IBL 2005

Significant differences in yield for treatment effect ($p < 0.0001$), genotype ($p < 0.0001$), and for G x E interaction ($p < 0.05$) were detected. The overall yield mean of the IBL population in Tumbaco 2005 was 1942 kg/ha. The mean yield under non-stress conditions was 2364 kg/ha, whereas the yield mean under stress conditions was 1521 kg/ha. The DII for the experiment was 0.36. The genotype producing largest yield was the donor parent NSL (3454 kg/ha). The check cultivar Mil Uno (2470 kg/ha) was placed in the second group along with genotypes C03131 (2303 kg/ha), and C03122 (2220 kg/ha). The yield mean of the genotypes ranged from 3454 to 1477 kg/ha. Significant genotypic differences for non-stress ($p < 0.0001$) and stress ($p < 0.0001$) were detected. Based on GM, genotypes C03131 (2235 kg/ha), C03122 (2142 kg/ha), C03102 (2078 kg/ha), C03110 (2055 kg/ha), C03160 (2032 kg/ha), C03121 (2028 kg/ha), parent NSL (3358 kg/ha), and check Mil Uno (2395) showed the best performance under stress and non-stress conditions. A high correlation (r= 0.84**) was observed between yield and biomass. Additionally, high correlations between yield and biomass under non-stress (r= 0.81**), and stress (r= 0.77**) were observed. The correlation between yield under stress and biomass under non-stress (r= 0.64**) was also significant. The variables such as number of pods per plant, number of seeds per pod, stem thickness, and 100 seed weight were not correlated with yield.

Table 9. Geometric mean yield, yield under non-stress conditions, and yield under stress conditions of the IBL population evaluated in Tumbaco, Ecuador. 2005.

Genotype	GM[1]	Stress	Non-stress	DSI[2]
	kg/ha			
IBLs				
C03131	2235	1746	2860	1.08
C03122	2142	1637	2803	1.16
C03102	2078	1722	2508	0.87
C03110	2055	1698	2488	0.88
C03160	2032	1485	2780	1.29
C03121	2028	1606	2560	1.04
C03163	1985	1672	2358	0.81
C03108	1983	1697	2318	0.74
C03156	1901	1518	2382	1.01
C03150	1892	1652	2166	0.66
C03127	1797	1544	2091	0.73
C03155	1792	1530	2098	0.75
C03148	1770	1336	2346	1.20
C03104	1760	1450	2137	0.89
C03151	1746	1297	2349	1.24
C03154	1743	1315	2311	1.20
C03143	1711	1395	2099	0.93
C03125	1711	1505	1945	0.63
C03147	1676	1172	2397	1.42
C03117	1675	1335	2103	1.01
C03129	1652	1440	1895	0.67
C03119	1650	1338	2036	0.95
C03123	1581	1338	1868	0.79
C03149	1558	1306	1859	0.83
C03157	1523	1225	1894	0.98
C03161	1466	1295	1659	0.61
Parents				
NSL	3358	2649	4259	1.05
C97407	1861	1414	2448	1.17
Checks				
Mil Uno	2395	1866	3073	1.09
L88-63	2017	1435	2835	1.37
MEAN	1893	1521	2364	
LSD (0.05)		346	574	
CV (%)		13.9	14.9	
DII[3]				0.36

[1] $GM = (Ys \times Yp)^{1/2}$

[2] $DSI = [(1 - (Ys/Yp)]/DII$

[3] $DII = 1-(Xs/Xp)$

Significant differences in biomass were detected for treatment effect ($p < 0.0001$), genotype ($p < 0.0001$), and for G x E interaction ($p < 0.0001$). The overall mean for biomass was 4776 kg/ha. The mean biomass under non-stress was 5680 kg/ha and the biomass mean under stress conditions was 3872 kg/ha. Genotypes ranged from 3939 kg/ha to 7694 kg/ha. The genotype NSL (7694 kg/ha) showed the greatest biomass production, whereas genotypes L88-63 (6514 kg/ha), Mil Uno (6139 kg/ha), and C03122 (5708 kg/ha) had the next largest biomass production.

Significant differences in 100 seed weight were detected for treatment effect ($p < 0.0001$), genotype ($p < 0.0001$), and for G x E interaction ($p < 0.0001$). The overall mean 100 seed weight was 53 g. The mean of 100 seeds weight under non-stress experiment was 58 g compared to 48 g under stress conditions. Significant differences were detected between genotypes. The 100 seeds weight of the genotypes ranged from 22 to 73 g. The genotype with the higher 100 seeds weight was the control Mil Uno (73 g), followed by C03123 (69 g), C03121 (64 g), and C03110 (62 g). As expected, genotypes with the lowest 100 seeds weight were, the black bean, L88-63 (22 g), C03154 (42 g), NSL (45 g), and C03149 (46 g).

Significant differences in the number of lateral roots for treatment effect ($p < 0.0001$) and genotype ($p < 0.0001$) were detected, and the interaction G x E was not significant. The overall mean number of lateral roots was 10.3. The mean number under non-stress conditions was 12.1, while the mean number under stress conditions was 8.5 lateral roots per plant. The genotypes ranged from 7.6 to 12.8 lateral roots. The resistant control L88-63 (7.6 lateral roots) and the donor parent NSL (7.9 lateral roots) had the lowest number of lateral roots, while genotypes C03150, C03110, C03156, C03147, C03160, C03123, C03163, C03151, C03161, and Mil Uno produced the largest number of lateral roots (>10.8 lateral roots).

Significant differences in number of pods per plant for treatment effect ($p < 0.05$) and genotype ($p < 0.0001$) were detected, while G x E interaction was not significant. The overall mean was 9.4 pods per plant. The number of pods per plant under non-stress was 9.4, while the number of pods per plant under stress was 9.3. The genotypes ranged from 6.5 to 18.6 pods per plant. The genotypes showing the largest number of pods were the small-seeded genotypes L88-63 (18.6) and NSL (14.8).

No significant differences were detected in number of seeds per pod for treatment effect and G x E interaction. However, significant differences ($p < 0.0001$) for number of seeds per pod among genotypes were detected. The overall mean in the number of seeds per pod was 4.2. The number of seeds per pod in the genotypes ranged from 3.1 to 5.4. The genotypes with the largest number of seeds per pod were C03147 (5.4 seeds/pod), C03149 (5.2 seeds/pod), C03156 (5.1 seeds/pod), and C03131 (5.0 seeds/pod). These genotypes produced more seeds per pod than either parents C97407 (4.1 seeds/pod) and NSL (4.5 seeds/pod).

Table 10. Yield, biomass, harvest index (HI), 100 seeds weight, number of lateral roots per plant, number of pods per plant, and number of seeds per pod across water treatments of the IBL population evaluated in Tumbaco, Ecuador. 2005.

Genotypes	Yield (kg/ha)	Biomass (kg/ha)	HI	100 seed weight	No lateral roots/plant	No seeds/pod	Pods/plant
	—— kg/ha	——		(g)			
IBLs							
C03102	2115	4314	0.49	57	9.1	4.1	9.3
C03104	1794	4439	0.4	54	9.4	3.6	9.1
C03108	2007	4328	0.46	53	9.3	4.3	8.2
C03110	2093	5258	0.4	62	12.0	3.9	6.5
C03117	1719	4231	0.41	48	9.6	4.1	10.1
C03119	1687	4597	0.37	54	10.0	4.2	6.8
C03121	2083	4708	0.44	64	10.8	3.6	12.1
C03122	2220	5708	0.38	58	8.7	3.7	9.7
C03123	1603	4681	0.35	69	11.9	3.1	11.6
C03125	1725	4547	0.39	49	9.2	4.2	10.3
C03127	1818	4944	0.37	53	9.7	4.1	9.8
C03129	1667	4069	0.41	49	9.8	4.3	7.7
C03131	2303	4842	0.47	56	9.1	5.0	8.4
C03143	1747	4592	0.38	50	9.0	4.3	9.7
C03147	1784	4153	0.42	51	11.9	5.4	8.6
C03148	1841	4667	0.39	55	10.4	4.2	9.7
C03149	1583	4083	0.39	46	10.5	5.2	8.0
C03150	1909	4889	0.41	56	12.8	4.5	9.9
C03151	1823	4578	0.4	52	11.1	4.7	9.5
C03154	1813	3939	0.45	42	9.6	4.6	8.5
C03155	1814	4067	0.45	55	10.2	3.9	9.2
C03156	1950	4958	0.4	50	12.0	5.1	8.6
C03157	1560	4139	0.38	55	10.7	4.6	7.5
C03160	2133	5278	0.41	55	11.9	4.5	9.5
C03161	1477	4139	0.35	47	10.9	4.6	8.8
C03163	2015	4653	0.44	57	11.7	3.7	10.1
Parents							
NSL	3454	7694	0.45	45	7.9	4.5	14.8
C97407	1931	4125	0.46	51	9.6	4.1	8.3
Checks							
L88-63	2135	6514	0.34	22	7.6	4.3	18.6
Mil Uno	2470	6139	0.41	73	12.0	3.3	9.9
MEAN	1942	4776	0.41	53	10.3	4.2	9.6
LSD (0.05)	335	868	0.05	4.0	1.9	0.6	2.0
CV (%)	14.9	15.8	11.2	6.6	16.3	12.3	18.3

SGT

Significant differences in yield for treatment ($p < 0.0001$) and genotype ($p < 0.0001$) effect were detected, and G x E interaction was not significant. The overall yield mean for the SGT in Tumbaco was 1521 kg/ha. The yield of the genotypes under non-stress conditions was 1632 kg/ha, whereas the mean yield for genotypes under stress conditions was 1410 kg/ha with a DII = 0.14 for the experiment. The yield of the 16 genotypes ranged from 1140 to 1833 kg/ha. Genotypes Paragachi (1833 kg/ha), L88-63 (1825 kg/ha), and Mil Uno (1817 kg/ha) were the top yielding genotypes and the genotype more affected by stress treatment was ABE 4. Under stress conditions the genotypes with acceptable performance were L88-63, Paragachi, Mil Uno, ACE 2, ARME 2, and RAB 655, and the same genotypes were also the top yielding genotypes based on GM.

Table 11. Geometric mean (GM) yield, yield under stress conditions, yield under non-stress conditions, drought susceptibility index (DSI), and maturity of the 16 genotypes in SGT in Tumbaco, Ecuador. 2005.

Genotypes	GM[1]	Stress	Non-stress	DSI[2]	Maturity
		kg/ha			(days)
PARAGACHI	1832	1772	1894	0.46	110
L88-63	1825	1820	1830	0.04	103
MIL UNO	1815	1731	1903	0.65	108
ACE2	1673	1591	1760	0.69	105
RAB655	1624	1494	1765	1.10	105
ARME2	1604	1583	1625	0.18	112
ABE 4	1596	1336	1907	2.14	108
POA10	1504	1422	1591	0.76	110
ACE1	1497	1316	1702	1.62	116
YxAs7	1441	1304	1591	1.29	111
YUNGUILLA	1416	1291	1554	1.21	114
COCACHO	1414	1276	1566	1.32	92
RAB651	1363	1251	1486	1.13	99
AFR476	1324	1200	1460	1.27	108
SEQ1016	1192	1183	1201	0.11	112
C. BOLA 60	1131	994	1286	1.62	91
MEAN	1516	1410	1632		106
LSD (0.05)		336	386		2.2
CV (%)		14.3	14.1		1.8
DII[3]				0.14	

[1]GM= $(Ys \times Yp)^{1/2}$
[2]DSI= $[(1 - (Ys/Yp)]/DII$
[3]DII= $1-(Xs/Xp)$

Significant difference in HI for genotype ($p < 0.0001$) was detected. There were no significant differences for treatment effect and G x E interaction. The overall mean for HI was 0.4. The harvest index in the genotypes ranged from 0.33 to 0.46. The genotypes showing the greatest HI were ACE 2 (0.46), Cocacho (0.45), AFR476 (0.43), ARME 2 (0.43), ABE 4 (0.41). The genotypes with the lower harvest index were SEQ 1016 (0.33), L88-63 (0.37), POA 10 (0.37), and RAB651 (0.38).

Significant differences in 100 seed weight for treatment effect ($p < 0.1$), genotype ($p < 0.0001$), and G x E interaction ($p < 0.1$) were detected. The overall mean for 100 seeds weight in the experiment was 44.5 g. The mean under non-stress conditions was 45 per 100 g seeds, while the mean under stress conditions was 44 g. The genotypes ranged from 21 to 62 g per 100 seeds. The genotypes with the largest seeds were ACE 1, Mil Uno, and ABE 4, while the genotypes with the smallest seeds were L88-63 (20 g/100 seeds), RAB651 (22 g/100 seeds), RAB655 (24 g/100 seeds), and AFR476 (27 g/100 seeds). According to the orthogonal contrasts, only ABE4 ($p < 0.01$), ARME 2 ($p < 0.05$), Mil Uno ($p < 0.05$), and Paragachi ($p < 0.05$) were affected by the stress showing a reduction in seed weight.

Significant differences in the plant height for treatment ($p < 0.0001$), genotype ($p < 0.0001$), and G x E interaction ($p < 0.1$) were observed. The mean plant height of the experiment was 44.5 cm. Plant height under non-stress conditions was 46 cm, while height under stress conditions was 43 cm. Plant height ranged from 34 to 56 cm among genotypes.

Significant differences in the number of lateral roots for treatment ($p < 0.0001$) and genotype ($p < 0.0001$) were detected, and G x E interaction was not significant. The overall mean in number of lateral roots was 9.2. The genotypes under non-stress conditions produced 9.9 lateral roots, while the genotypes under stress produced 8.4 lateral roots. The number of lateral roots ranged from 6.7 to 12.0 among genotypes. The genotypes showing the greatest number of lateral roots were Yunguilla (12.0), POA 10 (11.8), YxA (10.8), and ACE 1 (10.2). The genotypes showing the lowest number of lateral roots were L88-63 (6.7), AFR476 (7.6), RAB655 (7.5), Canario Bola (8.0), RAB 651 (8.2), Paragachi (8.3), Mil Uno (8.5), and ABE 4 (8.7).

No significant differences for treatment effect and G x E interaction were detected in the number of pods per plant or seeds per pod. However, significant genotypic differences for were detected in the number of pods per plant ($p < 0.0001$), and number of seeds per pod ($p < 0.0001$). The overall number of pods mean per plant was 9.0 and the overall mean for number of seeds per pod was 4.2. The number of pods per plant ranged from 5.9 to 14.9. Genotypes with the largest number of pods per plant were RAB655 (14.9), L88-63 (14.7), and RAB 651 (14.2). The genotypes showing the largest number of seed per plant were RAB655 (5.4), RAB 651 (5.2), AFR 476 (5.1), and L88-63 (4.9).

Table 12. Yield, biomass, harvest index (HI), 100 seeds weight, plant height, stem thickness, number of lateral roots, number of pods per plant, and number of seeds per plant across treatments of 16 genotypes at the SGT in Tumbaco, Ecuador. 2005.

Genotype	Yield	Biomass	H.I.	100 seeds weight	Plant Height	Stem thickness	No lateral roots	No pods/plant	No seeds/pod
	— kg/ha —			(g)	(cm)	(mm)			
PARAGACHI	1833	4903	0.38	47	46	7	8.3	8.1	4.4
L88-63	1825	5003	0.37	21	48	7.6	6.7	14.7	4.9
MIL UNO	1817	4453	0.41	61	43	6.4	8.5	7.8	3.7
ACE2	1675	3711	0.46	49	40	6.1	9.7	5.9	4.5
RAB655	1630	4167	0.39	24	46	7.3	7.6	14.9	5.4
ABE 4	1622	3961	0.41	60	40	6.2	8.7	7.4	3.8
ARME2	1604	3792	0.43	53	44	6.8	9	8.1	3.9
ACE1	1509	3934	0.39	62	47	6.9	10.2	5.9	4.6
POA10	1506	4084	0.37	53	46	6.5	11.8	7	3.8
YxAs7	1448	3834	0.38	55	44	6.5	10.8	7.3	2.8
YUNGUILLA	1422	3653	0.39	53	47	6.7	12	7.4	3.4
COCACHO	1421	3208	0.45	42	36	5.1	9.5	7.9	4
RAB651	1368	3633	0.38	22	39	7.1	8.2	14.2	5.2
AFR476	1330	3147	0.43	27	56	7.6	7.6	12.1	5.1
SEQ1016	1192	3583	0.33	50	52	7	9.8	6.6	4.4
C. BOLA 60	1140	2772	0.41	40	34	5.4	8	9.4	3.7
MEAN	1521	3865	0.4	45	44	6.6	9.2	9	4.2
LSD (0.05)	255	659	0.04	3	5	0.6	2	2.1	0.7
CV (%)	14.3	14.5	9.6	5.4	8.7	8.3	18.6	19.7	13.6

The Pearson correlation analysis showed significant correlations between yield under stress and biomass (r= 0.88), yield under non-stress and biomass (r= 0.76**), 100 seed weight and no. of pods per plant (r= -0.92**), 100 seeds weight and no. of seeds per pod (r= -0.72**), plant height and stem thickness (r= 0.81***), and no. of pods per plant and no. of seeds per pod (r= 0.67**).

DISCUSSION

In Montcalm, the yield of 26 IBL was not consistent over the two years of testing. The overall yield mean in MC2004 (2502 kg/ha) was considerably higher than the overall mean yield in MC2005 (1669 kg/ha). The low yield of 2005 can be attributed to a severe attack of common bacterial blight (CBB) and variable plant stands was variable due germination problems in the plots. Additionally, low seed yield was related to the low translocation of carbohydrates from leaves and stems, since excessively high vegetative biomass production was observed compared with MC2004. This resulted in low harvest indices in 2005. Similar DII values were observed between years. DII was 0.27 in MC 2004 and 0.20 in MC2005. The environmental conditions in Montcalm 2004 and 2005 were not conducive for severe drought stress, however, the combined analysis of variance detected significant differences between water treatments in 2004. Only five genotypes were identified with high GM yield in both years, C03131, C03147, C03151, C03157, and C03163. The genotype C03121 was the top yielding genotype in MC2004, but was the lowest yielding genotype in MC2005. The severe infection of CBB (4.5) appeared to have reduced the yield of this genotype in 2005.

In Ecuador, genotypes C03102, C03110, C03121, C03122, C03131 and C03160 exceeded 2000 kg/ha based on the GM yield. These genotypes also had acceptable seed size. Genotype C03122, however, showed leaf deformity, probably the result of large genetic distance or gene pool differences between the two parents (Andean vs. Mesoamerican), and genotype C03110 did not possess a commercial cranberry seed type. The prevalent leaf deformity and the lack of commercial traits will likely cause rejection of these genotypes by farmers, so these genotypes will not be advanced in the breeding program. The unexpected high yield in Mil Uno under water stress conditions was interesting, since it is an Andean cultivar with no known drought resistance characteristics. Mil Uno is one of the preferred genotypes identified in participatory evaluations carried out under farmer's field conditions in Chota and Mira valleys in Ecuador (Pulse Beat, 2005), where drought is known to occur. Mil Uno was identified as the top yielding genotypes in Tumbaco 2005 under both stress and non-stress conditions. The drought resistance in Mil Uno could be improved to levels closer to the potential yield of Mil Uno under non-stress conditions through crosses with other drought resistant genotypes identified in this study.

Root rot score and seed size were also considered as important selection criteria. Therefore, Genotypes C03151 and C03155, which were not among the top yielding genotypes in Tumbaco, were identified as potential parents for future evaluation in Ecuador.

The high correlation observed between yield and biomass in MC2004 and Tumbaco 2005 agrees with the results obtained by Acosta-Gallegos and Adams (1991) and Abebe and Brick (2003), where high biomass can be used as criteria to select for drought resistant genotypes.

In 2005, the SGT experiment in Tumbaco had a DII = 0.14 versus 0.36 for the IBL study. This is the lowest DII registered in the drought experiments conducted in Montcalm and Tumbaco. Despite similarities in precipitation and irrigation management between the two drought experiments conducted in Tumbaco, the low DII value was not surprising. The SGT experiment includes genotypes previously identified as drought resistant in Ecuador such as SEQ1016, Paragachi, and AFR 476 (Programa Nacional de Leguminosas. 1995), and drought resistant genotypes from other countries such as L88-63, RAB 651, and RAB 655. These genotypes could have combined to reduce the drought effect across the experiment by producing higher yields under stress. The combined analysis of variance showed significant differences between the two water treatments and genotypes with high DSI values such as ABE4 (2.14), C. Bola (1.62), and ACE1 (1.62) confirm the severity of the drought in this trial and the overall susceptibility to drought in these three standard cultivars (Table 10). Genotypes 'Cocacho' and 'C. Bola 60' showed earliness, but these genotypes had the lowest yield. This is supported by the conclusions of Subbarao et al. (1995) that earliness is generally associated with low yield.

