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The Relationships between Stem Characters and Lodging Tolerance in Tef (*Eragrostis tef*) Genotypes

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ጤፍ በብዙ ሚሊየኖች ለሚቆጠሩ ኢትዮጵያዊያን ለምግብነት፣ ለእንስሶች ምግብ፣ ለቤት መስሪያነት እና ለመኝታ የሚያገለግል ዘርፈ ብዙ የሰብል አይነት ነዉ፡፡ ነገር ግን በተለያዩ የምርት ማነቆዎች ምክንያት ከጤፍ የሚገኘው ምርት ከሌሎች የብርዕ ሰብሎች ከሚገኘው ምርት ጋር ሲነጻጸር ትንሽ ነው፡፡ የሰብል ግሸበት የጤፍን ምርት እና ምርታማነቱን ለማሳደግ የሚደረገውን የምርምር ስራ እየገቱ ካሉ ማነቆዎች ውስጥ አንዱ ነው፡፡ የሰብል ቁመት፣ የሰብል ግንድ ውፍረት እና ስፋት፣ የአንጓ ቁጥር እና ርዝመት የብርዕ ሰብሎችን የግሸበት ባህርይ ከሚወስኑ ባህሪያት መካከል ይገኙበታል፡፡ የሰብል ግንድ ባህሪያት ከግሸበት ጋር ያላቸውን ትስስር ማወቅ ግሸበትን የሚቋቋሙ የጤፍ ዝርያዎችን በምርምር ለማውጣት የሚደገረውን ስራ በእጅጉ እነደሚያግዝ ይታመናል፡፡ ከዚህ በፊት የተደረጉ የምርምር ስራዎች የሰብል ግንድ ባህሪያት ከግሸበት ግር ያላቸውን ትስስር ለማወቅ የሚያስችል መሰረትን ቢጥሉም የሰብሉን የግንድ ባህሪያት ከማዳረስ አንጻር ውስን ነበሩ፡፡ በዚህ የምርምር ስራ አንድ መቶ የጤፍ ዝርያዎችን በሶስት የተለያዩ አካባቢዎች በመዝራት ከዚህ በፊት በተጠኑት የግንድ ባህሪያት ላይ ተጨማሪ የግንድ ባህሪያትን አካቶ በማጠናት ከዚህ በፊት የነበረውን ዕውቀት ለማስፋት ተሞክሯል፡፡ ይህ ጥናት ከዚህ በፊት የጤፍን የግሸበት ባህርይ ሊወስኑ ይችላሉ ከተባሉት የግንድ ባህሪያት በተጨማሪ የአጓ እና የፔደንክል ርዝመት ግሸበትን የሚቋቋሙ የጤፍ ዝርያዎችን ለማውጣት በሚደረገው ምርምር ውስጥ ትኩረት ሊሰጣቸው እንደሚገባ አመላክቷል፡፡

Abstract

In cereals, stem characters such as plant height, culm thickness and diameter and the number of internodes and their length are among the factors known to modulate lodging tolerance, a key trait in the development of high yielding tef varieties. Knowledge of the relationship between stem characters and lodging has significant implications with respect to designing sound breeding strategies for tef (Eragrostis tef), a staple cereal crop for millions of people in Ethiopia. Previous studies were limited mainly to plant height and the diameter of the two basal culm internodes. With the aim of expanding this knowledge by exploring additional stem characters, one-hundred tef landraces were studied at three different experimental sites and affirmative evidence was obtained showing that in addition to plant height the length of internodes and peduncle are apt to breeding lodging tolerance in tef.

Introduction

Stem characters including culm length, culm width, number of internodes, peduncle length, panicle length, and plant height are known to affect lodging tolerance in cereals. Of these, plant height has been the center of focus in breeding lodging tolerance in wheat (*Triticum aestivum* L.) and rice (*Oryza sativa* L.) (Dalrymple, 1986; Khush, 1999), and barley (*Hordeum vulgare* L.) (Grausgruber *et al.*, 2002). In addition to plant height, however, lodging also depends on the physical properties of the main culm (Ookawa and Ishihara, 1993). For instance, in wheat, barley and oats (*Avena sativa* L.), stem lodging is usually caused by one of the bottom two internodes buckling (Berry *et al.*, 2004; Neenan, 1975) and results in the upper stem and ear lying on the ground horizontally. Similarly, in tef, stem lodging leads to the displacement of the upper part of the plant including the seed-bearing panicle from vertical position towards the ground (Seyfu, 1993).This behavior can be observed particularly at maturity in the field and has affected the seed and straw yield both in quantity and quality and could make hand harvesting problematic.