From the crosses conducted in the greenhouse in Michigan, the second backcross population: Mil Uno x RAB 651, ABE 4 x L88-63, ABE 4 x RAB 651, ACE 2 x RAB 651 will be selfed and IBL populations will be developed for future evaluations and studies in Ecuador. Each of the selected recurrent parents is representative of the three most popular seed classes in the Ecuadorian market. The IBL populations will be evaluated in collaboration with INIAP in Ecuador in future years.

CONCLUSIONS

Based on high GM yield, yield under stress, 100 seed weight, and seed quality, five genotypes from the IBL population were selected: C03121, C03131, C03155, C03151, and C03102. Additionally, the reaction to CBB must be considered, and genetic resistance should be incorporated in lines C03121, C03155, and C03151, otherwise the outstanding characteristics shown by these genotypes for drought resistance and commercial qualities could be negated by the disease.

Based on performance in the field under water stress conditions, genotypes Paragachi, RAB651, NSL, and L88-63 were selected as drought resistant. These drought resistant sources will be crossed with genotypes Mil Uno, ACE2 and ABE4, since these genotypes possess commercial seed traits demanded by farmers and consumers in Ecuador. Mil Uno also showed acceptable yield under both stress and non-stress conditions in Ecuador, whereas ACE 2 and ABE 4 showed high potential yield under non-stress conditions.

Genotypes showing the highest geometric yield mean and the lowest DSI values were the top yielding genotypes under stress conditions. Collecting data on GM and DSI requires that two treatments be evaluated, which requires more work and land resources. Given the low G x E interaction observed for yield across water treatments it may be possible to make gains in drought tolerance by selection in a single stress environment. Therefore, selection only under stress conditions could be conducted in production fields in Ecuador, where land resources are scarce. All selected lines, however, will be evaluated under irrigation prior to release as varieties as yield potential is an important criteria.

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CHAPTER II

INTRODUCTION

Traditional methods to identify drought resistant cultivars are time consuming, weather dependant, and space limited. Consequently, plant physiologists and breeders have attempted to develop alternative methods to evaluate cultivars for drought resistance under controlled environments such as growth chambers, greenhouses, or laboratory conditions (Ogbonnaya et al., 2003; Price et al., 1997). These non-conventional methods could permit the evaluation of large number of genotypes to maximize the likelihood of identifying drought resistant cultivars, while reducing cost, time, and space (Pennypacker et al., 1990). However, resistance to drought, expressed on the basis of yield, is the result of complex interactions of different traits that can only be determined under field conditions (Singh, 1992). Methods for assessing drought resistance may be affected by the difficulty of simulating the natural environment where the plant experiences water stress. Consequently, the data from such experiments may be poorly correlated with field results (White et al., 1994). Therefore, researchers need to reproduce a stress environment to select genotypes with superior performance under specific field conditions, or must focus on single traits such as root development or shoot architecture with large influence on drought resistance in different environments (Ludlow, 1989; Sponchiado et al., 1989; White and Castillo, 1989). The objectives of this research were to: i) to identify bean genotypes expressing differences in root traits during first 30 days of growth under stress conditions in the greenhouse, ii) to identify root variables that are correlated with yield data from field experiments,and iii) to validate the PVC-tube methodology as a selection tool for identifying drought resistant bean genotypes.

MATERIALS AND METHODS

Plant material.- A cranberry common bean IBL population (C97407*2/'Negro San Luis' (NSL)), described in Chapter I, and a group of common bean genotypes, identified as the standard genotype test (SGT), were grown in the Michigan State University greenhouse during the Summer and Fall 2004. Roots traits of these genotypes were studied in three experiments consisting of 13 genotypes each (Table 1). The 26 genotypes from the IBL population were randomly divided in two groups (IBL1 and IBL2) of 13 genotypes each to facilitate their evaluation due to limited greenhouse space (Table 13). To complete 16 entries in each experiment, lines L88-63 (Drought resistant), C97407 (IBL population recurrent parent) and variety 'Negro San Luis' (IBL population donor parent) were included as controls. Genotypes in the SGT are shown in Table 14.

Experiment management. - Three seeds of each genotype were planted in a 1.0 m x 0.10 m-PVC-tube and thinned after seven days after planting (dap) to only one plant per tube. The PVC tubes were, previously, cut longitudinally to allow opening without causing root damage. Coarse sand was used as medium to grow the plants. Twenty-eight dap, the sand was carefully washed from the roots and the roots were fixed in 5% ethanol. The roots were maintained on ice up to 48 h before being scanned and analyzed using the WinRHIZO™ (Regent Instruments Inc., 2000, Quebec, Canada) software.

Table 13. Characteristics of the common bean genotypes in experiments IBL1 and IBL2 used to conduct the root study. Michigan State University. 2004.

IBL1 experiment			IBL2 experiment		
Genotype	Growth habit	Seed size (g)	Genotype	Growth habit	Seed size (g)
C03108	I	51	C03102	III	49
C03117	I	46	C03104	I	50
C03119	III	50	C03110	I	58
C03121	I	53	C03123	I	48
C03122	I	48	C03127	I	45
C03125	I	45	C03129	I	55
C03151	III	51	C03131	I	53
C03154	I	34	C03143	I	51
C03155	I	50	C03147	III	43
C03157	III	56	C03148	I	43
C03160	III	48	C03149	III	36
C03161	III	38	C03150	III	51
C03163	I	42	C03156	III	45
C97407	I	47	C97407	I	47
L88-63	II	24	L88-63	II	24
NSL	III	38	NSL	III	38

Table 14. Characteristics of the common bean genotypes in SGT experiment used to conduct the root study. Michigan State University. 2004.

Genotype	Grow habith	Source	Seed size	Seed type
Yunguilla	I	INIAP	Large	Red mottled
Paragachi	II	INIAP	Medium	Red mottled
ACE 1	I	INIAP	Medium	Yellow
ACE 2	I	INIAP	Medium	Yellow
ABE 4	I	INIAP	Large	White
POA 10	I	CIAT	Medium	Red mottled
AFR 476	I	CIAT	Medium	Red mottled
YxAs7	I	INIAP	Large	Red mottled
SEQ 1016	II	CIAT	Large	Yellow
L88-63	II	MSU	Small	Black
RAB 651	II	CIAT	Medium	Red
RAB 655	II	CIAT	Medium	Red
C97407	I	MSU	Large	Cranberry
ARME 2	II	INIAP	Medium	Red mottled
Mil Uno	I	Landrace	Large	Purple mottled
Cocacho	I	Landrace	Medium	Canario

Irrigation management. - Water and (half-strength) Hoagland's solution were used to irrigate the PVC tubes. The plants received the same amount of Hoagland's solution during the first week after planting until plant emergence. After the first week, different irrigation amounts were applied to each water treatment. In order to avoid differences in fertility, the (half-strength) Hoagland's solution was used whenever both treatments were irrigated, otherwise, plants under non-stress were irrigated only with water. Moisture conditions were controlled throughout the experiment using tensiometers at 0.3 m depth. The genotypes under non-stress conditions were irrigated when the tensiometers exceeded 15 cbars, while the genotypes under stress were maintained above 35 cbars. Genotypes under stress conditions were irrigated when severe dehydration symptoms for more than two days were observed. Differences in the amount of water/solution used to irrigate each experiment were due to differences in water demand of each experiment caused by differences in ambient temperature (Table 15).

Table 15. Amount of water/solution applied, date of the experiment, mean temperature, and relative humidity registered in the root study. Michigan State University. MI 2004.

Experiment	Amount of water/solution (ml)		Months	T (°C)*	RH (%)*
	Stress	Non-stress			
GST	250	575	04-05	24.0	51.9
IBL1	625	975	06-07	27.2	43.0
IBL2	750	1050	08-09	27.6	43.9
Average	542	867		26.3	46.3

* Ambient temperature and relative humidity collected during 21 days after plant emergence.

Variables recorded.- Total root length (TRL), length of the taproot (LTR), projected root area (PA), root volume (RV), average root diameter above 0.3m (DA above 0.3m), average root diameter below 0.3 m (DA below 0.3m), number of lateral roots (NLR), and root length in each width category (A= 0.0-0.5; B= 0.5-1.0; C= 1.0-2.0; and D> 2.0 mm) were recorded.

Statistical analyses

Analysis of variance (ANOVA) was calculated for each experiment. Data from the greenhouse at MSU were analyzed as split plot design using INFOSTAT 2.0 (Universidad Nacional de Cordova, 2002). Water treatment was considered as the whole plot and genotypes were considered as the sub plot. Means, coefficient of variance (CV) were calculated for each ANOVA. Less Significant Difference (LSD; 0.05) test was calculated for each variable with statistical difference detected. The degree of association between traits related with yield and root development was calculated with through the

Pearson coefficient values (r) using PROC CORR and PROC REG (SAS Institute Inc., 2000).

RESULTS

SGT experiment. – Significant differences were found in total root length (TRL) for treatment effect ($p < 0.01$) and genotype ($p < 0.05$) (Figure 2) in the SGT experiment. The mean value for TRL for all genotypes was 2577 cm under both stress and non-stress conditions. Genotypes showed a reduction of 15.7 % in total root length from 2797 cm under non-stress to 2358 cm under stress conditions. The genotypes exhibiting the shortest TRL length were AFR 476 (1960 cm), and L 88-63 (1998 cm), while C97407 (3168 cm), and POA 10 (3225 cm) showed the largest values. The analysis of root length distribution for each root category (Table 16) showed that the fine roots in categories A and B possessed the longest roots with 69.9 % (1802 cm) and 21.6 % (558 cm) of the total root length respectively. Roots in category C, corresponding to the tap root, comprised only 7.7 % of the total root length, whereas roots in category D represented an apparently insignificant percentage of 0.4 % (7 cm) of the total root length. A separate analysis of the root distribution of the four root categories in each water treatment (Figures 2, 3) showed significant root length reductions in all categories under water stress. Root length in categories A and B under stress conditions were reduced by 9.8 and 15.9 %, respectively, when compared to genotypes under non-stress. Roots in categories C and D were dramatically reduced by 51.7 and 40.0 %, respectively, under stress conditions.

Table 16. Root length and percentage of the total root length in categories A (0.0 – 0.5mm), B (0.5 – 1.0 mm), C (1.0 – 2.0 mm), and D (> 2.0 mm) under water stress and non stress conditions in two different depths of the PVC tube and in the whole PVC-tube in SGT experiment. Michigan State University. MI 2004.

	Root Category															
	A				B				C				D			
	Stress		Non-stress		Stress		Non-stress		Stress		Non-stress		Stress		Non-stress	
Region of the tube	Length (cm)	%	Length (cm)	%	Length (cm)	%	Length (cm)	%	Length (cm)	%	Length (cm)	%	Length (cm)	%		%
Above 0.3 m	1150	74.1	1426	69.5	323	20.1	454	22.1	70	4.5	147	7.2	5	0.3	10	0.5
Below 0.3 m	559	69.4	468	62.8	187	23.2	152	20.4	58	7.2	120	16.1	2	0.2	2	0.3
Total	1709	72.6	1894	68.2	510	21.7	606	21.8	129	5.5	267	9.6	7	0.3	12	0.4

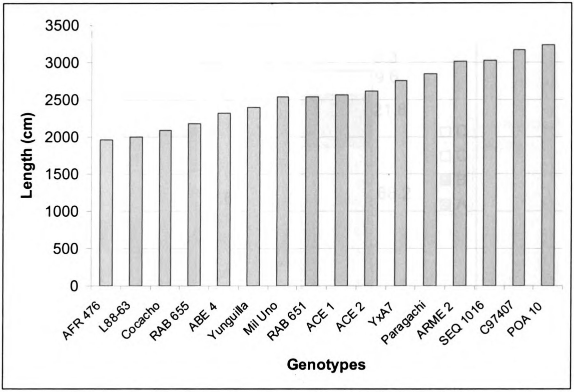

Figure 2. Total root length of the 16 bean genotypes in the SGT experiment.

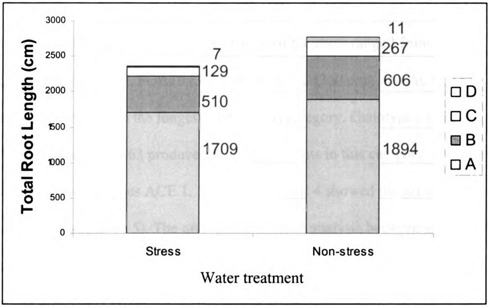

Figure 3. Root length in four root categories under two water treatments in SGT experiment.

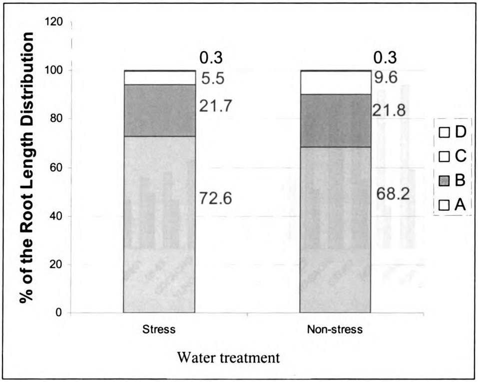

Figure 4. Percentage of the total root length in four root categories under two water treatments in SGT experiment.

The root category C was the only category that showed statistical differences for the interaction effect ($p < 0.1$). The length of the roots ranged from 62.5 cm to 447 cm. SEQ 1016 (447 cm), POA10 (371 cm), ARME2 (360 cm), and ACE1 (348 cm) under non-stress produced the longest roots in this category. Genotypes AFR 476, RAB 655, RAB 651, and L88-63 produced the shortest roots in this category under both stress and non stress. Genotypes ACE 1, YxAs7, and ABE 4 showed the greatest root reduction under stress (Figure 5). The orthogonal contrast analysis between genotypes under stress and non-stress allowed the identification of genotypes that were not affected by drought stress and produced the same root length in category C under both conditions. These genotypes included AFR 476, Cocacho, L 88-63, Paragachi, RAB 651, RAB 655, and Yunguilla that did not differ significantly under stress and non-stress (p <0.1).

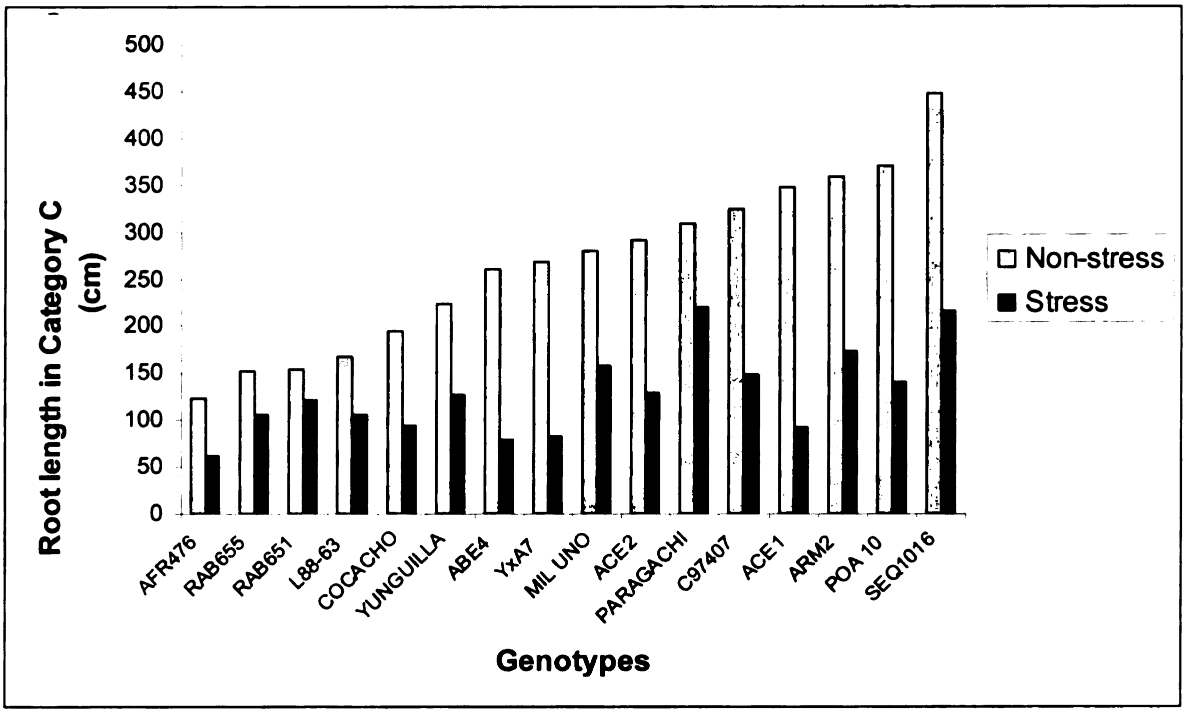

Figure 5. Root length of the 16 bean genotypes in category C (1.0 – 2.0 mm), under stress and non-stress conditions in the SGT experiment.

Significant differences in taproot length for treatment effect ($p < 0.01$) were detected. Genotypes under stress conditions developed longer taproots (67.5 cm) than under non-stress conditions (60.3 cm) and there were no significant differences for either genotype or interaction effect.

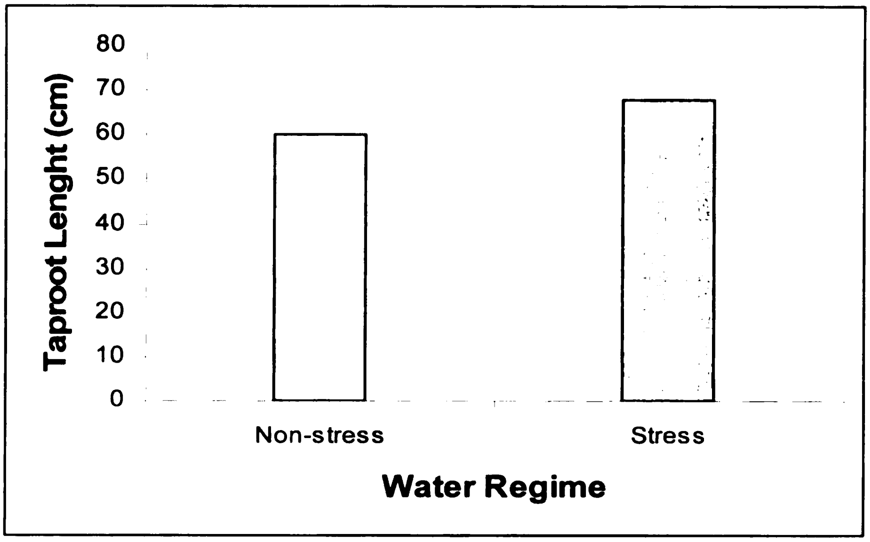

Figure 6. Taproot length of the 16 bean genotypes under two water treatments in SGT experiment.

Significant differences in the number of lateral roots were detected for treatment ($p < 0.0001$) and genotype ($p < 0.0001$) effects. The genotypes responded to stress conditions by decreasing the number of lateral roots. Under non-stress conditions, the mean number was 12.9 lateral roots, while under stress conditions the average was 9.8 lateral roots and the overall mean was 11.3 lateral roots. The number of lateral roots ranged from 7.8 to 14. 3. Genotypes with the smallest number of lateral roots were L88-63 (7.8), RAB 655 (8.3), and RAB 651 (10.0), whereas ACE 2 (14.2), and POA 10 (14.3) had the largest number of lateral roots (Figure 7).

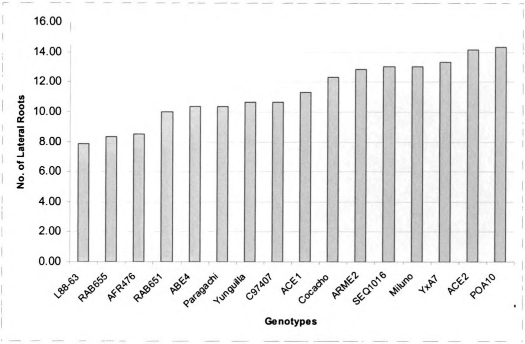

Figure 7. Number of lateral roots of the genotypes in SGT.