Tef [*Eragrostis tef* (Zucc.) Trotter] is a key food security crop in Ethiopia and a healthy lifestyle food alternative elsewhere. The development and adoption of high yielding varieties has increased tef's productivity and production over the past few years but lodging remains a challenge (Assefa *et al.*, 2011). A plethora of phenotypic characters have been investigated in hundreds of tef germplasm and include characters that are related to seed and biomass yield (Assefa *et al.*, 2002b; Assefa *et al.*, 2001b) and their quantitative trait variation (Assefa *et al.*, 2002a; Assefa *et al.*, 2001a), qualitative and phonologic characters (Kefyalew *et al.*, 2000). However, the main objective of these studies has been limited mainly to describing the phenotypic trait variation of the germplasm collections in general. In addition, in the context of lodging tolerance, these studies explored the variations in diameters and/or strengths of the basal internodes and/or main culm and the correlation of panicle length/weight, peduncle length, and plant height with lodging tolerance.

The effect of the length of basal internodes on lodging has been demonstrated in rice (Hoshikawa, 1990). According to our knowledge, the effect of the lengths of the lower basal culm internodes on the lodging tolerance behavior of tef plants has not been addressed or reported so far. In a field experiment conducted at two locations (Assefa *et al.*, 1999; Assefa *et al.*, 2001b) reported a significant variation in the length of the first two basal internodes across the locations but didn't link this variation with lodging. In wheat and rice, breeding for short plant height has resulted in the development of lodging tolerant and high yielding varieties (Dalrymple, 1986; Hargrove and Cabanilla, 1979). In contrast, in tef, breeding for short plant stature combined with higher yield has remained a challenge to date for several reasons (Assefa *et al.*, 2011).

In the race to develop lodging tolerant tef plants the question of how short the tef plant should be and which part of the main culm should get shortened is not clear yet and needs further research. In the present study, we investigated the effect of the length of the lower basal internodes on lodging by conducting a field experiment at three locations using one hundred diverse tef germplasm.

Materials and Methods

Field experiment

The field experiment was conducted in 2013 at *Debre Zeit*, *Alem Tena*, and *Holetta* experimental sites representing three different tef growing areas in Ethiopia (Table 1) using a 10 × 10 simple lattice square design (Yates, 1936) with two replications. In each experimental site, genotypes were hand sown on plots comprising two rows of 50 cm long with 50 cm spacing between the rows. All other agronomic practices were carried out as recommended for the respective locations.

Plant materials and growth room experiment

Three hundred tef accessions (hereafter referred to as 'genotypes') representing wide tef growing regions in Ethiopia (Table 2) were used for this study. Seed samples were obtained from the Gene Bank at the Ethiopian Institute of Biodiversity (EBI, https//.www.ebi.gov.org), Ethiopia. The genotypes are collections from farmers' fields and represent locally adapted varieties. They were first screened under controlled growth conditions with 12 h dark and 12 h light at the Institute of Plant Sciences, University of Bern, Switzerland (https//.www.ips.ch). Based on visual assessment, one-hundred genotypes were selected for subsequent field testing.

Data collection and analysis

At each experimental site observations were made and data were recorded on per plant and plot basis for eleven stem characters including; number of tillers, number of fertile tillers, length (cm) of the 1st, 2nd, 3rd basal internodes, and length of the 4th, 5th, and 6th internodes, peduncle length (cm), panicle length (cm), plant height (cm), and lodging index (%). Lodging was scored using the method of Caaldicott and Nuttall (1979 whereby the degree of lodging (angle of leaning) from the perpendicular was scored on a 1 - 5 scale and the severity was estimated as the percentage of the plot stand manifesting each degree of lodging. The lodging index was then calculated as the average of the product sum of each degree of lodging and severity divided by five. The stem characters we focused on are important components of tef's straw and seed yield as well as its generic ability to tolerate lodging. Data on the number of tillers and the number of fertile tillers was recorded before flowering and at maturity, respectively. Data on the length of the 1st and 2nd basal internodes, the 3rd, and the nth internodes was taken soon after heading.

Mean values of the eleven stem characters from each genotype were computed from three randomly selected plants and used for subsequent descriptive statistics. Analysis of Variance, Pearson Correlations Analysis were made using packages in R (R Core Team, 2013).

Table 1. Description of the three experimental sites

Location	Geographic coordinate	Temperature Min-max (^{0}C)	Altitude (m)	Rainfall (mm)	Soil type/color
Holetta	(9°3' N, 38°30' E)	6.13 - 22.2	2400	1100	Nitosol (Clay/red soil)
Debre Zeit	(8° 44' N, 38° 58' E)	8.9 - 28.3	1860	800	Pelic vertisols (Black clay soil)
Alem Tena	(8.30' N, 38.95' E)	12.0 – 28.0	1611	500	Alfisols (Light sandy soil)

Table 2. Information on the designated name of accessions, region, approximate area of collection and altitude. Accession names are given by the Ethiopian Biodiversity Institute (EBI)

Accession No.	Region of collection	Approximate area	Altitude (m)
234375	*Tigray/Adwa*	*Mehakelegnaw*	1000
242568	*Tigray/Adwa*	*Mehakelegnaw*	1380
212602	*Amhara S/Wollo*	*Tenta*	2690
243492	*Amhara S/Wollo*	*Tenta*	2935
212603	*Amhara S/Wollo*	*Meqdela*	2750
212592	*Amhara S/Wollo*	*Kola-Temben*	2010
235326	*Tigray/Wukro*	*Woqro*	2860
243488	*Amhara/S/Wollo*	*Qalu*	2180
243515	*Tigray/Temben*	*Degu-Temben*	2580
215356	*Ormiya/Bale*	*Gaserana Gololcha*	2500
229984	*Ormiya/Bale*	*Goro*	2120
55100	*Omiya/Harerghe*	*Chiro*	2030
237742	*Ormiya/Bale*	*Adaba*	2380
237687	*Ormiya/S/Shewa*	*Dendi*	2150
230771	*Ormiya/Borena*	*Moyale*	1200
237125	*Ormiya/N/Shewa*	*Kewot*	1360
230586	*Ormiya/Bale*	*Ginir*	1450
237695	*Ormiya/W/Shewa*	*Ambo*	2390
229759	*Amhara E/Gojam*	*Enbese Sar Mider*	2610
229770	*Amhara E/Gojam*	*Awebel*	2700
55062	*Amhara E/Gojam*	*Enemay*	2560
236529	*Amhara W/Gojam*	*Denbecha*	2060
55184	*Amhara W/Gojam*	*Bure Wenberema*	2590
212708	*Amhara N/Gondar*	*Wegera*	2800
212715	*Amhara S/Gondar*	*Fogera*	2100
212706	*Amhara E/Gojam*	*Enarj Enawega*	2600
228969	*Amhara E/Gojam*	*Guzamn*	2480
229758	*Amhara E/Gojam*	*Gunecha Siso Enese*	2500
229763	*Amhara/E/Gojam*	*Enbise Sar Mider*	2610
55185	*Amhara/Agew Awi*	*Banja*	2580
212700	*Amhara/E/Gojam*	*Debay Telategen*	2540
202950	*Oomiya/Jimma*	*Sokoru*	1390
212930	*SNNP/N/Omo*	*Bonke*	2250
236091	*SNNP/Hadiya*	*Limo*	2240
212923	*SNNP/Hadiya*	*Konteb*	2300
202949	*SNNP/Hadiya*	*Goro*	1120
225751	*SNNP/OMO*	*ArbaMinch*	1100
236088	*SNNP/OMO*	*Humbo*	1450
241674	*SNNP/Bench Maji*	*Konso*	1460
2225761a	*SNNP/N/OMO*	*Kucha*	1290
212482	*Semen Shewa*	*Siyadebrina wayu ens*	1490
212616	*Debub Wello*	*Ambasel*	1460
212617	*Debub Wello*	*Ambasel*	1380
212834	*Bale*	*Mennana herena bulu*	1250
212835	*Bale*	*Mennana herena bulu*	1340
212931	*Semen omo*	*Gofa zuria*	1400
212933	*Semen omo*	*Gofa zuria*	1360
225751	*Semen omo*	*Arba minch zuria*	1100
225759	*Semen omo*	*Kucha*	1290
225760	*Semen omo*	*Kucha*	1290
225761	*Semen omo*	*Kucha*	1290
229982	*Bale*	*Mennana herena bulu*	1440
230578	*Bale*	*Nensebo*	1180
230579	*Bale*	*Mennana herena bulu*	1150
230580	*Bale*	*Mennana herena bulu*	1150
230584	*Bale*	*Ginir*	1180