Significant differences in projected root area were detected for treatment ($p <$ 0.0001) and genotype ($p < 0.0001$) effects. Under water stress conditions, the projected area mean was 102 cm^2 and under non-stress conditions was 134 cm^2. The overall mean for projected area in STG experiment was 118 cm^2. The projected root area across the genotypes ranged from 82 to 152 cm^2. AFR 476 (82 cm^2) and L88-63 (88 cm^2) had the lowest projected area under the two water treatments. Genotypes showing the largest projected root area were ARME 2 (144 cm^2), C97407 (146 cm^2), POA 10 (151 cm^2), and SEQ 1016 (152 cm^2) (Figure 8). Statistical differences were observed in projected root area for genotype above 0.3 m ($p < 0.0001$) and below 0.3 m ($p < 0.05$) in the PVC tube.

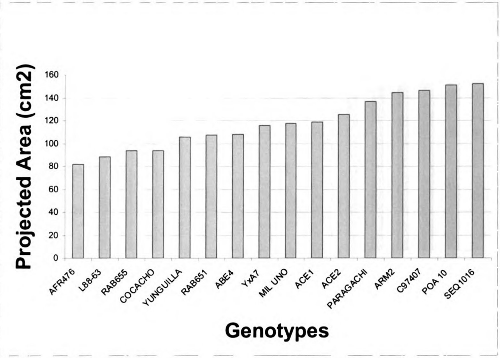

Figure 8. Projected root area (cm^2) of the 16 bean genotypes in SGT experiment.

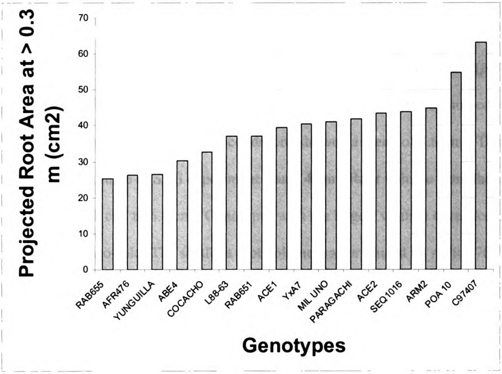

Figure 9. Projected root area (cm^2) of the 16 bean genotypes below 0.3 m of the PVC-tube in SGT experiment.

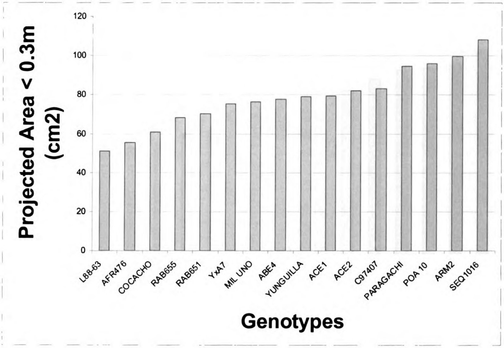

Figure 10. Projected root area (cm^2) of the 16 bean genotypes in SGT experiment above 0.3 m of the PVC-tube.

Significant differences in root volume were detected for treatment ($p < 0.001$) and genotype ($p < 0.001$) effects. Genotypes under non-stress conditions showed a mean of 5.2 cm^3 and genotypes under stress conditions showed a mean of 3.6 cm^3. The overall mean of root volume in STG experiment was 4.4 cm^3. Root volume from the genotypes ranged from 2.8 cm^3 to 6.1 cm^3. Genotypes with the largest volume exceeded the smallest genotypes by two-fold. The smallest root volume was produced by AFR 476 (2.8 cm^3), L88-63 (3.1 cm^3), RAB 655 (3.2 cm^3), and Cocacho (3.4 cm^3), whereas genotypes C97407 (5.5 cm^3), ARME 2 (5.5 cm^3), POA 10 (5.7 cm^3), and SEQ 1016 (6.1 cm^3) produced the greatest volume (Figure 11).

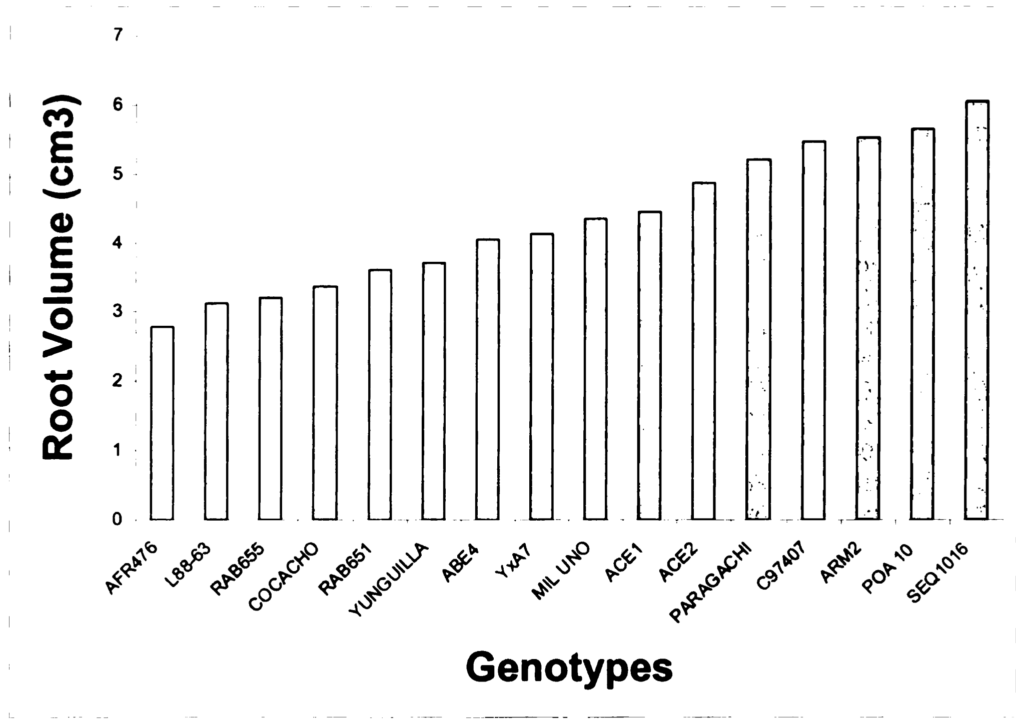

Figure 11. Root volume (cm^3) of the 16 bean genotypes in SGT.

Table 17. Total root length (TRL), length of the taproot (LTR), number of the lateral roots (No of LR), projected root area (PA), root volume (RV), root length in category A (RL (A)), category B (RL (B)), category C (RL(C)), and category D (RL (D)) for 16 genotypes in STG experiment grown in greenhouse in Michigan State University, MI 2004.

Genotype	TRL (cm)	LTR (cm)	No of LR	PA (cm2)	RV (cm3)	RL (A) (cm)	RL (B) (cm)	RL (C) (cm)	RL (D) (cm)
POA 10	3225	69	14.3	150.9	5.7	2237	714	256	18
C97407	3168	76	10.7	146.4	5.5	2179	739	236	14
SEQ1016	3028	58	13	152.1	6.1	2032	645	331	21
ARME2	3008	61	12.8	144.4	5.5	2075	652	267	14
PARAGACHI	2852	62	10.3	136.5	5.2	1972	587	265	13
YxA7	2761	66	13.3	116	4.1	1857	606	175	6
ACE2	2611	65	14.2	125.7	4.9	1768	618	211	14
ACE1	2563	70	11.3	118.7	4.5	1796	539	220	8
RAB651	2542	69	10	107.4	3.6	1865	535	138	4
MIL UNO	2540	66	13	117.5	4.4	1759	563	220	8
YUNGUILLA	2402	55	10.7	105.6	3.7	1720	499	176	6
ABE4	2316	56	10.3	108.2	4.1	1604	516	170	8
RAB655	2178	60	8.3	93.5	3.2	1586	435	129	3
COCACHO	2085	63	12.3	93.7	3.4	1476	463	145	2
L88-63	1998	57	7.8	88.2	3.1	1443	413	137	5
AFR476	1960	69	8.5	81.7	2.8	1459	406	93	2
MEAN	2577	64	11.3	117.9	4.4	1802	558	198	9
LSD (0.05)	670	ns	2.8	28.8	1.2	508	128	76	8
CV (%)	22.5	18.1	21.3	21.2	23.4	24.4	19.8	33.2	75.8

IBL1 experiment.- Significant differences in total root length were detected for treatment effect ($p < 0.0001$), genotype ($p < 0.0001$), and the G x E interaction ($p < 0.1$) in the IBL1 experiment. The overall mean for total root length was 3890 cm. There was a reduction of 24.8% in total root length among genotypes under stress. The total root length of the genotypes under non-stress was 4441 cm, and under stress was 3340 cm. The length of the genotypes ranged from 3046 to 4872 cm. The genotypes with the greatest root length were C03157 (4872 cm), C03121 (4619 cm), C03151 (4387 cm), C03119 (4386 cm), C03117 (4350 cm), C03163 (4250 cm), and C03155 (4158 cm). The resistant control, L88-63 (3485 cm), and the resistant parent, NSL (3176 cm) ranked in the lowest group along with C03125 (3046 cm), C03161 (3185 cm), C03108 (3380 cm), C03122 (3491 cm), and C03154 (3578 cm) (Figure 12). The orthogonal contrast analysis showed that the total root length of C03108, C03117, C03122, C03125, C03154, C03161, and L88-63 did not differ significantly ($p < 0.1$) under stress and non-stress treatments (Figure 13). Additionally, significant differences were detected in all root length categories for genotype (A ($p < 0.001$), B ($p < 0.0001$), C ($p < 0.005$), and D ($p < 0.001$)).

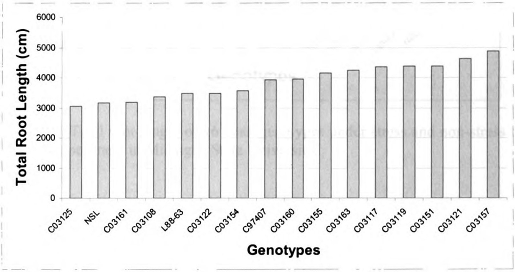

Figure 12. Total root length average of two treatments of 16 bean genotypes in IBL1 experiment in Michigan State University.

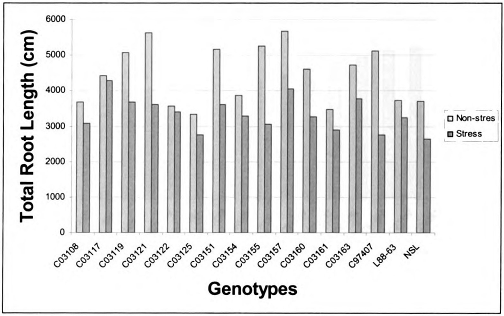

Figure 13. Total root length of 16 bean genotypes under stress and non-stress conditions in IBL1 experiment in Michigan State University.

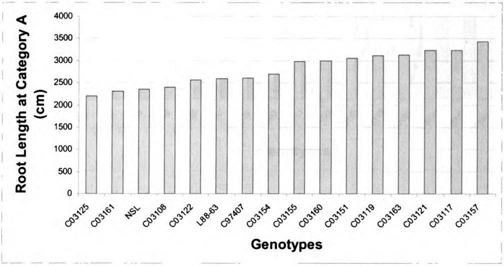

Figure 14. Root length of 16 bean genotypes in category A in IBL1 experiment in Michigan State University.

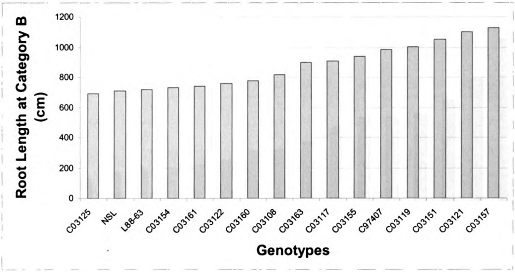

Figure 15. Root length of 16 bean genotypes in category B in IBL1 experiment in Michigan State University.

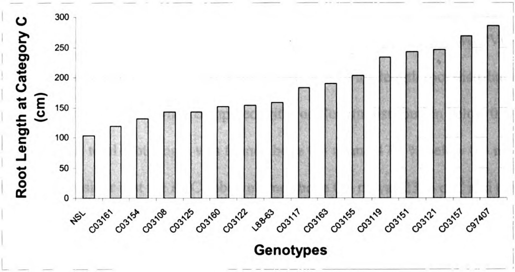

Figure 16. Root length of 16 bean genotypes in category C in IBL1 experiment in Michigan State University.

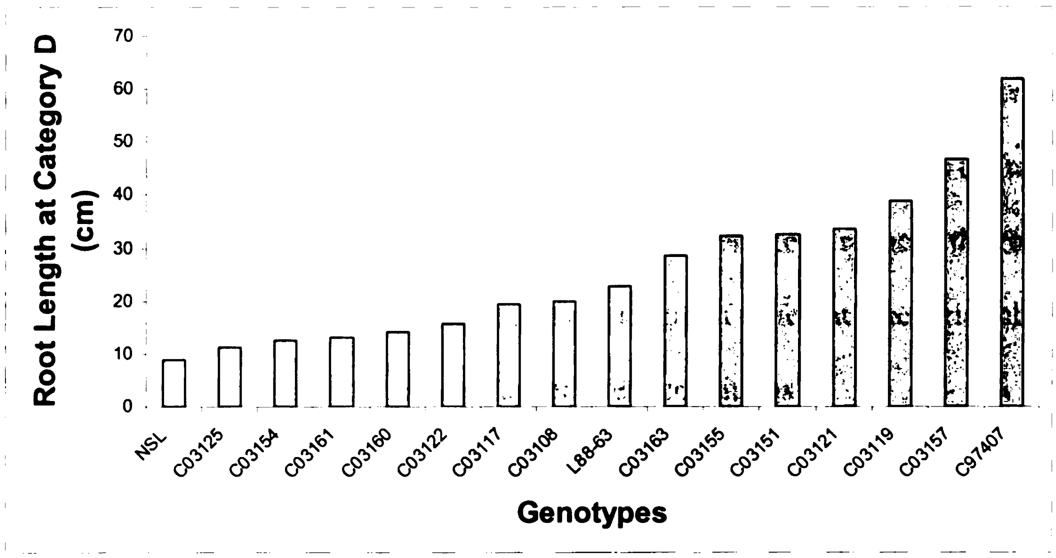

Figure 17. Root length of 16 bean genotypes in category D in IBL1 experiment in Michigan State University.

The analysis of root distribution in the IBL1 experiment in the two PVC-tube regions showed that there were no major differences in the length root distribution in the PVC-tubes above 0.3 m when compared with root length distribution below 0.3 m, since 52.7 % of the total root length was found above 0.3 m and 47.3 % below 0.3 m. However, one must consider that the PVC-tube volume above 0.3 m was 2356 cm^3 and the PVC-tube volume below 0.3 m was 5498 cm^3. Therefore, more root density per volume (0.87 cm/cm^3) was observed above 0.3 m of the PVC tube than below 0.3 m (0.33 cm/cm^3). Under non-stress conditions, the root density above 0.3 m was 0.9 cm/cm^3, while under stress conditions the root density decreased to 0.81 cm/cm^3. The root density reduction became more severe when comparing root density above 0.3 m under non-stress conditions (0.41 cm/cm^3) with root density below 0.3 m under stress conditions (0.26 cm/cm^3). The distribution analysis in each category showed that the thinner roots were the longest. Category A represented 72.2 % (2807 cm) of the total root length (3891 cm), compared to 22.4 % (87.3 cm) for category B, 4.8 % (185 cm) for category C, and 0.7%

(26 cm) for category D. The percentage of distribution of root length decreased in all the categories under stress conditions except in category A. The root length of category A was 70.2 % of the total root length under non-stress, whereas under stress the total root length of category A was 74.8 %. The IBL1, under water stress, reduced the root length in all categories and the percentages of the root length in different categories changed increasing the proportion of thin roots under stress conditions.

Table 18. Root length and Root density at two different depths of the PVC-tube in IBL1 experiment.

	Average		**Stress**		**Non-stress**	
PVC-tube region (m)	**Length (cm)**	**Density (cm/cm^3)**	**Length (cm)**	**Density (cm/cm^3)**	**Length (cm)**	**Density (cm/cm^3)**
above 0.3	2052.5	0.87	1908	0.81	2197	0.93
below 0.3	1838.5	0.33	1433	0.26	2244	0.41

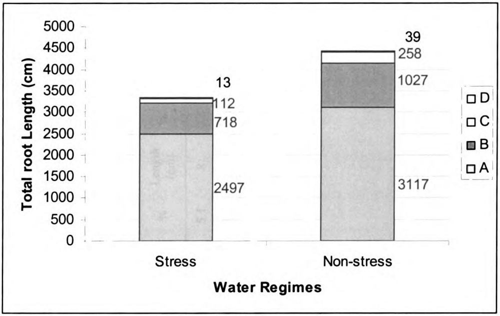

Figure 18. Root length of IBL1 experiment per category under stress and non-stress conditions.

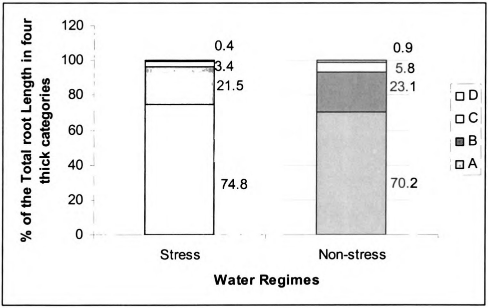

Figure 19. Percentage of root length per root category in IBL1 experiment.

Table 19. Total root length, root length above 0.3 m of the PVC-tube, root length below 0.3 m of the PVC-tube, percentage of root distribution per category, percentage of root distribution per category above 0.3 m, and percentage of root distribution per category below 0.3 m under stress and non-stress conditions for 16 genotypes in IBL1 experiment grown in greenhouse in Michigan State University, MI 2004.

	Root Category															
	A				B				C				D			
	Stress		Non-stress		Stress		Non-stress		Stress		Non-stress		Stress		Non-stress	
PVC-tube region	Length (cm)	%	Length (cm)	%	Length (cm)	%	Length (cm)	%	Length (cm)	%	Length (cm)	%	Length (cm)	%	Length (cm)	%
< 0.3 m	1441	75.6	1586	72.2	396	20.8	483	22	63	3.3	112	5.1	8	0.4	16	0.7
> 0.3 m	1056	73.7	1532	68.3	322	22.5	544	24.2	49	3.4	146	6.5	5	0.3	22	1
Total	2497	74.8	3117	70.2	718	21.5	1027	23.1	112	3.4	258	5.8	13	0.4	39	0.9

Significant differences in taproot length were detected for treatment effect, but not for genotype and G x E interaction. Genotypes under stress reduced the length of the taproot from 79 cm under non-stress to 63 cm. The taproot length of the genotypes ranged from 60 to 84 cm, and the overall mean of the experiment was 71 cm.

Significant differences in number of lateral roots were detected for treatment effect ($p < 0.001$) and genotype ($p < 0.001$). The mean of the number of lateral roots was reduced from 9.7 lateral roots under non-stress conditions to 7.1 lateral roots under stress conditions. The number of lateral roots ranged from 5.3 to 11 lateral roots. The overall mean of number of lateral roots was 8.4. Genotypes NSL (5.3) and C03160 (6.8) had the lowest number of lateral roots, whereas C97407 (9.5) and C03119 (11) had the greatest number of lateral roots in IBL1 experiment.

Significant differences in projected root area were detected for treatment effect ($p < 0.001$), genotype ($p < 0.0001$) and G x E interaction ($p < 0.05$). The overall mean of projected area was 166 cm^2. The mean root area produced by genotypes under non-stress conditions was 199 cm^2, whereas the mean under stress was 132 cm^2. The projected root area of genotypes in IBL1 experiment ranged from 126 to 219 cm^2. The genotypes showing the largest projected area were C03157 (219 cm^2), C03121 (203 cm^2), C03151 (196 cm^2), C97407 (195 cm^2), C03119 (194 cm^2), and C03163 (181 cm^2), whereas the drought resistant parent NSL (126 cm^2) and the control L88-63 (143 cm^2) produced the smallest projected root area. The orthogonal contrast analysis showed that the projected root area of genotypes C03108, C03117, C03122, C03125, C03154, C03161, L88-63, and NSL were not reduced significantly ($p < 0.1$) under stress conditions. The remaining genotypes were affected by water stress with reduced projected root area.

No significant differences in projected area above 0.3 m were detected, however, significant differences in projected root area below 0.3 m were detected for genotypes ($p < 0.001$). The means of the projected area above 0.3 m ranged from 67.1 to 105.5 cm^2, while the means of the projected area below 0.3 m ranged from 48.0 to 126.4 cm^2. The mean areas were 84.2 and 81.4 cm^2 above 0.3 m and below 0.3 m, respectively.

Significant differences in root volume were detected for treatment effect ($p < 0.0001$), genotype ($p < 0.0001$), and G x E interaction ($p < 0.01$). The overall mean root volume for all genotypes was 5.7 cm^3. The root volume mean for genotypes under non-stress was 7.2 and under stress was 4.2 cm^3. Root volume of the genotypes ranged from 3.9 to 8.0 cm^3. Genotypes C03157 (8.0 cm^3), C97407 (7.8 cm^3), C03121 (7.2 cm^3), C03151 (7.0 cm^3), C03119 (6.9 cm^3), and C03155 (6.3 cm^3) had the largest root volume. The orthogonal contrast analysis showed that root volume under water stress conditions was not reduced for genotypes C03108 ($p > 0.1$), C03117 ($p > 0.1$), C03122 ($p > 0.1$), C03125 ($p > 0.1$), C03154 ($p > 0.1$), C03161 ($p > 0.1$), L88-63 ($p > 0.1$), and NSL ($p > 0.1$). The remaining genotypes reduced the root volume under stress conditions. Additionally, root volume under stress showed correlation ($r= -0.64$) with the geometric mean of genotypes grown in Tumbaco in 2005.

Significant differences in root/shoot ratio were detected for treatment effect ($p< 0.05$) and genotype ($p< 0.0001$) in IBL1 experiment. The overall mean of shoot/root ratio was 2.3. The mean under non-stress treatment was 2.4, while under water stress was 2.1. Genotypes ranged from 1.63 to 3.16 for shoot/root ratio. The genotypes exhibiting the largest values for root/shoot ratio were NSL (3.16), C03151 (3.06), L88-63 (2.76), C03117 (2.68), and C03155 (2.58).

Table 20. Total root length (TRL), length of the taproot (LTR), number of the lateral roots (No of LR), root weight (RW), surface area (SA), projected area (PA), and root volume (RV) for 16 genotypes in IBL1 experiment in Michigan State University, MI 2004.

Genotypes	TRL (cm)	LTR (cm)	No of LR	RW (g)	SA (cm^2)	PA (cm^2)	RV (cm^3)
C03157	4872	81	8.3	12.3	687	219	8
C03121	4619	75	8.5	10.8	639	203	7.2
C03151	4387	72	9	11.2	614	195	7
C03119	4386	78	11	11.4	608	194	6.9
C03117	4350	84	9.2	10.3	550	175	5.6
C03163	4250	76	7.8	10.3	551	175	5.9
C03155	4158	70	8.8	10.5	568	181	6.3
C03160	3945	72	6.8	10	486	155	4.8
C97407	3941	62	9.5	11.8	611	195	7.8
C03154	3578	73	8.2	7.9	440	140	4.4
C03122	3491	68	7.7	8.4	456	145	4.8
L88-63	3485	78	7.8	8.2	449	143	4.7
C03108	3380	63	8.5	9.1	457	145	5
C03161	3185	62	9.2	7.7	410	130	4.2
NSL	3176	60	5.3	7.7	396	126	3.9
C03125	3046	65	8.8	8.5	399	127	4.2
MEAN	**3890**	**71**	**8.4**	**9.8**	**520**	**166**	**5.7**
LSD (0.05)	**786**	**ns**	**1.8**	**2.5**	**132**	**42**	**2.0**
CV (%)	**17.5**	**23.2**	**18.6**	**22.5**	**22.0**	**22.0**	**30.3**

Table 21. Root length in category A (RL (A)), category B (RL (B)), category C (RL(C)), and category D (RL (D)) for 16 genotypes in IBL1 experiment in MSU, MI 2004.

Genotypes	RL (A) (cm)	RL (B) (cm)	RL (C) (cm)	RL (D) (cm)
C03108	2398	819	143	20
C03117	3241	907	183	19
C03119	3110	1003	234	39
C03121	3240	1100	246	33
C03122	2562	759	154	16
C03125	2198	694	143	11
C03151	3062	1050	242	32
C03154	2702	732	131	13
C03155	2982	941	204	32
C03157	3431	1126	269	47
C03160	2999	779	152	14
C03161	2313	740	119	13
C03163	3131	900	190	29
C97407	2608	986	286	62
L88-63	2587	718	158	23
NSL	2353	710	104	9
MEAN	**2807**	**873**	**185**	**26**
LSD (0.05)	**619**	**196**	**94**	**23**
CV (%)	**19.1**	**19.4**	**44.1**	**76.8**

IBL2 experiment.- No significant differences in taproot length were detected in IBL2 experiment. Significant differences were detected only for treatment effect ($p < 0.001$). The taproot mean of the IBL2 experiment under non-stress conditions was 51.0 cm, producing a deeper taproot than genotypes under stress conditions, which showed a mean of 42.7 cm. Genotypes under stress exhibited a reduction in taproot length of 16.3%. The taproot length overall mean was 46.8 cm and the taproot length of the genotypes ranged from 39.7 cm to 62.5 cm.

Significant differences in number of lateral roots were detected for treatment effect ($p < 0.0001$). The genotypes under stress reduced the number of lateral roots (7.6), compared with genotypes under non-stress (10.8). There were no significant differences for genotype and G x E interaction. The overall mean number of lateral roots in IBL2 experiment was 9.2 and the number of lateral roots in IBL2 experiment ranged from 7.5 to 10.2 lateral roots.

Significant differences in root weight were detected for treatment ($p < 0.05$) and genotype ($p < 0.0001$) effects. Root weight of IBLs under non-stress was 3.2 g, while the root weight of IBLs under stress was 2.9 g. The overall mean for root weight in IBL2 experiment was 3.1 g. The root weight of the IBLs ranged from 2.2 g to 4.6 g. Genotypes C97407 (4.6 g) and C03123 (4.2 g) had the largest root weight, whereas NSL (2.2 g) and L88-63 (2.5 g) had the lightest weight.

No significant differences in total root length were detected for treatment effect, however, there were statistical differences for genotype ($p < 0.001$) in IBL2 experiment. The total root length in IBL2 ranged from 1278 cm to 2647 cm. The total root length overall mean was 1741 cm. C97407 (2647 cm), C03150 (2320 cm), and C03123 (2085 cm) included the genotypes with the longest total roots, while L88-63 (1417 cm) and NSL (1504 cm) were the genotypes with the shortest root length.

No significant differences in projected root area were detected for treatment effect and the G x E interaction, but significant differences were detected for genotype ($p < 0.001$). The overall mean of projected root area was 80 cm^2. The projected root area in genotypes ranged from 59.7 cm^2 to 118.4 cm^2. C97407 (118.4 cm^2), C03123 (106.0 cm^2), and C03150 (104.4 cm^2) exhibited the largest projected root area, whereas L88-63 (64.8 cm^2) and NSL (66.2 cm^2) had the lowest projected area. Significant differences in projected root area were detected for genotypes above 0.3 m ($p < 0.0001$) and below 0.3 m ($p < 0.001$).

Significant differences in root volume were detected for genotype ($p < 0.001$), but there were no significant differences for treatment effect in the IBL2 experiment. The root volume overall mean was 3.0 cm^3. The genotypes root volume ranged from 2.2 to 4.3 cm^3. C03123 (4.3 cm^3), C97407 (4.2 cm^3), and C03150 (3.7 cm^3) had largest root volume, whereas NSL (2.3 cm^3) and L88-63 (2.4 cm^3) were among genotypes with the lowest root volume.

Significant differences in root category A were detected for genotypes ($p < 0.001$). The genotypes ranged from 836 cm to 1878 cm. C97407 (1877.7 cm), C03150 (1668.4 cm), C03149 (1468.2 cm), and C03148 (1458.5 cm) were among the group of genotypes with the largest root length within category A. L88-63 (1018.8 cm) and NSL (1082.7 cm) were among the group of genotypes with the lowest root length.

Significant differences in length of root category B were detected for genotypes ($p < 0.0001$). The genotypes ranged from 300 to 603 cm. C97407 (603.3 cm), C03123 (545.

2 cm), C03150 (499.6 cm) were among the genotypes with the largest production of roots; whereas L88-63 (300 cm) and NSL (328 cm) were placed in the group with the lowest root production in B category.

Significant differences in root category C were detected for genotypes ($p <$ 0.0001). The genotypes ranged from 67 to 168 cm. C03123 (168.1 cm) and C97407 (145.0 cm) had the greatest root length in category C. L88-63 (76.3 cm) and NSL (77.9 cm) were among the genotypes with the lowest root length in this category.

Significant differences in root category D were detected for treatment effect ($p <$ 0.05). Genotypes under non-stress conditions showed greatest roots in this category with a mean of 26 cm, while genotypes under stress conditions showed a mean of 20 cm. No genetic differences were detected in this root category.

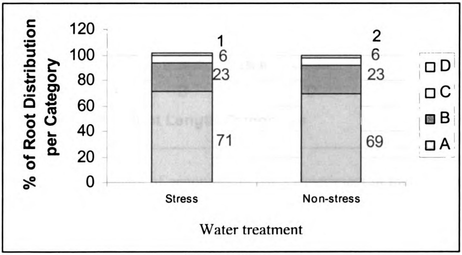

Figure 20. Percentage of root length per root category in IBL2 experiment in Michigan State University.

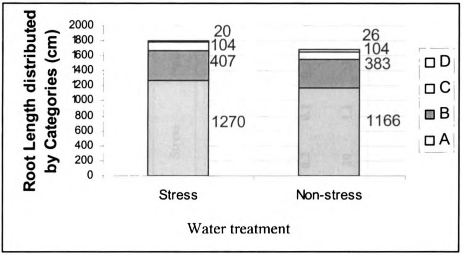

Figure 21. Root length of IBL2 experiment per category under stress and non-stress conditions in Michigan State University.

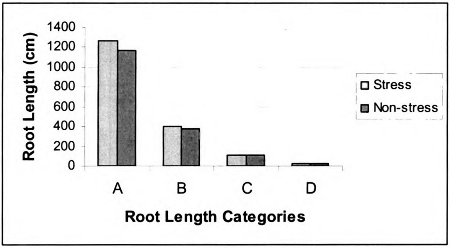

Figure 22. Root length of genotypes in IBL2 experiment in four different root categories under two water treatments in Michigan State University.

Table 22. Root length and percentage of root length of 16 genotypes in four root categories A (0.0 – 0.5mm), B (0.5 – 1.0 mm), C (1.0 – 2.0 mm), and D (> 2.0 mm) under stress and non-stress conditions in two different regions of the PVC-tubes in IBL2 experiment in Michigan State University, MI 2004.

	Root Category															
	A				B				C				D			
	Stress		Non-stress		Stress		Non-stress		Stress		Non-stress		Stress		Non-stress	
PVC-tube region	Length (cm)	%	Length (cm)	%	Length (cm)	%	Length (cm)	%	Lengt h (cm)	%	Length (cm)	%	Length (cm)	%	Length (cm)	%
Above 0.3 m	950	67.6	872	67.3	339	24.1	303	23.4	98	7.0	95	7.3	20	1.4	23	1.7
Below 0.3 m	320	81.0	294	76.6	68	17.2	80	20.8	6	1.5	9	2.3	0.2	0.1	0.25	0.1
Total	1270	70.5	1166	69.4	407	22.6	383	22.8	104	5.8	104	6.2	20	1.1	23	1.3

Significant differences in root diameter above 0.3 m were detected for genotype ($p < 0.05$). C03129 (0.56 mm), C03123 (0.53 mm), C03110 (0.53 mm), and C03104 (0.51 mm) had the greatest diameter, while NSL (0.46 mm) and L88-63 (0.49 mm) exhibited the smallest diameter.

Significant differences in root diameter below 0.3 m were detected for treatment ($p < 0.05$) and genotype ($p < 0.1$) effects. Genotypes under stress showed greater root diameter (0.32 mm) than genotypes under non-stress (0.27 mm). C03129 (0.19 mm) showed the thinnest root diameter.

Significant differences in shoot/root ratio were detected among genotypes ($p < 0.05$) in IBL 2 experiment. The overall mean was for shoot/root ratio 1.65. The shoot/root ratio in the genotypes ranged from 1.51 to 1.78. The drought resistant genotypes L88-63 and NSL and the recurrent parent C97407 were identified as genotypes showing the largest values of shoot/root ratio along with genotypes C03129, C03147, C03149, C03110, C03150, and C03156.

Table 23. Total root length (TRL), length of the taproot (LTR), number of the lateral roots (No of LR) , root weight (RW), surface area (SA), projected area (PA), and root volume (RV) for 16 genotypes in IBL2 experiment in Michigan State University, MI 2004.

Genotypes	TRL (cm)	LTR (cm)	No of LR	RW (g)	SA (cm3)	PA (cm2)	RV (cm3)
C97407	2647	63	8.7	4.6	372	118	4.2
C03150	2320	53	9.3	3.7	328	104	3.7
C03123	2085	50	9.5	4.2	333	106	4.3
C03149	2072	50	10.2	3.8	295	94	3.4
C03148	1994	47	9.3	2.9	280	89	3.3
C03147	1893	51	10	3.7	279	89	3.4
C03156	1874	49	9.8	3.2	266	85	3.1
C03131	1597	46	9.7	2.5	213	68	2.3
C03104	1560	46	9.2	3.1	238	76	2.9
C03143	1527	46	8.2	2.6	214	68	2.4
NSL	1504	41	7.5	2.2	208	66	2.3
C03129	1480	41	9.7	3.1	240	76	3.3
L88-63	1417	44	8.3	2.5	204	65	2.4
C03102	1305	40	8.8	2.4	188	60	2.2
C03127	1296	43	9.5	2.5	187	60	2.2
C03110	1278	41	9.2	2.4	202	64	2.6
MEAN	**1741**	**46.8**	**9.2**	**3.1**	**253**	**80**	**3.0**
LSD (0.05)	**575**	**ns**	**ns**	**0.8**	**69**	**22**	**0.8**
CV (%)	**28.6**	**24.4**	**17.6**	**21.5**	**23.7**	**23.7**	**24.0**

Table 24. Root length in categories A (RL (A)), B (RL (B)), C (RL(C)), and D (RL (D)) for 16 genotypes in IBL2 experiment in Michigan State University, MI 2004.

Genotypes	RL (A) (cm)	RL (B) (cm)	RL (C) (cm)	RL (D) (cm)
C97407	1878	603	145	21
C03150	1668	500	128	23
C03149	1468	461	116	26
C03148	1458	395	112	28
C03156	1346	392	107	29
C03123	1338	545	168	33
C03147	1313	438	120	23
C03131	1176	338	69	15
C03143	1092	326	93	16
NSL	1083	328	78	15
C03104	1037	387	106	27
L88-63	1019	300	76	22
C03129	977	361	110	32
C03102	904	317	67	17
C03127	898	302	79	16
C03110	836	330	91	22
MEAN	**1218**	**395**	**104**	**23**
LSD (0.05)	**463**	**119**	**33**	**ns**
CV (%)	**32.9**	**26.0**	**27.1**	**54.7**

DISCUSSION

Genotypes under stress conditions showed reduced root weight and volume in SGT experiment. The root length reduction was observed in all the root categories, however, a greater reduction was detected in category C than thinner roots in categories A and B was observed. The reduction caused by the stress was not proportional in every root category. In order to increase the efficiency in water absorption with a relatively extensive root system a reduction in energy spent is needed. This could result in decrease in production of thick roots that are highly expensive for plants to produce. The total root length reduction was 15.7%; however, the reduction in categories A and B was only 9.2 and 0.1% showing a less reduction in root length compared with root category C.

Table 25. Percentage of reduction of four root categories (A-D) of SGT experiment under stress conditions related with the same category under non-stress conditions. MI 2004.

	Non-stress	Stress	
Category	% of the total length	% of the total length	% of reduction
A	68.2	72.6	-6.5
B	21.8	21.7	0.5
C	9.6	5.5	42.7
D	0.4	0.3	25.0
Total	100	100	

The increase in percentage of thin roots and reduction in percentage of thick roots was confirmed through the distribution analysis of roots by size category in each water treatment. The percentage of root length distribution varied largely in all categories, except category B when compared between the two water treatments. Roots in category A occupied 72.6 % of the total root length under stress, while roots in category A occupied 68.2% of the total root length under non-stress. The percentage in category B was similar in both treatments with 21.7 % under stress and 21.8 % under non-stress, whereas categories C and D showed a percent reduction from 9.6 % to 5.5 % and from 0.4 % to 0.3 % under non-stress conditions to stress conditions respectively. The proportional increase in roots in category A under stress could be the response of the plant to the water deficit resulting in an increase in the root volume coverage in an attempt to access more of the available water.

Genotypes SEQ1016, and Paragachi showed the longest roots in category C under stress conditions (Table 32). The large root production by the two genotypes in category C was equivalent to some genotypes under non-stress conditions. SEQ 1016 and Paragachi have been identified as drought resistant cultivars in the semi arid environments of Ecuador (Programa Nacional de Leguminosas. 1995). Thus, the large root production suggests that these genotypes could be developing long tap roots to avoid the drought stress by exploring deeper regions. Further investigation to observe if these genotypes can produce deep taproots under field conditions would be valuable.

Root growth is determined by factors such as container shape and size, water, and mineral availability (Gerard et al., 1982), and genotype (Ho et al., 2005). We expected to find genetic differences in the length of tap root between genotypes due to the different genetic background the SGT genotypes, but no statistical differences were detected. One can anticipate that genotypes under non-stress conditions did not reach deeper regions of the PVC-tube, since the water availability was sufficient in shallow regions of the PVC-tube. However, genotypes under stress conditions would show different results, where some genotypes would be able to produce longer taproots and others not, since roots under stress needed to explore greater depths to meet the water requirements (Ontiveros-Cortes et al., 2004). The expected differences among genotypes were observed in other variables under study such as shoot weight, number of lateral roots, total root length, projected root area, root volume, root length in categories A, B, C, and D, where the genotypes under non-stress conditions showed more root tissue production than genotypes under stress conditions (Tables 32 and 33).

Root volume was one of the variables with the clearest differences among genotypes under the two water treatments. Genotypes under stress conditions showed a reduced root volume of 30.8%.

No significant differences were observed in variables TRL, PA, DA, and RL (A) and RL (B) when the roots were analyzed below depths of 0.3m (Table 36 and 37). The genotypes showed large and clear differences above 0.3 m, where the treatment and genetic effect had a larger effect than below 0.3m depth.

Statistical differences for treatment effect were detected in all variables evaluated in the IBL1 experiment. Additionally, the genotypes were affected by water stress and reduced the length of tap root. The reduction in the length of the taproot differs from the results observed in SGT experiment.

Changes in the percentage of root distribution per category were observed when comparing stress with non-stress treatments. The percentage of root length in category A under stress increased (74.8 %) compared with the percentage of root length under non-stress conditions (70.2 %). A small reduction was observed in root category B, but reductions were observed in categories C and D (Table 18 and Figure 19). The production of thick roots demands more investment of energy and, since the plant needs to absorb as much water as possible, the plant favors production of thinner roots resulting in reduction of thick roots. The more severe reductions in root volume or root projected area under stress conditions compared with the minor reduction in the root length in category A. An analysis of number of root tips would provide more information related with the production of roots and how the roots are distributed in the PVC-tube. Quantification of number of tips was not possible in this experiment since the roots were cut to fit in the trays to allow the scanning. As a consequence, the number of tips would not be accurate because the software would not have distinguished between root tips and the cut ends of the root.

The analyses of the projected root area and root volume in IBL1 produced the same results with the only difference that genotype C03155 was grouped in the first group as the greatest root volume producer, instead of genotype C03163 that was grouped in the first group of projected root area.

Genotypes NSL and L88-63, the two drought resistant checks, had large shoot/root ratio values. The shoot/root ratio showed that these genotypes were able to produce more biomass above ground than the others. Included in the group with the largest shoot/root ratio were genotypes C03151, C03117, and C03155, and the later two genotypes possess a type I growth habit.

The results observed in the taproot length in IBL2 experiment did not agree with results in the SGT experiment, where genotypes under stress produced deeper roots than genotypes under non-stress, but were in agreement with the result obtained in IBL1 experiment in which genotypes reduced the length of the taproot under stress. In the IBL2 experiment, temperatures above 30 °C were recorded during the first and second week in the greenhouse (Figure 25). With high temperatures in the greenhouse, more water evaporation or transpiration might have occurred and affected the experiment creating uneven moisture concentration along the PVC-tubes with low moisture content in the bottom part of the PVC-tube. In this kind of greenhouse experiments the homogeneity in the soil is difficult to control (Kramer, 1983), and the tensiometers that were used in these experiments limits the moisture control to the PVC-tube region where the tip is localized.