230585	*Bale*	*Ginir*	1180
230586	*Bale*	*Ginir*	1450
230771	*Borena*	*Moyale*	1200
230772	*Borena*	*Moyale*	1200
230773	*Borena*	*Moyale*	1220
230774	*Borena*	*Moyale*	1280
234375	*Mehakelegnaw*	*Adwa*	1000
234376	*Mehakelegnaw*	*Mereb lehe*	1370
234377	*Mehakelegnaw*	*Mereb lehe*	1360
237125	*Semen Shewa*	*Kewet*	1360
237126	*Semen Shewa*	*Kewet*	1250
237133	*Debub Wello*	*Kombolcha*	1480
237134	*Debub Wello*	*Kombolcha*	1480
237136	*Debub Wello*	*Kombolcha*	1490
237137	*Debub Wello*	*Kombolcha*	1490
237149	*Semen Wello*	*Kobo*	1490
237150	*Semen Wello*	*Kobo*	1480
237151	*Semen Wello*	*Kobo*	1470
237153	*Debubawi*	*Alamata*	1500
237159	*Debubawi*	*Alamata*	1450
237187	*Mehakelegnaw*	*Abergele*	1450
237199	*Mehakelegnaw*	*Adwa*	1470
237203	*Mehakelegnaw*	*Adwa*	1430
237205	*Mehakelegnaw*	*Mereb lehe*	1350
238177	*Mehakelegnaw*	*Abergele*	1400
238178	*Mehakelegnaw*	*Abergele*	1460
238179	*Mehakelegnaw*	*Abergele*	1460
238180	*Mehakelegnaw*	*Abergele*	1480
239304	*Arssi*	*Jeju*	1270
239305	*Arssi*	*Jeju*	1340
241667	*Misrak Shewa*	*Boset*	1450
241668	*Misrak Shewa*	*Boset*	1450
241674	*Bench maji*	*Konso special*	1460
242568	*Mehakelegnaw*	*Adwa*	1380

Results and Discussion

Tiller Number Dynamics

Tillering is the process of the outgrowth of lateral culms that grow at the ground level from nodes of none-elongated internodes (Hussien *et al.*, 2014). In grasses it is an important trait and is one of the mechanisms used to maximize total plant light capture and grain production (Evers and Vos, 2013) and is affected by the growing conditions a cereal plant experiences. Our strategy to use three different experimental sites allowed us to observe the differential performance of the genotypes. Overall, the performance of the genotypes differed significantly ($P \leq 0.05$) for most of the stem characters, we investigated across the three sites. For instance, genotypes produced more tillers and fertile tillers per plant at *Alem Tena* (Fig. 1a), the warmest location in our study. The experiment at *Debre Zeit* was damaged by insect attack and we recorded data on the remaining plants. This incidence seems to have affected the performance of the genotypes at this location.

The proportion of tillers that were fertile at maturity at *Alem Tena* was 86% (11% less than that at *Holetta* and 8% less than the fertile tillers at *Debre Zeit)*. At Holetta, 97%

of the tillers were fertile. According to our result, warmer growth conditions during the early growth stages at *Debre Zeit* and *Alem Tena* compared to *Holetta*, which is a cool highland, seem to promote high tillering. In contrast, we noted that fertile tillers tend to develop more in the colder experimental sites as compared to the warmer experimental sites where moisture stress is common at the later stage of plant development. Given the importance of tillers and the scale of our study, we suggest that tiller number dynamics needs to be considered in future replicated tef trials.

Genetic variability in the major components of tef culm

The main stem of a tef plant is divided into internodes, peduncle and panicle and all together account for the total plant height. Phenotypic diversity of stem characters has been extensively studied and documented. From our results (Fig. 1 and Table 3) we observe that plant height was big 104.0 cm at *Alem Tena* followed by 96.2 cm at Debre Zeit and 102.4 cm at Holetta. Accordingly, lodging index proportionally varied from 75.0% at Alem Tena to 52.5% at Debre Zeit to 62.0% at Holetta further supporting the fact that plant height is one of the stem characters that could be targeted for breeding lodging tolerance in tef.