Genetic differences in the number of lateral roots in the IBL2 experiment were expected to be detected since genetic differences were observed in IBL1 experiment. The assumption was based on differences between the parents (C97407 and NSL) used as checks in IBL1 experiment. However, in IBL2 experiment statistical differences were not detected for number of lateral roots. In the data collected in IBL1 experiment, NSL produced 4 lateral roots under stress conditions, while NSL produced 4.7 lateral roots under water stress conditions in IBL2. However, NSL in IBL1 experiment under non-stress produced 6.7 lateral roots, while in IBL2 under non-stress it produced 10.3 lateral roots. The high number of lateral roots produced by NSL under non-stress conditions might be one reason why there were no significant differences in lateral roots for genotypes in IBL2.

Probably, the results would have been reproducible if the environment would have been better controlled. If it is not possible to control the environment for future experiments, it would important to collect more information on light intensity and the moisture in different regions of the PVC-tube to identify, uncontrolled factors that might interfere. Additionally, temporal information of the root parameters could be important, so differences in early and late stages might be identified.

The root diameter above 0.3 m depth under non-stress conditions showed a smaller diameter than the root diameter of roots under stress conditions in this region of the PVC-tube. This difference is caused by the greater abundance of roots from category A above 0.3 m than below 0.3m (Tables 52 and 54).

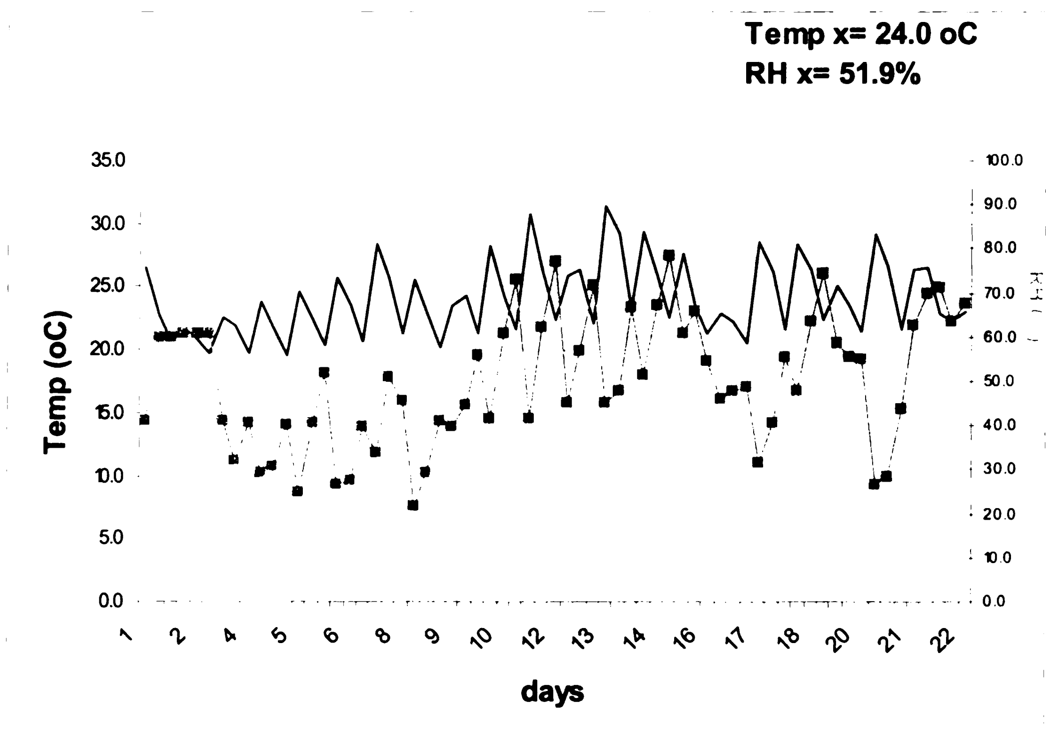

Figure 23. Temperature and Relative humidity in the greenhouse from Watchdog 3529 in STG experiment.

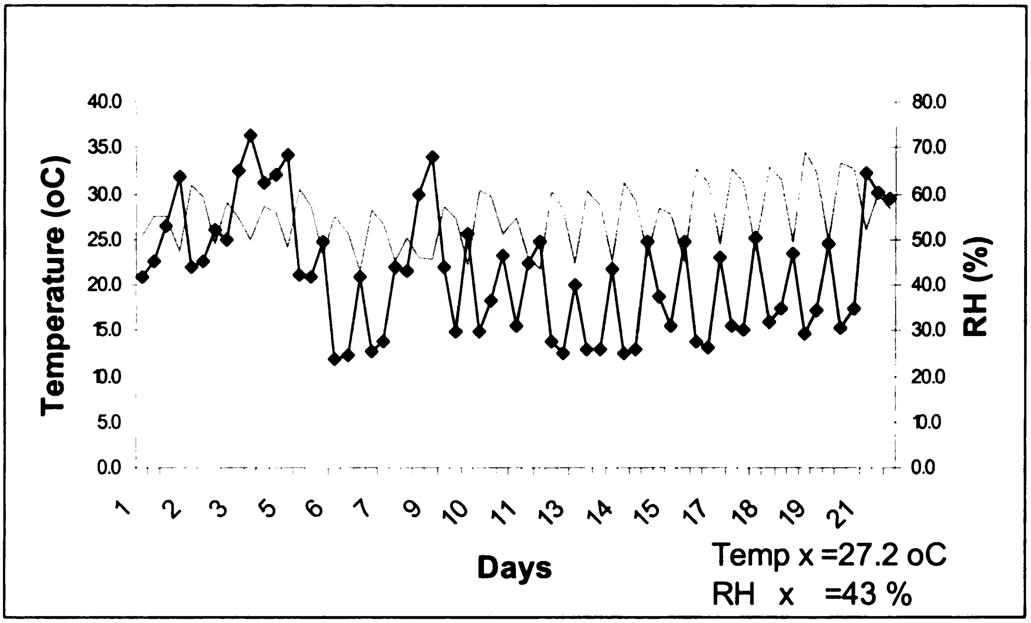

Figure 24. Temperature and Relative humidity in the greenhouse from Watchdog 3529 in IBL1 experiment.

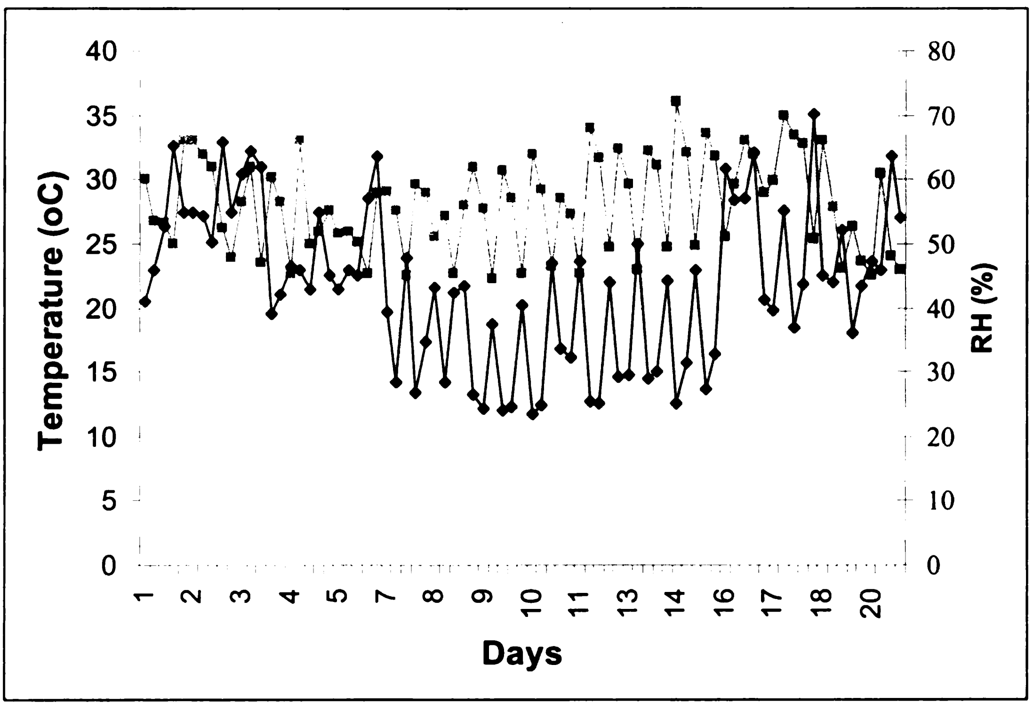

Figure 25. Temperature and Relative humidity in the greenhouse from Watchdog 3529 in IBL2 experiment.

To calculate the effect caused by the water reduction, the reduction in root length of categories C and D, and reduction in root volume can be used as parameter, since the greatest reduction was observed in these variables.

The contrasting result in the length of taproot between SGT and the IBL1 and IBL2 experiments, where genotypes in SGT responded to drought conditions by increasing the root length, whereas in IBL 1 and 2 experiments the reduced length of the taproot, could be attributed to genetic differences in the populations. Drought resistant genotypes in SGT produced longer taproots to avoid the drought. The second hypothesis is that the genotypes in SGT developed longer taproots due to different moisture amounts and distribution in the PVC-tubes. Factors to consider include: Initial moisture in the sand, moisture in different regions of the PVC-tube, and plant evaporation and transpiration caused by changes in temperature. Some genotypes in the SGT were previously identified as drought resistant (Table 2) and it is likely that the strategy to resist drought in these genotypes was to develop longer taproots.

No significant differences were observed in TRL for treatment effect in the IBL2 experiment. Reasons for lack of differences in treatment effect could be due to: 1) the severity of water stress between stress and non-stress was similar and the genotypes under the two water treatments were affected with the same intensity, 2) insufficient stress was applied in the stress treatment to cause differences, or 3) The increase in the irrigation with water and nutrient solution affected the growth of the roots, limiting the growth just to the top of the PVC-tube, or 4) a combination of each of these factors. Most likely the results were caused by a combination of each of the environmental factors. The mean for TRL in IBL1 was 3890 cm while the overall mean in IBL2 for TRL was 1741 cm. The same results were obtained in projected area and root volume, where the overall means for projected area and root volume in IBL1 experiment were 166 cm^2 and 5.7 cm^3, respectively. In the IBL2 experiment the overall means for projected area and root volume were 80 cm^2 and 3.0 cm^3. The significant reduction of the overall means in IBL2 suggests that genotypes under both stress conditions and non-stress conditions were affected simultaneously.

The temperature and the relative humidity recorded in the greenhouse in IBL1 (27.2 °C, RH=43%) and IBL2 (27.6 °C, RH=43.9%) experiments did not show large differences, however, there were days when greenhouse temperatures exceeded 33°C in the IBL2 experiment. According to Thung and Rao (1999), high environmental temperature accompanied with high soil temperature strongly inhibits deeper growth of tap and lateral roots. Finally, additional irrigation was applied in IBL2 experiment (Table 14), since plants showed symptoms of dehydration during the growing period. The extra water and nutrients could explain the shallow and shorter roots that developed. This type of root development demonstrates the tradeoff existing in roots to reach nutrients and water (Ho et al., 2005).

No correlation between the variables recorded in the greenhouse experiments and field data yield under stress, non-stress, and geometric means were observed, except the negative correlation between root volume under stress conditions in IBL1 experiment and GM in Tumbaco 2005. We could hypothesize that genotypes which produce large root volumes are not resistant to drought conditions present in Tumbaco, if IBL2 experiment would have showed such correlation, however, the correlation was not detected.

Environmental conditions in IBL2 experiment were different compared with IBL1 experiment and it might be the reason for these differences.

The shoot/root ratio in IBL2 did not show a large a distribution as the distribution shown in IBL1. However, The drought resistant checks were grouped statistically with genotypes that exhibited the largest values of shoot/root ratio. The low correlations between shoot/root ratio differ from the high correlation ($r^2 = 0.99$) reported by Mayaki et al. (1976) in soybean. This would suggest that under the conditions in PVC-tubes the shoot cannot be used to predict rooting depth.

CONCLUSIONS

Genotypes AFR476, Cocacho, L88-63, Paragachi, RAB 651, RAB 655, and Yunguilla had the least root reduction under water stress conditions in the STG experiment. Paragachi, L88-63, Mil Uno and RAB655 also produced the largest GM yield in 2005 at Tumbaco. Stable root production under stress and non-stress conditions shown by the five genotypes can be regarded as drought tolerance and the trait could be combined with genotypes showing great yield potential and commercial seed as Mil Uno, ABE4 and ACE2 genotypes.

The interaction effect of water treatment and the genotypic differences allowed identifying genotypes less affected by the water stress condition in the IBL1 experiment. Therefore, genotypes which were not affected by water stress treatment could be considered drought tolerant under the stress conditions of the experiment. The genotypes C03151, C03117, C03155, C03161, and C03122 in IBL1 experiment were least plastic in respond to stress for total root length, projected root area, root volume, and shoot/root ratio variables. In the IBL2 experiment, there was no interaction effect between genotype and treatment. Total root length and the shoot/root ratio variables were used to select the genotypes with superior root production without significant reduced shoot production. The genotypes selected were C03110, C03129, C03149, and C03150.

Low correlations were observed between GM yield and variables monitored in the greenhouse experiments. However, the PVC-tube methodology allowed quantification of water stress effects and genotypic differences among genotypes. Genotypes responded to water stress in the PVC-tubes by reducing the root length in all the root categories, but preferentially in thicker roots, which require more energy to produce and maintain. Therefore reduction of root biomass in this category could be considered an energy saving strategy that allows the plant to continue to expand in length in search for water but at a lower carbon cost.

Genotypic differences in taproot length were not detected in this experiment. Perhaps an experiment with a more highly controlled soil moisture gradient may have been able to detect such differences. Another factor that impacts root length is the soil substrate. In our experiment, sand was used as the medium and sand does not generate as much resistance to root growth as would typical field soils under drought stress.

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Appendix A

DATA TABLES FROM DROUGHT EXPERIMENTS CONDUCTED IN THE FIELD IN MICHIGAN AND ECUADOR

Table 26. Yield, biomass, harvest index (HI), 100 seed weight, number of pods per plot, number of seeds per pod, and stem thickness of the 26 IBLs evaluated under non-stress conditions in Michigan, US. 2004.

	Yield (kg/ha)		Biomass (kg/ha)		HI		100 seeds weight (g)		No pods/plant		No seeds/pod		Stem thickness (mm)
Genotypes	Non-stress	Stress	Non-stress	Stress	Non-stress	Stress	Non-stress	Stress	Non-stress	Stress	Non-stress	Stress	Non-stress
IBLs													
C03102	3181	2389	5665	4338	0.56	0.55	64	53	8.4	7.5	4.3	3.7	6.0
C03104	3139	2427	5521	4371	0.57	0.55	57	53	9.5	8.8	4.0	3.6	5.7
C03108	3356	2412	5626	3972	0.6	0.6	57	49	8.8	7.6	4.9	4.2	5.7
C03110	3220	2377	6094	4621	0.53	0.52	67	61	9.1	9.9	4.1	4.0	6.1
C03117	2346	1441	4157	2675	0.57	0.54	53	46	11.3	7.8	4.1	4.0	5.9
C03119	2612	2259	5099	4572	0.5	0.49	57	63	8.4	8.0	4.3	4.4	6.3
C03121	3140	2709	6538	5847	0.48	0.47	67	66	13.3	9.8	3.8	2.8	5.4
C03122	3250	2422	6166	4944	0.53	0.49	58	58	10.7	7.8	3.8	4.0	6.1
C03123	2558	1760	7250	4542	0.37	0.39	72	65	10.8	9.4	2.9	2.8	5.6
C03125	2981	1795	5702	3913	0.52	0.46	49	45	10.3	8.2	4.6	4.4	5.2
C03127	2572	1880	5448	3910	0.47	0.48	53	46	9.8	8.8	4.4	4.3	5.6
C03129	3125	2293	6060	4822	0.52	0.48	58	53	10.7	10.3	4.4	3.9	5.4
C03131	2873	2177	5217	3821	0.55	0.57	57	50	9.5	9.7	4.3	4.2	6.1
C03143	2644	2311	5501	5069	0.48	0.46	53	51	8.8	8.7	3.9	4.2	5.9
C03147	3223	2113	6680	4799	0.49	0.45	58	56	7.6	8.4	4.8	5.0	6.0
C03148	2917	1740	6977	5415	0.42	0.32	56	51	9.8	9.7	3.9	4.4	5.8
C03149	2820	1369	7253	5876	0.39	0.24	48	43	10.8	8.0	5.5	4.6	5.8
C03150	2827	1640	6782	4243	0.42	0.4	57	55	11.5	8.0	4.6	3.9	5.6
C03151	3322	2409	6476	4789	0.51	0.49	58	56	10.1	8.9	4.7	3.9	6.0
C03154	2717	1484	5609	3020	0.49	0.48	51	42	10.9	8.1	4.3	4.9	5.9
C03155	2607	2321	5366	4546	0.49	0.51	58	55	14.4	9.4	4.4	3.7	6.4
C03156	2714	1959	6466	5000	0.42	0.4	54	51	10.6	8.6	4.1	4.3	5.5
C03157	2787	2289	7388	6044	0.39	0.38	63	61	8.7	7.8	4.8	4.0	5.7
C03160	2954	1624	7526	5165	0.39	0.32	54	50	10.3	9.0	4.4	4.6	5.3
C03161	2523	2297	5955	5718	0.42	0.4	45	44	9.6	8.6	4.3	5.0	5.5
C03163	2928	2203	5642	4229	0.52	0.52	63	56	8.6	8.4	4.4	4.0	6.1
Parent													
C97407	2650	2127	4799	3808	0.55	0.56	59	53	10.7	12.0	4.6	4.3	6.1
Checks													
Taylor Hort	2496	2429	4384	4167	0.57	0.58	65	56	7.3	9.1	4.4	4.1	6.2
L88-63	3221	2592	7368	5524	0.44	0.5	21	23	14.4	11.6	5.0	5.5	6.9
B98311	2895	2268	6990	5273	0.42	0.43	25	23	17.7	16.7	5.0	5.0	7.7
MEAN	2887	2117	6057	4634	0.49	0.47	55	51	10.4	9.2	4.4	4.2	5.9
LSD (0.05)	678	665	1512	1345	0.07	0.09	4.3	5.3	3.4	3	0.9	0.8	0.2
CV (%)	14.4	19.2	15.3	17.8	8.5	11.9	4.7	6.4	20.2	20.2	13.1	11	7

Table 27. Yield, biomass, harvest index (HI), flowering, maturity, common bacterial blight reaction (CBB), and desirability score DS of 26 IBL evaluated under stress and non-stress conditions in Michigan, US. 2004.

	Yield (kg/ha)		Biomass (kg/ha)		HI		Flowering (days)		Maturity (days)		CBB[1] (1-9)		DS[2] (1-9)	
IBLs	Stress	Non-stress	Stress	Non-stress	Stress	Non-stress	Stress	Non-stress	Stress	Non-stress	Stress	Non-stress	Stress	Non-stress
C03157	2218	2506	8235	10507	0.27	0.24	41.7	41.8	103.0	103.3	3.5	4.0	4.3	4.1
C03143	1807	2618	7809	8035	0.23	0.33	37.7	37.8	96.3	97.3	4.0	3.5	3.3	5.1
C03110	1821	2433	7532	7554	0.24	0.32	37.2	37.3	94.7	96.3	3.0	2.0	4.8	5.6
C03151	1885	2225	5500	10442	0.34	0.21	40.7	39.8	101.3	103.3	4.5	5.0	2.3	3.6
C03131	1635	2514	5411	5893	0.30	0.43	38.7	40.3	99.0	99.0	3.5	3.0	3.8	4.1
C03147	2122	1896	8342	7864	0.25	0.24	39.7	39.3	101.7	103.0	4.0	3.5	3.3	3.6
C03154	1507	2418	4578	4216	0.33	0.57	38.7	41.3	98.0	102.3	2.0	2.0	4.8	3.6
C03163	1930	1797	5243	8163	0.37	0.22	39.2	42.3	98.7	96.3	3.5	3.0	4.3	3.6
C03155	1717	1990	7219	6879	0.24	0.29	39.2	41.8	98.7	99.7	4.5	4.5	3.8	4.1
C03127	1519	2041	5788	8112	0.26	0.25	38.7	37.8	98.3	99.3	5.0	5.0	3.3	3.6
C03156	1512	1929	8459	8141	0.18	0.24	42.2	43.3	103.7	105.3	3.5	3.0	3.3	4.1
C03125	1522	1914	6234	7534	0.24	0.25	38.7	38.3	98.7	100.7	4.0	3.5	3.3	4.6
C03119	1724	1571	6961	6709	0.25	0.23	41.7	39.3	99.3	100.7	4.5	4.5	2.8	3.1
C03129	1799	1449	6819	6685	0.26	0.22	38.7	38.3	102.3	100.3	3.0	3.0	5.3	4.6
C03104	1256	2056	6788	4280	0.19	0.48	39.7	37.3	95.0	95.7	3.0	2.0	4.3	4.1
C03108	1238	1958	4572	8472	0.27	0.23	36.7	38.8	96.7	98.3	4.0	2.0	3.3	5.1
C03123	1295	1812	4627	9767	0.28	0.19	39.2	40.3	96.3	98.7	4.0	4.0	3.3	3.6
C03150	1426	1596	11444	9406	0.12	0.17	41.7	43.3	104.0	105.0	4.0	4.0	2.8	4.1
C03117	1518	1497	4886	5292	0.31	0.28	37.7	38.8	96.3	97.7	3.5	2.5	3.8	4.6
C03102	1247	1766	4855	5981	0.26	0.30	37.7	37.8	97.7	98.7	4.0	3.0	3.3	4.6
C03160	1351	1585	9868	8742	0.14	0.18	39.7	40.3	103.7	105.7	3.5	3.5	3.8	3.6
C03149	1117	1581	8129	6199	0.14	0.26	40.7	41.8	103.7	104.7	4.5	4.0	2.8	4.6
C03148	1094	1481	3533	9971	0.31	0.15	37.7	38.3	100.7	100.7	4.0	3.5	3.3	3.6
C03161	1218	1142	7654	5850	0.16	0.20	40.2	39.3	100.7	102.7	4.0	4.0	3.3	4.1
C03122	1085	1055	6219	4815	0.17	0.22	37.2	37.3	96.7	96.7	3.5	3.0	4.3	4.6
C03121	957	598	3799	8619	0.25	0.07	39.2	38.8	95.3	96.7	4.5	4.5	2.3	3.6
Parent														
C97407	1720	2009	6422	7148	0.27	0.28	37.2	38.3	94.7	95.7	2.5	2.0	4.8	5.1
Checks														
Taylor Hort	1074	1332	3236	6086	0.33	0.22	37.2	37.8	93.7	95.3	3.5	2.5	4.8	4.6
L88-63	1892	1698	5644	7004	0.34	0.24	38.2	38.3	93.3	96.0	3.5	3.5	3.8	4.6
B98311	1672	1778	6239	6015	0.27	0.30	37.7	39.3	95.0	95.7	3.0	3.5	4.3	4.1
Mean	1529	1808	6402	7346	0.25	0.26	39.0	39.4	98.6	99.7	3.7	3.4	3.7	4.2
LSD	629	589	1644	1262	0.05	0.04			3.0	2.8				
CV (%)	27.7	24	31.8	22.4	21.8	19.8			1.9	1.7				

[1] CBB = Common bacterial blight reaction in a scale 1 to 5, where 1 = resistant plant, and 5 = susceptible plant.

[2] DS = Desirability score in a scale 1 to 9, where 1= worst, and 9 = best.

Table 28. Yield, biomass, harvest index (HI), 100 seed weight, number of pods per plot, number of seeds per pod under, and number of lateral roots under non-stress and stress conditions of the IBLs evaluated in Tumbaco, Ecuador. 2005.

	Yield (kg/ha)		Biomass (kg/ha)		Harvest index		100 seeds weigth (g)		No pods/plant		No seeds/pod		No lateral roots	
Genotypes	Non-stress	Stress	Non-stress	Stress	Non-stress	Stress	Non-stress	Stress	Non-stress	Stress	Non-stress	Stress	Non-stress	Stress
IBLs														
C03102	2508	1722	5028	3600	0.50	0.48	62	52	8.8	9.8	4.4	3.7	10.1	8.1
C03104	2137	1450	5194	3683	0.41	0.39	58	50	9.5	8.7	4.0	3.1	11.4	7.3
C03108	2318	1697	4917	3739	0.47	0.45	57	49	9.4	6.9	4.6	4.0	11.3	7.3
C03110	2488	1698	6194	4322	0.41	0.39	69	55	7.9	5.2	3.9	3.9	14.2	9.8
C03117	2103	1335	5139	3322	0.41	0.40	51	45	9.8	10.4	4.0	4.1	10.8	8.3
C03119	2036	1338	4694	4500	0.43	0.30	61	47	6.9	6.7	3.9	4.4	11.8	8.3
C03121	2560	1606	4861	4556	0.53	0.35	72	56	11.7	12.5	3.8	3.5	12.2	9.4
C03122	2803	1637	6944	4472	0.40	0.36	64	53	9.3	10.0	3.7	3.7	10.3	7.1
C03123	1868	1338	5667	3694	0.33	0.36	74	63	10.2	13.0	3.1	3.1	14.7	9.1
C03125	1945	1505	5283	3811	0.37	0.40	51	46	9.8	10.8	4.1	4.3	10.5	7.8
C03127	2091	1544	5583	4306	0.38	0.36	58	47	9.6	10.1	4.1	4.0	11.8	7.5
C03129	1895	1440	4583	3556	0.42	0.41	53	45	8.9	6.5	4.3	4.2	10.8	8.8
C03131	2860	1746	5611	4072	0.51	0.43	64	48	8.3	8.6	4.8	5.2	11.5	6.7
C03143	2099	1395	5222	3961	0.41	0.35	53	46	10.4	9.0	4.2	4.4	9.9	8.1
C03147	2397	1172	5028	3278	0.47	0.36	57	45	9.8	7.4	5.2	5.5	13.1	10.7
C03148	2346	1336	5833	3500	0.40	0.39	58	52	9.8	9.5	4.8	3.5	12.8	8.0
C03149	1859	1306	5028	3139	0.37	0.42	50	41	8.3	7.8	5.6	4.8	13.8	7.1
C03150	2166	1652	6028	3750	0.37	0.44	63	49	9.3	10.4	4.8	4.2	15.8	9.8
C03151	2349	1297	5139	4017	0.46	0.33	58	45	11.0	8.1	4.4	4.9	13.5	8.6
C03154	2311	1315	4694	3183	0.49	0.41	46	38	8.4	8.5	4.2	5.1	11.1	8.0
C03155	2098	1530	4750	3383	0.44	0.45	58	52	10.0	8.4	3.7	4.0	12.4	8.0
C03156	2382	1518	6250	3667	0.38	0.42	56	44	9.4	7.8	5.1	5.1	13.0	10.9
C03157	1894	1225	4972	3306	0.38	0.37	58	53	8.5	6.6	4.6	4.5	12.3	9.1
C03160	2780	1485	6944	3611	0.41	0.42	61	49	10.2	8.8	4.5	4.5	13.8	9.9
C03161	1659	1295	4361	3917	0.38	0.33	49	45	9.5	8.0	4.6	4.5	12.8	9.0
C03163	2358	1672	5222	4083	0.46	0.41	59	54	10.0	10.2	4.0	3.5	13.5	9.9
Parents														
NSL	4259	2649	9556	5833	0.45	0.45	48	41	13.3	16.3	4.6	4.3	9.1	6.8
C97407	2448	1414	4944	3306	0.49	0.43	53	49	9.1	7.6	4.0	4.2	11.4	7.8
Checks														
Mil Uno	3073	1866	7722	4556	0.40	0.41	84	62	9.8	10.1	3.4	3.2	14.3	9.7
B04647	2835	1435	9000	4028	0.32	0.36	26	19	21.3	15.8	3.0	5.5	7.8	7.4
MEAN	2364	1521	5680	3872	0.42	0.39	58	48	9.9	9.3	4.3	4.2	12.1	8.5
LSD (0.05)	574	346	1516	852	0.08	0.07	7.3	3.6	2.7	3.1	0.9	0.7	3.0	2.4
CV (%)	14.9	13.9	16.3	13.5	11.6	10.7	7.7	4.6	16.4	20.2	14.4	9.7	15.4	17.3

Table 29. Stem thickness, plant canopy height, days to harvest, and root rot score in a scale 1 to 9 under non-stress and stress conditions of the IBLs evaluated in Tumbaco, Ecuador. 2005.

	Stem thickness		Plant canopy high		Days to harvest		Root rot score (1-9)*	
Genotype	Non-stress	Stress	Non-stress	Stress	Non-stress	Stress	Non-stress	Stress
IBLs								
C03102	6.2	6.8	34.3	37	111	100	5.3	5.3
C03104	5.6	5.8	29.0	30	106	96	4.3	5.3
C03108	6.3	5.4	35.7	32	109	97	5.0	5.7
C03110	6.5	6.4	34.7	37	108	97	6.3	6.0
C03117	6.3	6.6	37.3	31	102	96	5.3	5.3
C03119	5.7	5.9	34.0	43	112	105	5.0	4.7
C03121	6.2	5.7	24.0	32	113	103	5.7	5.3
C03122	6.6	7.0	34.7	39	114	105	5.0	4.7
C03123	6.2	6.1	22.3	28	114	108	5.0	5.7
C03125	6.1	6.4	31.7	33	106	97	5.7	4.7
C03127	6.2	6.8	33.7	30	109	104	6.0	5.0
C03129	6.0	5.8	31.0	31	104	97	6.3	5.0
C03131	5.8	6.6	35.3	38	113	100	4.0	5.0
C03143	6.5	6.7	35.0	34	108	101	5.7	4.7
C03147	6.4	6.8	35.0	41	115	109	4.7	5.7
C03148	6.5	6.9	34.3	38	114	104	5.3	5.3
C03149	6.0	5.8	36.3	42	114	114	4.7	5.7
C03150	5.7	6.5	35.7	34	114	114	4.7	5.7
C03151	6.9	6.1	38.0	42	111	104	4.7	5.3
C03154	5.8	6.0	36.3	37	109	97	4.7	5.3
C03155	6.5	5.9	36.0	31	100	96	4.7	4.0
C03156	6.1	6.2	39.0	44	116	111	5.3	5.0
C03157	5.7	5.8	31.7	41	115	115	5.0	5.0
C03160	6.2	5.8	37.7	34	114	111	4.7	6.3
C03161	5.6	5.7	35.3	40	115	105	5.0	4.3
C03163	7.1	6.8	39.7	38	110	99	5.3	5.3
Parents								
NSL	5.4	6.1	28.3	24	112	99	4.0	3.7
C97407	6.2	5.6	30.7	32	98	96	4.7	5.0
Checks								
Mil Uno	12.3	7.6	39.0	46	115	108	5.3	5.7
B04647	8.3	8.7	52.3	49	116	105	2.3	2.3
MEAN	6.4	6.3	34.6	36	111	103	5.0	5.1
LSD (0.05)	2.8	1.1	8.2	6.2	4.9	4.8	1.1	1.4
CV (%)	26.3	11.0	14.4	10.6	2.7	2.9	14.0	16.6

* Scale 1 to 9, where 1 is no-symptoms and 9 is death plant due to the pathogen.

Table 30. Yield, biomass, harvest index (HI), 100 seed weight, number of pods per plot under non-stress and stress conditions of the SGT evaluated in Tumbaco, Ecuador. 2005.

	Yield (kg/ha)		Biomass (kg/ha)		Harvest index		100 seed weight (g)		No lateral roots	
Genotypes	Non-stress	Stress	Non-stress	Stress	Non-stress	Stress	Non-stress	Stress	Non-stress	Stress
ABE 4	1907	1336	4750	3172	0.40	0.42	62	56.7	9.8	7.5
ACE1	1702	1316	4478	3389	0.38	0.39	62	60.7	11.4	9.0
ACE2	1760	1591	3889	3534	0.45	0.46	47	50.0	10.9	8.4
AFR476	1460	1200	3083	3211	0.49	0.37	27	26.7	8.4	6.7
ARME2	1625	1583	4167	3417	0.39	0.46	55	50.7	9.8	8.2
C. BOLA 60	1286	994	3100	2444	0.41	0.41	39	40.3	8.8	7.1
COCACHO	1566	1276	3583	2833	0.44	0.45	42	43.0	9.7	9.3
L88-63	1830	1820	5055	4950	0.36	0.37	20	21.3	7.3	6.1
MIL UNO	1903	1731	4445	4461	0.43	0.39	63	58.3	9.8	7.2
PARAGACHI	1894	1772	5167	4639	0.37	0.38	49	44.7	8.8	7.7
POA10	1591	1422	4306	3861	0.38	0.37	52	53.7	11.4	12.2
RAB651	1486	1251	3944	3322	0.37	0.38	22	22.3	8.5	7.8
RAB655	1765	1494	4611	3722	0.38	0.40	25	23.7	8.2	6.9
SEQ1016	1201	1183	3694	3472	0.32	0.34	49	49.7	10.4	9.2
YUNGUILLA	1554	1291	4056	3250	0.39	0.40	53	52.7	12.9	11.0
YxAs7	1591	1304	4195	3472	0.38	0.38	56	54.7	12.1	9.4
MEAN	1632	1410	4158	3572	0.40	0.40	45	44.3	9.9	8.4
LSD (0.05)	386	336	941	929	0.07	0.05	4.2	3.7	3.2	2.4
CV (%)	14.2	14.3	13.6	15.6	11.2	7.7	5.6	5.1	19.5	17.2

Table 31. Stem thickness, number of seeds per pod, number of pods per plant, plant height, days to harvest, and root rot score under non-stress and stress conditions of the SGT evaluated in Tumbaco, Ecuador. 2005.

	Stem thickness (cm)		No seeds/pod		No pods/plant		Plant height (cm)		Days to harvest		Root rot score (1-9)	
Genotypes	Non-stress	Stress	Non-stress	Stress	Non-stress	Stress	Non-stress	Stress	Non-stress	Stress	Non-stress	Stress
ABE 4	6.8	5.7	4.0	3.5	7.8	6.9	42	38	112	103	5.3	5.7
ACE1	6.9	6.9	4.3	4.9	5.4	6.4	48	45	116	116	5.0	4.0
ACE2	6.0	6.1	4.3	4.7	6.0	5.7	42	38	105	105	4.7	4.3
AFR476	7.5	7.6	5.2	5.0	11.0	13.2	56	56	109	106	3.0	2.7
ARME2	6.8	6.8	4.0	3.9	8.8	7.5	48	40	114	110	4.3	4.0
C. BOLA 60	5.7	5.1	3.6	3.7	9.8	8.9	36	33	92	90	5.7	6.0
COCACHO	5.3	5.0	3.8	4.1	7.4	8.4	39	32	92	91	6.0	5.7
L88-63	7.7	7.5	5.4	4.5	14.5	14.9	48	48	104	102	2.7	2.3
MIL UNO	6.8	6.1	3.6	3.7	8.4	7.2	45	41	110	106	4.7	5.0
PARAGACHI	7.3	6.6	4.6	4.3	8.5	7.6	46	46	113	107	4.7	4.0
POA10	6.7	6.4	3.9	3.6	7.0	6.9	49	43	111	108	5.3	5.7
RAB651	7.2	7.0	5.1	5.3	13.4	15.0	42	36	99	98	2.7	2.7
RAB655	7.5	7.1	5.2	5.5	14.6	15.1	49	43	106	104	2.3	2.7
SEQ1016	7.2	6.8	4.7	4.2	7.2	5.9	49	55	114	110	5.0	5.0
YUNGUILLA	6.7	6.7	3.6	3.3	6.4	8.4	50	44	112	106	5.0	4.0
YxAs7	6.5	6.4	2.4	3.2	6.4	8.2	46	43	112	109	5.0	5.3
MEAN	6.8	6.5	4.2	4.2	8.9	9.1	46	43	108	104	4.5	4.3
LSD (0.05)	0.7	1.1	1.0	0.9	2.5	3.4	6	7	3	3	1.1	1.1
CV(%)	6.4	10.0	14.4	12.8	16.9	22.0	8.0	9.4	1.5	2.0	14.3	15.6

APPENDIX B

DATA TABLES FROM DROUGHT EXPERIMENTS CONDUCTED IN THE GREENHOUSE IN MICHIGAN

Table 32. Total root length (TRL), surface area (SA), projected area (PA), root volume (RV), root length in category A (RL (A)), category B (RL (B)), category C (RL(C)), and category D (RL (D)) for 16 bean genotypes above 0.3 m of the PVC-tube in STG experiment in Michigan State University, MI 2004.

Genotype	TRL (cm)	SA (cm2)	PA (cm2)	RV (cm3)	DA (mm)	RL (A) (cm)	RL (B) (cm)	RL (C) (cm)	RL (D) (cm)
ABE4	1735	244.7	77.9	2.8	0.44	1226	383	101	7
ACE1	1776	249.0	79.3	2.9	0.43	1269	380	120	7
ACE2	1763	258.4	82.2	3.1	0.47	1201	430	121	12
AFR476	1435	173.7	55.3	1.7	0.39	1105	283	46	2
ARM2	2196	312.7	99.6	3.6	0.45	1553	478	152	12
C97407	1825	261.4	83.2	3.1	0.45	1267	414	132	12
COCACHO	1442	191.5	61.0	2.0	0.43	1065	304	71	2
L88-63	1254	389.8	51.2	1.6	0.41	932	256	64	2
MIL UNO	1760	240.1	76.4	2.7	0.43	1256	392	105	6
PARAGACHI	2080	295.3	94.5	3.4	0.46	1475	437	142	10
POA 10	2105	301.6	96.0	3.5	0.45	1473	480	138	15
RAB651	1749	221.2	70.4	2.3	0.4	1329	339	78	3
RAB655	1680	214.1	68.1	2.2	0.4	1261	345	72	2
SEQ1016	2220	340.0	108.2	4.2	0.49	1500	496	209	16
YUNGUILLA	1875	248.3	79.1	2.6	0.42	1376	389	105	6
YxA7	1935	237.3	75.5	2.5	0.41	1321	407	87	4
MEAN	1802	261.2	78.6	2.8	0.43	1288	388	109	7
LSD (0.05)	336	ns	17.3	0.8	0.04	237	77	50	7
CV (%)	16.1	57.0	19.0	26.3	9.5	15.9	17.2	40.0	85.0

Table 33. Total root length (TRL), surface area (SA), projected area (PA), root volume (RV), root length in category A (RL (A)), root length in category B (RL (B)), root length in category C (RL(C)), and root length in category D (RL (D)) for16 bean genotypes below 0.3 m of the PVC-tube in STG experiment in Michigan State University, MI 2004.

Genotypes	TRL (cm)	SA (cm2)	PA (cm2)	RV (cm3)	DA (mm)	RL (A) (cm)	RL (B) (cm)	RL (C) (cm)	RL (D) (cm)
ABE4	582	95.2	30.3	1.3	0.53	378	132	69	1.0
ACE1	787	123.9	39.4	1.6	0.5	527	159	100	1.5
ACE2	848	136.4	43.4	1.8	0.55	568	188	90	2.2
AFR476	524	82.9	26.4	1.1	0.53	354	123	47	0.5
ARME2	812	140.8	44.9	2.0	0.56	522	174	115	1.8
C97407	1343	198.5	63.2	2.4	0.51	912	325	104	2.5
COCACHO	644	102.7	32.7	1.3	0.54	411	160	74	0.7
L88-63	745	116.3	37.0	1.5	0.54	510	158	73	3.1
MIL UNO	781	129.0	41.0	1.7	0.54	503	171	115	1.9
PARAGACHI	772	131.8	42.0	1.8	0.56	497	150	122	3.1
POA 10	1119	172.5	54.9	2.2	0.5	764	234	118	3.1
RAB651	793	116.4	37.1	1.4	0.47	536	196	60	1.1
RAB655	498	79.5	25.3	1.0	0.52	325	90	57	1.2
SEQ1016	808	137.6	43.9	1.9	0.54	531	149	123	5.0
YUNGUILLA	527	83.3	26.5	1.1	0.5	344	111	72	0.5
YxA7	826	127.0	40.4	1.6	0.49	536	198	89	1.7
MEAN	775	123.4	39.3	1.6	0.52	514	170	89	2
LSD (0.05)	472	63	20	0.7	ns	ns	102	41	ns
CV (%)	52.8	44.3	44.3	39.1	11.7	58.9	51.9	39.7	129.0

Table 34. Total root length (TRL), length of the taproot (LTR), number of the lateral roots (No of LR), projected area (PA), root volume (RV) for 16 bean genotypes under two water treatments in STG experiment in Michigan State University, MI 2004.