The experiment at Debre Zeit has sustained a pest attack at the early stage and may be one of the reasons for poor stand establishment and in turn for shorter plant height of the genotypes relative to slightly comparable values obtained at Alem Tena and Holetta. Peduncle length was high at Alem Tena (25.8 cm) followed by Holetta (12.6 cm) and Debre Zeit (10.7 cm). On the other hand, panicle length was high at Holetta followed by Debre Zeit and Alem Tena (Table 3). The tef genotypes in this study showed variable lengths of basal internodes with no apparent pattern.

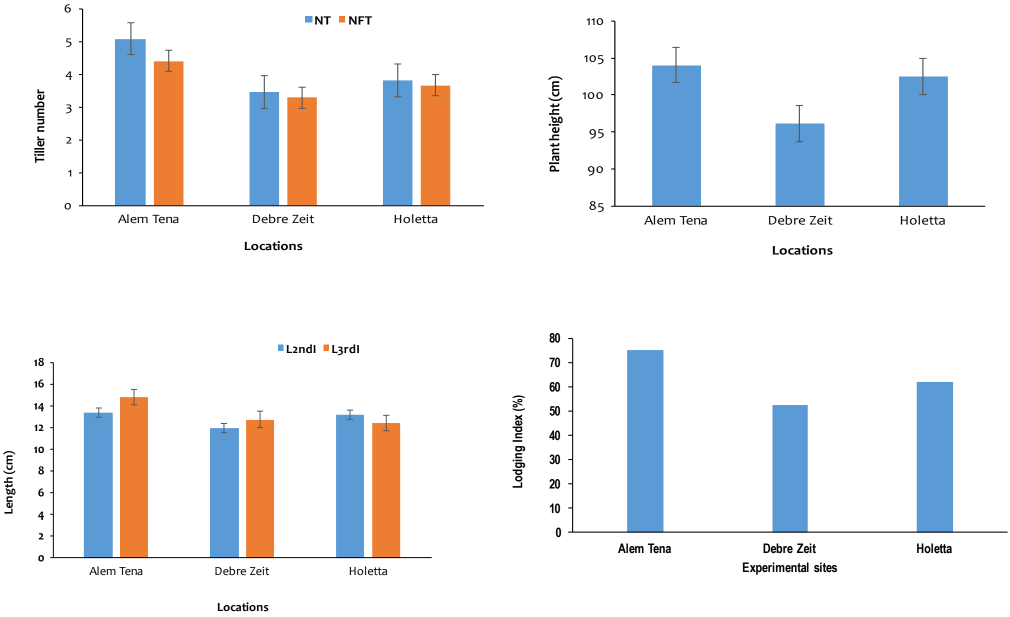


Figure 1. Comparison of mean values of stem characters of tef genotypes measured at three locations. (a) the number of tillers and the number of fertile tillers per plant (b) plant height (cm), (c) the length of the 2nd and 3rd internode (cm) and (d) lodging index (%).

Table 3. Means of lodging related plant and stem characters of tef genotypes grown at three contrasting experimental sites

Stem character	Mean performance		
	Alem Tena	Debre Zeit	Holetta
Number of tillers per plant	5.0	3.5	3.8
Number of fertile tillers per plant	4.3	3.3	3.7
Length of the 1st basal internode (cm)	10.6	11.5	12.0
Length of the 2nd basal internode (cm)	13.3	11.9	13.1
Length of the 3rd basal internode (cm)	14.6	12.7	12.3
Length of the 4th internode (cm)	13.7	12.1	14.0
Length of the 5th internode (cm)	10.0	8.2	8.7
Length of the 6th internode (cm)	2.6	2.2	1.3
Peduncle length (cm)	13.4	10.7	12.6
Panicle length (cm)	25.8	27.0	28.3
Plant height (cm)	104.0	96.2	102.4
Lodging index (%)	75.0	52.5	62.0

Caveats in the lodging tolerance index in tef

In this study, we estimated lodging index based on subjective scores given to individual plots. For practical reasons, however, we would like to breakdown the elements in the lodging tolerance index. The tendency of a plant to lodge widely differs among genotypes and is dependent on the environment (Berry, 2013). Although lodging can be scored on individual plant or plot basis, four main modes of lodging tolerance are recognized on a 1 to 5 scale: 1 = highly tolerant; 2 = tolerant; 3 = moderately tolerant; 4 = susceptible; and 5 = highly susceptible.