	TRL (cm)		LTR (cm)		No of LR		PA (cm2)		RV (cm3)	
Genotype	Non-stress	Stress	Non-stress	Stress	Non-stress	Stress	Non-stress	Stresss	Non-stress	Stress
ABE4	2632	2001	58	54	10.3	10.3	128.8	87.5	5	3.1
ACE1	3101	2025	65	76	14	8.7	155.5	81.9	6.2	2.7
ACE2	2586	2635	59	71	16.3	12	132	119.3	5.4	4.4
AFR476	2056	1863	62	76	9.7	7.3	89.2	74.3	3.2	2.3
ARM2	3271	2744	58	64	15	10.7	161.5	127.3	6.4	4.6
C97407	3410	2926	73	78	11.3	10	170.8	121.9	6.8	4.1
COCACHO	2085	2085	58	68	14.3	10.3	97.8	89.6	3.7	3.1
L88-63	1880	2117	50	64	9	6.7	88.8	87.5	3.4	2.9
MIL UNO	2804	2277	65	67	16	10	133.6	101.4	5.1	3.6
PARAGACHI	3156	2549	62	62	11.7	9	149.8	123.1	5.7	4.7
POA 10	3414	3035	62	76	15.3	13.3	175.8	126	7.1	4.2
RAB651	2811	2273	61	77	9.7	10.3	118.6	96.2	4	3.2
RAB655	2275	2081	58	63	9	7.7	99.6	87.3	3.5	2.9
SEQ1016	3489	2567	62	55	15	11	179.1	125.2	7.2	4.9
YUNGUILLA	2679	2125	55	55	13.3	8	121.6	89.6	4.4	3
YxA7	3104	2418	59	72	16	10.7	135.3	96.7	5.2	3.1
MEAN	2797	2358	60	67	12.9	9.8	133.6	102.2	5.2	3.5
LSD (0.05)	1198		26.9		4.9		51.6		2.1	
CV (%)	22.5		18.1		21.3		21.2		23.4	

Table 35. Root length in category A (RL (A)), root length in category B (RL (B)), root length in category C (RL(C)), and root length in category D (RL (D)) for 16 bean genotypes under two water treatments in STG experiment in Michigan State University, MI 2004.

	RL (A) (cm)		RL (B) (cm)		RL (C) (cm)		RL (D) (cm)	
Genotype	Non-stress	Stress	Non-stress	Stress	Non-stress	Stress	Non-stress	Stress
ABE4	1774	1434	585	447	261	79	12	5
ACE1	2085	1507	655	423	348	92	13	3
ACE2	1684	1853	596	640	292	130	15	13
AFR476	1495	1423	436	376	123	63	2	3
ARME2	2204	1946	688	616	360	173	20	8
C97407	2213	2144	854	624	324	148	20	9
COCACHO	1431	1522	457	469	196	94	2	3
L88-63	1306	1580	400	427	168	106	6	4
MIL UNO	1908	1610	606	521	280	159	10	6
PARAGACHI	2185	1758	649	524	309	220	13	13
POA 10	2238	2236	779	650	371	141	26	9
RAB651	2054	1675	599	471	154	121	4	5
RAB655	1634	1538	436	434	152	106	4	3
SEQ1016	2318	1745	702	588	447	216	23	18
YUNGUILLA	1878	1562	570	429	224	128	7	6
YxA7	1901	1812	692	520	268	82	9	3
MEAN	1894	1709	606	510	267	129	11	7
LSD (0.05)	508		128		76		8	
CV (%)	24.4		19.8		33.2		75.8	

Table 36. Total root length (TRL), surface area (SA), projected area (PA), root volume (RV), and root diameter average (DA) for 16 bean genotypes above 0.3 m of the PVC-tube under two water treatments in STG experiment in Michigan State University, MI 2004.

	TRL (cm)		SA (cm2)		PA (cm2)		RV (cm3)		DA (mm)	
Genotype	Non-stress	Stress	Non-stress	Stress	Non-stress	Stress	Non-stress	Stress	Non-stress	Stress
ABE4	2136	1333	314.1	175.2	100.0	55.8	3.7	1.9	0.47	0.42
ACE1	2255	1297	344.8	153.2	109.7	48.8	4.3	1.5	0.37	0.45
ACE2	1960	1566	298.3	218.4	94.9	69.5	3.7	2.5	0.48	0.39
AFR476	1574	1297	189.4	158.0	60.3	50.3	1.8	1.5	0.48	0.45
ARM2	2431	1960	350.4	275.0	111.6	87.6	4.1	3.1	0.39	0.42
C97407	2066	1585	312.0	210.7	99.3	67.0	3.8	2.3	0.46	0.42
COCACHO	1539	1344	208.4	174.6	66.3	55.6	2.2	1.8	0.48	0.39
L88-63	1265	1242	167.1	612.6	53.2	49.1	1.8	1.5	0.43	0.41
MIL UNO	2091	1429	297.2	183.0	94.6	58.3	3.4	1.9	0.42	0.46
PARAGACHI	2335	1825	325.6	264.9	104.7	84.3	3.7	3.1	0.45	0.39
POA 10	2371	1839	376.9	226.2	120.0	72.0	4.8	2.2	0.45	0.41
RAB651	1960	1539	242.3	200.2	77.1	63.6	2.4	2.1	0.5	0.4
RAB655	1784	1575	230.1	198.0	73.3	63.0	2.4	2.0	0.39	0.47
SEQ1016	2588	1853	409.2	270.8	130.2	86.2	5.1	3.2	0.4	0.41
YUNGUILLA	2140	1611	289.5	207.2	92.2	65.9	3.1	2.1	0.5	0.44
YxA7	2335	1535	292.3	182.2	93.0	58.0	3.3	1.8	0.43	0.38
MEAN	2052	1552	290.5	231.9	92.5	64.7	3.4	2.2	0.44	0.42
LSD (0.05)	336		172		17.3		0.8		0.04	
CV (%)	16.1		57.0		19.0		26.3		9.5	

Table 37. Root length in category A (RL (A)), category B (RL (B)), category C (RL(C)), and category D (RL (D)) for 16 genotypes above 0.3 m of the PVC-tube under two water treatments in STG experiment in Michigan State University, MI 2004.

Genotype	RL (A) (cm)		RL (B) (cm)		RL (C) (cm)		RL (D) (cm)	
	Non-stress	Stress	Non-stress	Stress	Non-stress	Stress	Non-stress	Stress
ABE4	1476	976	480	287	169	32	11	4
ACE1	1534	1004	510	250	199	42	12	2
ACE2	1305	1097	471	388	171	71	13	10
AFR476	1194	1015	325	241	53	39	1	2
ARM2	1689	1417	531	426	195	110	17	8
C97407	1381	1153	494	334	174	90	16	7
COCACHO	1109	1022	343	265	87	55	2	2
L88-63	922	943	265	246	77	50	2	2
MIL UNO	1472	1041	454	330	155	54	9	3
PARAGACHI	1663	1286	504	371	158	127	11	9
POA 10	1554	1393	587	373	207	68	23	6
RAB651	1490	1169	389	290	79	77	2	4
RAB655	1324	1198	376	314	81	62	3	2
SEQ1016	1708	1293	580	412	280	138	20	11
YUNGUILLA	1553	1199	445	332	135	74	7	5
YxA7	1447	1194	513	302	136	37	6	2
MEAN	1426	1150	454	323	147	70	10	5
LSD (0.05)	237		77		50		7	
CV (%)	15.9		17.2		40.0		85.0	

Table 38. Total root length (TRL), surface area (SA), projected area (PA), and root volume (RV) for 16 bean genotypes below 0.3 m of the PVC-tube under two water treatments in STG experiment in Michigan State University, MI 2004.

Genotype	TRL (cm)		SA (cm2)		PA (cm2)		RV (cm3)	
	Non-stress	Stress	Non-stress	Stress	Non-stress	Stress	Non-stress	Stress
ABE4	496	667	90.6	99.7	28.8	31.7	1.3	1.2
ACE1	846	728	143.9	103.9	45.8	33.1	1.9	1.2
ACE2	626	1069	116.5	156.2	37.1	49.7	1.7	1.9
AFR476	483	566	90.6	75.2	28.8	23.9	1.4	0.8
ARM2	840	784	156.8	124.8	49.9	39.8	2.4	1.6
C97407	1344	1341	224.6	172.3	71.5	54.8	3.0	1.8
COCACHO	546	742	98.8	106.6	31.5	33.9	1.4	1.2
L88-63	614	875	111.9	120.7	35.6	38.4	1.6	1.4
MIL UNO	713	848	122.5	135.6	39.0	43.1	1.7	1.7
PARAGACHI	821	723	141.7	121.9	45.1	38.8	2.0	1.6
POA 10	1042	1196	175.5	169.5	55.9	54.0	2.4	1.9
RAB651	851	734	130.3	102.5	41.5	32.6	1.6	1.1
RAB655	491	505	82.6	76.4	26.3	24.3	1.1	0.9
SEQ1016	902	714	153.0	122.3	48.8	38.9	2.1	1.7
YUNGUILLA	539	514	92.4	74.3	29.4	23.6	1.3	0.9
YxA7	769	883	132.7	121.4	42.2	38.6	1.9	1.3
MEAN	745	806	129.0	117.7	41.1	37.5	1.8	1.4
LSD (0.05)	472		63		20.1		0.7	
CV (%)	52.8		44.3		44.3		39.1	

Table 39. Root length in category A (RL (A)), category B (RL (B)), category C (RL(C)), and category D (RL (D)) for 16 bean genotypes at below 0.3 m of the PVC-tube under two water treatments in STG experiment in Michigan State University, MI 2004.

	RL (A) (cm)		RL (B) (cm)		RL (C) (cm)		RL (D) (cm)	
Genotype	Non-stress	Stress	Non-stress	Stress	Non-stress	Stress	Non-stress	Stress
ABE4	299	458	105	160	92	47	0.6	1.5
ACE1	551	503	145	173	149	50	1.4	1.6
ACE2	379	756	125	252	121	59	1.7	2.7
AFR476	301	408	111	134	70	24	0.3	0.6
ARM2	515	529	157	190	165	64	3.1	0.5
C97407	832	992	360	290	149	58	3.1	1.9
COCACHO	322	501	115	204	109	38	0.2	1.2
L88-63	384	637	135	180	91	56	3.9	2.3
MIL UNO	436	570	152	191	125	105	0.6	3.2
PARAGACHI	523	472	145	154	151	94	1.8	4.4
POA 10	684	843	192	277	164	73	2.7	3.6
RAB651	564	507	210	182	75	44	1.2	0.9
RAB655	310	340	60	120	71	44	0.8	1.5
SEQ1016	609	453	122	176	167	78	2.9	7.0
YUNGUILLA	325	363	125	97	89	55	0.5	0.4
YxA7	454	618	179	218	132	45	2.9	0.5
MEAN	468	559	152	187	120	58	2	2
LSD (0.05)	349		36		41		2.8	
CV (%)	58.9		51.9		39.7		129.0	

Table 40. Total root length (TRL), surface area (SA), projected area (PA), root volume (RV), root diameter average (DA), root length in category A (RL (A)), category B (RL (B)), category C (RL(C)), and category D (RL (D)) for 16 bean genotypes above 0.3 m of the PVC-tube in IBL1 experiment in Michigan State University, MI 2004.

Genotypes	TRL (cm)	SA (cm2)	PA (cm2)	RV (cm3)	DA (mm)	RL (A) (cm)	RL (B) (cm)	RL (C) (cm)	RL (D) (cm)
C03108	2079	283	90	3.1	0.43	1478	500	85	16
C03117	2047	257	82	2.6	0.40	1530	424	82	11
C03119	1945	231	74	2.2	0.37	1502	369	67	8
C03121	2396	317	101	3.4	0.41	1735	530	114	16
C03122	1916	257	82	2.8	0.42	1390	423	92	11
C03125	1693	219	70	2.3	0.40	1226	387	72	7
C03151	2360	331	105	3.8	0.44	1658	551	132	19
C03154	1919	227	72	2.2	0.38	1472	378	62	7
C03155	2172	279	89	2.9	0.41	1596	479	88	11
C03157	2327	290	92	2.9	0.39	1767	456	93	10
C03160	1817	211	67	2.0	0.36	1411	349	53	4
C03161	1966	252	80	2.6	0.41	1452	421	82	12
C03163	2070	269	86	2.9	0.39	1519	441	94	16
C97407	2167	309	98	3.6	0.44	1508	513	123	23
L88-63	1975	255	81	2.7	0.40	1472	390	94	18
NSL	1987	245	78	2.4	0.39	1494	421	66	7
MEAN	2052	264	84	2.8	0.40	1513	439	87	12
LSD (0.05)	408	87	ns	ns	ns	243	ns	ns	ns
CV (%)	17.2	28.4	28.4	41.9	13.2	13.9	32.3	55.7	99.2

Table 41. Total root length (TRL), surface area (SA), projected area (PA), root volume (RV), root diameter average (DA), root length in category A (RL (A)), category B (RL (B)), category C (RL(C)), and category D (RL (D)) for 16 bean genotypes below 0.3 m of the PVC-tube in IBL1 experiment in Michigan State University, MI 2004.

Genotype	TRL (cm)	SA (cm2)	PA (cm2)	RV (cm3)	DA (mm)	RL (A) (cm)	RL (B) (cm)	RL (C) (cm)	RL (D) (cm)
C03108	1300	174	56	1.9	0.42	920	319	57	4
C03117	2303	293	93	3.0	0.4	1710	483	101	9
C03119	2440	377	120	4.7	0.49	1608	634	167	31
C03121	2223	322	103	3.8	0.45	1504	569	133	17
C03122	1575	200	64	2.0	0.39	1172	336	62	5
C03125	1354	180	57	1.9	0.43	971	307	71	4
C03151	2027	283	90	3.2	0.44	1404	499	110	13
C03154	1659	213	68	2.2	0.41	1230	355	69	6
C03155	1986	289	92	3.4	0.46	1386	462	116	22
C03157	2545	397	126	5.1	0.49	1663	670	175	37
C03160	2128	275	88	2.9	0.4	1588	431	99	10
C03161	1219	157	50	1.6	0.41	861	319	37	1
C03163	2179	281	90	3.0	0.41	1612	459	95	12
C97407	1774	303	96	4.2	0.51	1100	473	163	38
L88-63	1511	194	62	2.0	0.41	1114	328	63	5
NSL	1189	151	48	1.5	0.41	859	289	38	2
MEAN	1838	256	81	2.9	0.43	1294	433	97	14
LSD (0.05)	768	113	36	1.5	0.06	576	160	66	19.6
CV (%)	36.2	38.4	38.4	44.7	11.9	38.5	32.0	59.0	125.1

Table 42. Length of the taproot (LTR), number of the lateral roots (No of LR), root weight (RW), total root length (TRL), projected area (PA), root volume (RV) for 16 bean genotypes under two water treatments in IBL1 experiment in Michigan State University, MI 2004.

	LTR (cm)		No of LR		RW (g)		TRL (cm)		PA (cm2)		RV (cm3)	
Genotype	Non-stress	Stress	Non-stress	Stress	Non-stress	Stress	Non-stress	Stress	Non-stress	Stress	Non-stress	Stress
C03108	74	52	9.7	7.3	11.2	7.0	3677	3082	165	125	5.9	4.1
C03117	77	92	10.3	8.0	11.8	8.7	4414	4285	186	164	6.2	5.0
C03119	85	70	13.7	8.3	15.7	7.2	5077	3694	239	148	9.0	4.8
C03121	86	63	10.7	6.3	15.4	6.1	5620	3618	268	139	10.2	4.2
C03122	71	64	9.0	6.3	9.6	7.2	3572	3410	150	140	5.0	4.6
C03125	67	63	9.0	8.7	10.9	6.2	3343	2749	146	108	5.0	3.4
C03151	78	66	10.3	7.7	14.5	7.9	5166	3607	237	154	8.6	5.3
C03154	80	66	9.3	7.0	9.8	6.1	3861	3295	158	122	5.1	3.6
C03155	91	49	10.0	7.7	14.5	6.6	5266	3051	238	123	8.6	4.0
C03157	83	78	9.7	7.0	16.9	7.7	5683	4061	272	166	10.6	5.4
C03160	79	64	8.0	5.7	13.6	6.5	4613	3277	194	116	6.4	3.2
C03161	79	45	11.7	6.7	9.5	5.9	3475	2894	144	117	4.7	3.8
C03163	80	72	8.7	7.0	12.9	7.7	4721	3779	208	142	7.4	4.3
C97407	75	49	10.0	9.0	18.3	5.3	5124	2758	276	113	11.9	3.8
L88-63	86	70	8.7	7.0	10.0	6.3	3736	3235	158	128	5.4	4.0
NSL	68	53	6.7	4.0	9.9	5.6	3702	2650	147	105	4.6	3.3
MEAN	79	63	9.7	7.1	12.8	6.7	4441	3340	625	415	199	132
LSD(0.05)	19.1		1.8		2.5		786		42		2.0	
CV (%)	23.2		18.6		22.5		17.5		22.0		30.3	

Table 43. Root length in category A (RL (A)), category B (RL (B)), category C (RL(C)), and category D (RL (D)) for 16 bean genotypes under two water treatments in IBL1 experiment in Michigan State University, MI 2004.

Genotypes	RL (A) (cm)		RL (B) (cm)		RL (C) (cm)		RL (D) (cm)	
	Non-stress	Stress	Non-stres	Stress	Non-stress	Stress	Non-stress	Stress
C03108	2551	2245	913	726	191	94	22	18
C03117	3187	3294	987	827	219	146	21	18
C03119	3462	2758	1217	790	337	130	61	17
C03121	3746	2734	1428	771	390	103	57	10
C03122	2636	2488	753	765	166	142	17	14
C03125	2374	2022	768	621	187	99	15	8
C03151	3556	2569	1246	853	321	164	43	21
C03154	2850	2554	827	638	168	95	17	8
C03155	3727	2237	1177	705	308	99	54	10
C03157	3866	2996	1346	906	394	144	78	15
C03160	3397	2602	961	597	235	69	21	8
C03161	2484	2141	836	643	142	96	13	14
C03163	3344	2919	1064	736	268	112	45	12
C97407	3224	1991	1313	659	475	97	114	10
L88-63	2741	2433	766	670	199	117	30	15
NSL	2731	1975	834	586	124	83	12	6
MEAN	3117	2497	1027	718	258	112	39	13
LSD (0.05)	219		196		33		23	
CV (%)	19.1		19.4		44.1		76.8	

Table 44. Total root length (TRL), surface area (SA), projected area (PA), root volume (RV), and root diameter average (DA) for 16 bean genotypes above 0.3 m of the PVC-tube under two water treatments in IBL1 experiment in Michigan State University, MI 2004.

	TRL (cm)		SA (cm2)		PA (cm2)		RV (cm3)		DA (mm)	
Genotypes	Non-stress	Stress	Non-stress	Stress	Non-stress	Stress	Non-stress	Stress	Non-stress	Stress
C03108	2011	2148	281	284	89	90	3.1	3.0	0.44	0.42
C03117	2316	1778	309	204	98	65	3.3	1.9	0.43	0.36
C03119	2092	1798	266	197	85	63	2.7	1.7	0.4	0.35
C03121	2605	2186	382	251	122	80	4.5	2.3	0.46	0.36
C03122	1996	1837	273	240	87	76	3.0	2.6	0.44	0.4
C03125	1797	1589	241	197	77	63	2.6	2.0	0.42	0.39
C03151	2538	2182	355	307	113	98	4.0	3.6	0.44	0.44
C03154	1987	1851	245	209	78	67	2.4	1.9	0.39	0.36
C03155	2316	2029	295	263	94	84	3.0	2.8	0.4	0.41
C03157	2650	2004	351	229	112	73	3.7	2.1	0.42	0.37
C03160	1952	1682	245	177	78	56	2.5	1.5	0.4	0.33
C03161	1997	1935	260	244	83	78	2.7	2.5	0.41	0.4
C03163	2296	1844	325	214	103	68	3.8	2.0	0.43	0.36
C97407	2342	1993	358	260	114	83	4.4	2.8	0.47	0.41
L88-63	2093	1856	283	227	90	72	3.1	2.2	0.42	0.38
NSL	2165	1808	273	217	87	69	2.8	2.1	0.4	0.38
MEAN	2197	1907	296	233	94	74	3.2	2.3	0.42	0.38
LSD (0.05)	408		87		28		1.3		0.06	
CV (%)	17.2		28.4		28.4		41.9		13.2	

Table 45. Root length in category A (RL (A)), category B (RL (B)), category C (RL(C)), and category D (RL (D)) for 16 bean genotypes above 0.3 m of the PVC-tube under two water treatments in IBL1 experiment in Michigan State University, MI 2004.