In cereals, plant height has long been the center of focus for developing dwarf/semi-dwarf lodging tolerant varieties. In tef, plant height is among the characters that show a moderate-to-strong correlation with lodging index. What is the difference between what constitutes the lodging index and the factors that modulate lodging resistance in tef? The lodging index of tef is derived from subjective scores given to a plant variety on a plot basis, mainly by observing to what extent the variety has fallen to the ground irrespective of its stem characteristics (Fig. 1). The most widely used formula is

$$\text{Lodging index} = [(S1 + S2 + Sn)/n] \times 100$$

Where:

S1, S2…Sn represent the number of subjective scores taken while, n is equivalent to the total number of scores.

Such a score can hardly account for the major factors that modulate lodging tolerance. This is because lodging tolerance is a complex trait that is affected by the plant's physiological and morphological characteristics and can be caused by environmental factors such as wind, hailstorm and heavy rain (Berry, 2013).

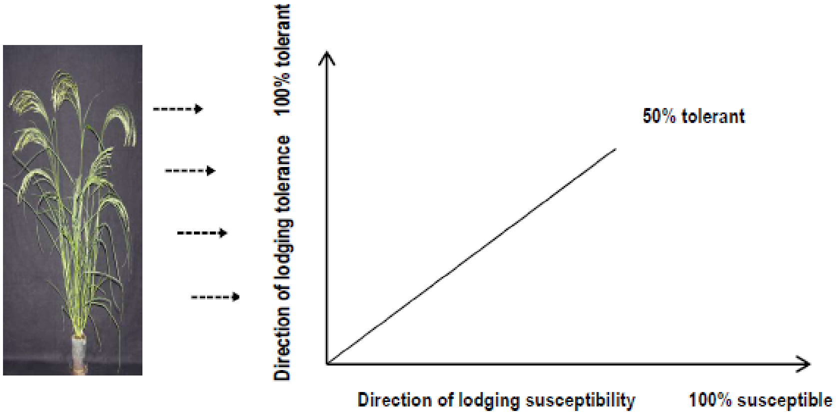


Figure 3. Measuring of lodging index in tef. Irrespective of the properties of the plant stem characteristics, lodging is measured subjectively by looking at how far the plants have fallen to the ground in horizontal direction. Such measurement obscures the critical factors modulating the lodging tolerance in tef.

According to the current lodging index estimation, what is measured is the proportion of the plant that has fallen to the ground in horizontal direction. Typically, three to five scores are taken per individual variety, per plot and averaged over the number of scores. Clearly, this metric of lodging index does not reflect all the factors that modulate lodging tolerance. For example, a short plant and a tall plant with thick stem could have similar lodging scores, making it difficult which trait and trait combinations to improve. From our data, we observe that, the plant height of Accession 55062 is 104cm while Accession 243492 has a similar plant height of 105cm. However, the two accessions had a lodging index of 70% and 81% respectively. This suggests that the subjective designation of lodging scores to a tef variety does not always reflect the reality and a better metric of lodging tolerance needs to be developed to account for the main factors that modulate lodging tolerance in tef.

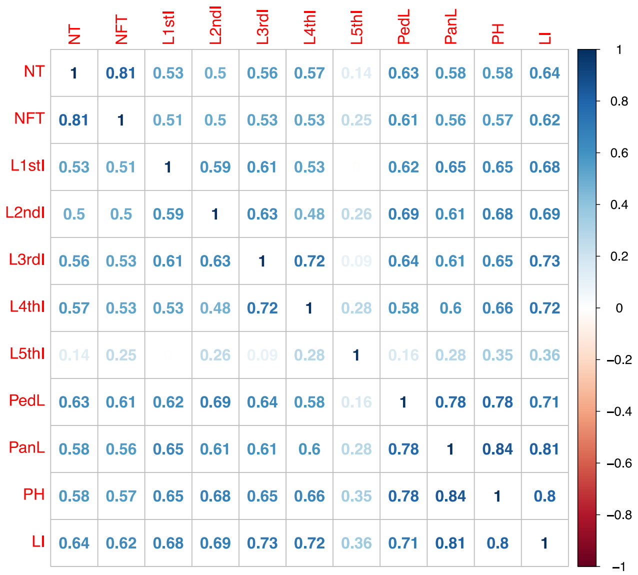
Genetic trait correlations reaffirm the importance of stem characters to breeding lodging tolerance in tef

Genetic trait correlations are important factors in quantitative genetics and breeding. They can be used as a signal for indirect selection as well as to improve correlated traits simultaneously (Chen *et al*., 2010). A strong correlation between plant height and lodging has been reported for several crops including wheat, maize, barley, and rice. Furthermore, as quantitatively inherited trait, lodging has been shown to be influenced by environmental factors (Berry, 2013). The phenotypic values of the stem characters that were measured from the tef genotypes under three contrasting experimental sites could show some degree of correlation with each other due to genetic effects and/or environmental factors. Hence, we were interested to examine if our data show such correlations. The mean values of each trait stored in a *CSV* file format were loaded in to R. Then, the Pearson correlation coefficients matrix was generated using the *corrplot* package. This correlation matrix was visualized with the same package and the correlogram in Fig. 2 was produced.