	RL (A) (cm)		RL (B) (cm)		RL (C) (cm)		RL (D) (cm)	
Genotypes	Non-stress	Stress	Non-stress	Stress	Non-stress	Stress	Non-stress	Stress
C03108	1416	1540	483	517	97	73	15	17
C03117	1667	1393	516	332	117	47	15	6
C03119	1576	1428	408	330	96	37	12	3
C03121	1752	1718	652	409	173	54	27	5
C03122	1449	1332	432	414	100	84	14	8
C03125	1290	1163	413	362	85	59	9	4
C03151	1799	1517	576	525	142	122	21	18
C03154	1492	1452	413	342	73	52	8	6
C03155	1724	1467	481	476	99	76	11	10
C03157	1961	1574	537	376	136	51	16	3
C03160	1460	1362	407	290	78	28	6	2
C03161	1454	1449	442	399	90	74	11	13
C03163	1608	1430	524	358	139	50	26	6
C97407	1582	1434	554	471	168	78	38	9
L88-63	1522	1423	429	351	118	71	25	11
NSL	1616	1372	459	382	81	50	9	4
MEAN	1586	1441	483	396	112	63	16	8
LSD (0.05)	243		164		56		13.9	
CV (%)	13.9		32.3		55.7		99.2	

Table 46. Total root length (TRL), surface area (SA), projected area (PA), root volume (RV), and diameter average (DA) for 16 genotypes below 0.3 m of the PVC-tube under two water treatments in IBL1 experiment in Michigan State University, MI 2004.

	TRL (cm)		SA (cm2)		PA (cm2)		RV (cm3)		DA (mm)	
Genotypes	Non-stress	Stress	Non-stress	Stress	Non-stres	Stress	Non-stress	Stress	Non-stress	Stress
C03108	1666	935	239	110	76	35	2.7	1.0	0.46	0.38
C03117	2098	2508	274	312	87	99	2.9	3.1	0.42	0.39
C03119	2984	1896	485	268	154	85	6.3	3.0	0.53	0.45
C03121	3015	1431	459	186	146	59	5.6	1.9	0.49	0.42
C03122	1576	1573	198	201	63	64	2.0	2.1	0.4	0.39
C03125	1547	1160	216	143	69	46	2.4	1.4	0.44	0.41
C03151	2628	1425	390	175	124	56	4.7	1.7	0.47	0.42
C03154	1875	1443	252	174	80	56	2.7	1.7	0.42	0.39
C03155	2951	1022	452	125	144	40	5.6	1.3	0.48	0.43
C03157	3033	2057	503	291	160	93	6.9	3.3	0.53	0.45
C03160	2661	1594	364	186	116	59	4.0	1.7	0.44	0.37
C03161	1479	959	191	124	61	39	2.0	1.3	0.41	0.41
C03163	2425	1934	330	233	105	74	3.7	2.3	0.41	0.41
C97407	2783	765	510	95	162	30	7.4	1.0	0.59	0.43
L88-63	1643	1379	213	175	68	56	2.2	1.8	0.4	0.41
NSL	1536	843	189	112	60	36	1.9	1.2	0.39	0.42
MEAN	2244	1433	329	182	105	58	3.9	1.9	0.46	0.41
LSD (0.05)	768		113		36		1.5		0.06	
CV (%)	36.2		38.4		38.4		44.7		11.9	

Table 47. Root length in category A (RL (A)), category B (RL (B)), category C (RL(C)), and category D (RL (D)) for 16 bean genotypes below 0.3 m of the PVC-tube under two water treatments in IBL1 experiment in Michigan State University, MI 2004.

	RL (A) (cm)		RL (B) (cm)		RL (C) (cm)		RL (D) (cm)	
Genotypes	Non-stres	Stress	Non-stres	Stress	Non-stres	Stress	Non-stres	Stress
C03108	1135	704	429	209	94	21	7	1
C03117	1519	1901	471	495	102	100	6	12
C03119	1886	1331	809	460	241	93	48	14
C03121	1993	1016	775	363	216	49	30	4
C03122	1187	1156	321	352	65	59	3	6
C03125	1084	858	355	259	102	40	6	3
C03151	1757	1052	670	328	179	42	23	3
C03154	1358	1102	414	296	95	43	9	3
C03155	2004	769	695	229	209	23	43	1
C03157	1905	1422	809	530	258	93	62	12
C03160	1936	1240	553	308	157	41	14	5
C03161	1030	692	394	244	52	22	2	1
C03163	1736	1489	541	378	129	62	19	5
C97407	1642	557	758	188	307	19	76	1
L88-63	1219	1010	337	319	81	46	5	4
NSL	1115	603	375	204	43	34	3	2
MEAN	1056	544	322	146	49	22	5	1056
LSD (0.05)	576		160		66		20	
CV (%)	38.5		32.0		59.0		125.1	

Table 48. Total root length (TRL), surface area (SA), projected area (PA), root volume (RV), diameter average (DA) for 16 bean genotypes above 0.3 m of the PVC-tube in IBL2 experiment in Michigan State University, MI 2004.

Genotypes	TRL (cm)	SA (cm2)	PA (cm2)	RV (cm3)	DA (mm)
C03102	1021	155	49	1.9	0.48
C03104	1249	200	64	2.6	0.51
C03110	1067	176	56	2.3	0.53
C03123	1726	285	91	3.8	0.53
C03127	1037	159	51	2.0	0.49
C03129	1186	206	65	3.0	0.56
C03131	1287	178	57	2.0	0.44
C03143	1277	185	59	2.2	0.46
C03147	1558	239	76	3.0	0.49
C03148	1567	234	75	2.9	0.49
C03149	1527	229	73	2.8	0.49
C03150	1717	256	81	3.1	0.48
C03156	1468	222	71	2.7	0.48
C97407	1577	243	77	3.0	0.49
L88-63	1137	172	55	2.1	0.49
NSL	1215	177	56	2.1	0.46
MEAN	1351	207	66	2.6	0.49
LSD (0.05)	322	49	16	0.8	0.06
CV (%)	20.6	20.6	20.6	25.9	11.0

Table 49. Root length in category A (RL (A)), category B (RL (B)), category C (RL(C)), and category D (RL (D)) for 16 bean genotypes above 0.3 m of the PVC-tube in IBL2 experiment in Michigan State University, MI 2004.

Genotypes	RL (A) (cm)	RL (B) (cm)	RL (C) (cm)	RL (D) (cm)
C03102	685	254	65	17
C03104	800	319	100	27
C03110	676	282	88	22
C03123	1078	460	155	33
C03127	688	260	74	16
C03129	744	304	105	32
C03131	922	285	65	15
C03143	894	277	89	16
C03147	1056	367	113	22
C03148	1101	333	105	28
C03149	1050	348	104	26
C03150	1191	390	113	23
C03156	1010	327	103	29
C97407	1047	390	120	20
L88-63	789	255	71	22
NSL	842	284	74	15
MEAN	911	321	96	23
LSD (0.05)	239	86	33	ns
CV (%)	22.8	23.1	29.2	55.7

Table 50. Total root length (TRL), surface area (SA), projected area (PA), root volume (RV), and root diameter average (DA) for 16 bean genotypes below 0.3 m of the PVC-tube in IBL2 experiment in Michigan State University, MI 2004.

Genotypes	TRL (cm)	SA (cm2)	PA (cm2)	RV (cm3)	DA (mm)
C03102	283	33	11	0.3	0.32
C03104	311	38	12	0.4	0.33
C03110	211	26	8	0.3	0.25
C03123	359	48	15	0.5	0.34
C03127	259	29	9	0.3	0.25
C03129	294	34	11	0.3	0.19
C03131	311	34	11	0.3	0.29
C03143	250	29	9	0.3	0.31
C03147	335	41	13	0.4	0.32
C03148	427	46	15	0.4	0.28
C03149	545	66	21	0.6	0.33
C03150	602	72	23	0.7	0.39
C03156	405	44	14	0.4	0.29
C97407	1070	129	41	1.2	0.39
L88-63	280	32	10	0.3	0.24
NSL	289	31	10	0.3	0.23
MEAN	390	46	15	0.4	0.30
LSD (0.05)	363	41	13	0.38	0.12
CV (%)	80.7	77.5	77.5	75.6	34.3

Table 51. Root length in category A (RL (A)), category B (RL (B)), category C (RL(C)), category D (RL (D)) for 16 bean genotypes below 0.3 m of the PVC-tube in IBL2 experiment in Michigan State University, MI 2004.

Genotypes	RL (A) (cm)	RL (B) (cm)	RL (C) (cm)	RL (D) (cm)
C03102	219	62	2	0.0
C03104	237	67	6	0.1
C03110	160	48	3	0.0
C03123	260	85	13	0.4
C03127	210	42	6	0.1
C03129	232	57	5	0.1
C03131	254	53	4	0.1
C03143	198	48	4	0.1
C03147	257	71	7	0.3
C03148	358	62	6	0.3
C03149	418	114	12	0.7
C03150	477	110	15	0.4
C03156	336	65	4	0.1
C97407	831	213	25	0.8
L88-63	230	45	5	0.3
NSL	241	45	4	0.1
MEAN	307	74	8	0.2
LSD (0.05)	296	65	9	ns
CV (%)	83.4	76.2	103.1	211.0

Table 52. Length of the taproot (LTR), number of the lateral roots (No of LR) , total root length (TRL), projected area (PA), root volume (RV) for genotypes under two water treatments in IBL2 experiment in Michigan State University, MI 2004.

Genotype	LTR (cm)		No of LR		Root weight		TRL (cm)		SA (cm3)		PA (cm2)		RV (cm3)	
	Non-Stress	Stress	Non-Stress	Stress	Non-Stress	Stress	Non-Stress	Stress	Non-Stress	Stress	Non-Stress	Stress	Non-Stress	Stress
C03102	39	41	10.3	7.3	2.2	2.6	1185	1424	182	193	58	62	2.3	2.1
C03104	52	39	11.0	7.3	2.9	3.2	1356	1764	212	265	67	84	2.7	3.2
C03110	47	35	9.7	8.7	2.4	2.4	1321	1236	202	201	64	64	2.5	2.7
C03123	61	39	11.0	8.0	4.7	3.7	2029	2140	329	337	105	107	4.4	4.3
C03127	44	43	12.0	7.0	2.8	2.2	1395	1197	201	173	64	55	2.4	2.1
C03129	47	35	11.0	8.3	3.5	2.6	1458	1502	237	243	76	77	3.3	3.3
C03131	45	47	10.7	8.7	2.4	2.5	1494	1701	220	206	70	65	2.6	2.0
C03143	52	40	8.7	7.7	2.6	2.6	1471	1583	194	233	62	74	2.1	2.8
C03147	50	51	13.0	7.0	3.7	3.7	1857	1929	288	270	92	86	3.6	3.1
C03148	50	45	11.3	7.3	3.2	2.6	1815	2173	271	288	86	92	3.5	3.1
C03149	48	53	12.3	8.0	3.5	4.1	1479	2665	240	350	77	111	3.1	3.7
C03150	62	44	12.0	6.7	4.1	3.3	2407	2232	341	315	109	100	3.9	3.6
C03156	54	45	10.3	9.3	3.3	3.2	1669	2079	242	291	77	93	2.9	3.3
C97407	68	57	9.3	8.0	5.3	4.0	2864	2430	389	355	124	113	4.2	4.2
L88-63	54	34	9.7	7.0	2.8	2.2	1628	1206	220	187	70	60	2.4	2.4
NSL	46	36	10.3	4.7	2.3	2.1	1452	1556	192	224	61	71	2.1	2.6
MEAN	51	43	10.8	7.6	3.2	2.9	1680	1801	248	258	79	82	3.0	3.0
LSD(0.05)	13		1.9		0.8		575		69		22		0.8	
CV (%)	24.4		17.6		21.5		28.6		23.7		23.7		24.0	

Table 53. Root length in category A (RL (A)), category B (RL (B)), category C (RL(C)), and category D (RL (D)) for 16 bean genotypes under two water treatments in IBL2 experiment in Michigan State University, MI 2004.

	RL (A) (cm)		RL (B) (cm)		RL (C) (cm)		RL (D) (cm)	
Genotypes	Non-Stress	Stress	Non-Stress	Stress	Non-Stress	Stress	Non-Stress	Stress
C03102	795	1013	293	340	75	59	22	12
C03104	896	1177	319	454	99	113	35	20
C03110	884	788	336	324	78	103	23	21
C03123	1302	1375	514	577	175	162	39	27
C03127	966	830	327	277	83	76	19	14
C03129	957	996	354	367	115	106	32	33
C03131	1047	1304	334	341	89	49	24	6
C03143	1089	1095	297	354	72	114	13	20
C03147	1248	1378	443	432	138	102	28	17
C03148	1274	1643	384	407	121	103	37	20
C03149	957	1979	370	553	117	115	35	18
C03150	1726	1611	515	485	138	119	28	19
C03156	1185	1506	358	425	93	121	32	27
C97407	2052	1703	658	548	137	153	17	25
L88-63	1218	820	314	286	76	77	20	24
NSL	1064	1102	312	345	66	90	11	18
MEAN	1166	1270	383	407	104	104	26	20
LSD (0.05)	164		119		33		15	
CV (%)	32.9		26.0		27.1		54.7	

Table 54. Total root length (TRL), surface area (SA), projected area (PA), root volume (RV), and root diameter average (DA) for 16 bean genotypes above 0.3 m of the PVC-tube under two water treatments in IBL2 experiment in Michigan State University, MI 2004.

	TRL (cm)		SA (cm2)		PA (cm2)		RV (cm3)		DA (mm)	
Genotypes	Non-Stress	Stress	Non-Stress	Stress	Non-Stress	Stress	Non-Stress	Stress	Non-Stress	Stress
C03102	1067	976	168	142	53	45	2.2	1.6	0.49	0.46
C03104	1087	1411	179	221	57	70	2.4	2.8	0.52	0.50
C03110	1034	1099	166	186	53	59	2.1	2.5	0.51	0.54
C03123	1539	1913	262	309	83	98	3.6	4.0	0.55	0.51
C03127	1101	974	167	151	53	48	2.1	1.9	0.49	0.49
C03129	1107	1265	194	217	62	69	2.9	3.1	0.56	0.56
C03131	1256	1318	192	165	61	53	2.4	1.6	0.49	0.40
C03143	1280	1274	172	198	55	63	1.9	2.5	0.43	0.49
C03147	1578	1538	252	225	80	72	3.3	2.7	0.51	0.46
C03148	1497	1637	238	230	76	73	3.2	2.6	0.53	0.45
C03149	1275	1778	213	245	68	78	2.9	2.7	0.54	0.44
C03150	1652	1783	249	263	79	84	3.0	3.1	0.49	0.46
C03156	1327	1609	203	242	65	77	2.5	2.9	0.48	0.48
C97407	1472	1682	217	269	69	86	2.6	3.4	0.47	0.51
L88-63	1273	1000	182	162	58	52	2.1	2.2	0.46	0.53
NSL	1189	1241	164	189	52	60	1.8	2.3	0.45	0.48
MEAN	1296	1406	201	213	64	68	2.5	2.6	0.50	0.49
LSD (0.05)	322		49		16		0.8		0.06	
CV (%)	20.6		20.6		20.6		25.9		11.0	

Table 55. Root length in categories A (RL (A)), B (RL (B)), C (RL(C)), and D (RL (D)) for 16 bean genotypes above 0.3 m of the PVC-tube under two water treatments in IBL2 experiment in Michigan State University, MI 2004.

	RL (A) (cm)		RL (B) (cm)		RL (C) (cm)		RL (D) (cm)	
Genotypes	Non-Stress	Stress	Non-Stress	Stress	Non-Stress	Stress	Non-Stress	Stress
C03102	700	670	271	237	74	56	22	12
C03104	690	909	264	375	92	107	35	20
C03110	676	675	263	301	73	102	23	21
C03123	957	1199	394	527	150	160	38	27
C03127	738	637	270	250	74	74	19	14
C03129	691	798	277	331	108	103	32	33
C03131	854	990	294	276	84	46	24	6
C03143	940	849	258	297	69	109	13	19
C03147	1045	1066	372	361	133	94	28	16
C03148	1014	1187	327	339	119	92	37	19
C03149	822	1278	306	389	112	95	35	16
C03150	1139	1244	372	408	113	113	28	18
C03156	911	1108	295	358	89	117	32	27
C97407	1001	1093	356	423	98	141	16	24
L88-63	923	655	260	249	70	72	20	24
NSL	849	835	267	300	62	87	11	18
MEAN	872	950	303	339	95	98	26	20
LSD (0.05)	239		86		33		15	
CV (%)	22.8		23.1		29.2		55.7	

Table 56. Total root length (TRL), surface area (SA), projected area (PA), root volume (RV), and diameter average (DA) for 16 bean genotypes below 0.3 m of the PVC-tube under two water treatments in IBL2 experiment in Michigan State University, MI 2004.

	TRL (cm)		SA (cm2)		PA (cm2)		RV (cm3)		DA (mm)	
Genotypes	Non-Stress	Stress	Non-Stress	Stress	Non-Stress	Stress	Non-Stress	Stress	Non-Stress	Stress
C03102	118	449	14	52	5	16	0.1	0.5	0.26	0.39
C03104	269	353	33	44	11	14	0.3	0.4	0.26	0.39
C03110	286	136	37	15	12	5	0.4	0.1	0.28	0.23
C03123	490	227	68	28	22	9	0.7	0.3	0.29	0.38
C03127	294	223	34	23	11	7	0.3	0.2	0.27	0.23
C03129	351	237	43	25	14	8	0.4	0.2	0.27	0.11
C03131	238	383	28	41	9	13	0.3	0.3	0.25	0.33
C03143	191	309	22	35	7	11	0.2	0.3	0.25	0.38
C03147	279	391	36	45	11	14	0.4	0.4	0.27	0.37
C03148	318	535	33	58	11	19	0.3	0.5	0.22	0.34
C03149	203	887	27	104	9	33	0.3	1.0	0.28	0.37
C03150	755	449	92	52	29	17	0.9	0.5	0.40	0.37
C03156	341	469	38	49	12	16	0.3	0.4	0.24	0.34
C97407	1393	748	171	86	55	27	1.7	0.8	0.40	0.38
L88-63	355	206	38	25	12	8	0.3	0.3	0.23	0.25
NSL	263	315	28	34	9	11	0.2	0.3	0.23	0.24
MEAN	384	395	46	45	15	14	0.5	0.4	0.28	0.32
LSD (0.05)	363		41		13		0.4		0.12	
CV (%)	80.7		77.5		77.5		75.6		34.3	

Table 57. Root length in category A (RL (A)), category B (RL (B)), category C (RL(C)), and category D (RL (D)) for 16 bean genotypes below 0.3 m of the PVC-tube under two water treatments in IBL2 experiment in Michigan State University, MI 2004.

Genotypes	RL (A) (cm)		RL (B) (cm)		RL (C) (cm)		RL (D) (cm)	
	Non-Stress	Stress	Non-Stress	Stress	Non-Stress	Stress	Non-Stress	Stress
C03102	95	343	21	103	1	3	0.01	0.01
C03104	206	268	56	79	7	5	0.07	0.03
C03110	208	113	73	23	5	1	0.05	0.00
C03123	345	176	119	50	25	2	0.81	0.06
C03127	228	193	58	27	9	2	0.11	0.01
C03129	266	198	77	36	8	3	0.12	0.03
C03131	193	315	41	65	5	3	0.09	0.11
C03143	149	246	40	57	3	6	0.00	0.22
C03147	203	312	71	71	6	8	0.05	0.60
C03148	259	456	57	68	2	11	0.01	0.67
C03149	135	701	63	164	4	20	0.05	1.24
C03150	587	367	143	76	25	6	0.48	0.36
C03156	274	398	63	67	5	4	0.11	0.08
C97407	1051	610	302	125	38	12	1.32	0.36
L88-63	294	165	54	37	6	4	0.09	0.41
NSL	215	267	45	45	4	3	0.00	0.11
MEAN	294	320	80	68	9	6	0.21	0.27
LSD (0.05)	296		65		9		0.58	
CV (%)	83.4		76.2		103.1		211.0	