The majority of the stem characters show a positive correlation with lodging index with correlation values ranging from R^2 =0.62 for number of fertile tillers per plant to R^2 =0.81 for peduncle length (Fig. 2). The length of the 1st and 2nd basal internodes had a moderately positive correlation R^2 = 0.65 and R^2 = 0.68 with lodging index. This result suggests that basal internodes affect lodging in tef and could be useful indicators of lodging tolerance in addition to other stem characters. To the best of our knowledge, the length of the first two basal internodes had not previously been associated with the lodging tolerance behavior of tef plants and needs further study.

A positive correlation between lodging index, plant height, panicle length and peduncle length was reported by Assefa *et al*. (2002). We found a similar result in this study. Among the trait combinations, lodging index was strongly correlated with panicle length R^2 = 0.81, plant height R^2 = 0.8, peduncle length R^2 = 0.71, length of the 3rd internode R^2 = 0.73 and length of the 4th internode R^2= 0.72. The strong correlation between plant height and lodging index has been reported for several crops including wheat, maize, barley, and rice. In fact, this particular correlation had served the rationale to improve lodging tolerance in rice and wheat through what is now known as 'The Green Revolution' (John, 1991; Hazell and Peter, 2009).

In a study conducted by (Tefera *et al.*, 2003) and (Debebe, 2014) panicle length and lodging index had very low negative correlation values (R^2 = -0.017, R^2 = -0.166), respectively. On the other hand, (Chanyalew, 2010) reported a highly significant negative correlation (R^2 = -0.581) in contrast to (Mewa, 2013) that reported a positive correlation value of (R^2 = 0.382). In contrast to these studies but in agreement with previous work by Assefa *et al*., (2002) that showed a strong correlation R^2 =0.87, the current work showed that panicle length had a strong and positive correlation (R^2 = 0.8) with lodging index indicating that this part of the main culm could be an important target for breeding lodging tolerance in tef. In recent years, tef breeders have been suggesting peduncle length as a breeding target for improving lodging tolerance (Assefa, personal communication). This seems to be apparent in this study in that peduncle length had a strong and positive correlation R^2 = 0.78 with lodging index. Under field conditions, tef genotypes with the same plant height can have varying lodging behavior (personal observation) suggesting that plant height per se may not be the sole factor and other stem characters including the length of basal internodes, culm strength, and panicle length could play a role in influencing the lodging behavior of tef plants. Given the contribution of the different stem characters to the lodging tolerance behavior of tef, a breeding strategy that is based on a plant ideotype combining the optimal combinations of stem characters needs to be adopted.



	NT	NFT	L1stl	L2ndl	L3rdl	L4thl	L5thl	PedL	PanL	PH	LI
NT	1	0.81	0.53	0.5	0.56	0.57	0.14	0.63	0.58	0.58	0.64
NFT	0.81	1	0.51	0.5	0.53	0.53	0.25	0.61	0.56	0.57	0.62
L1stl	0.53	0.51	1	0.59	0.61	0.53	0	0.62	0.65	0.65	0.68
L2ndl	0.5	0.5	0.59	1	0.63	0.48	0.26	0.69	0.61	0.68	0.69
L3rdl	0.56	0.53	0.61	0.63	1	0.72	0.09	0.64	0.61	0.65	0.73
L4thl	0.57	0.53	0.53	0.48	0.72	1	0.28	0.58	0.6	0.66	0.72
L5thl	0.14	0.25	0	0.26	0.09	0.28	1	0.16	0.28	0.35	0.36
PedL	0.63	0.61	0.62	0.69	0.64	0.58	0.16	1	0.78	0.78	0.71
PanL	0.58	0.56	0.65	0.61	0.61	0.6	0.28	0.78	1	0.84	0.81
PH	0.58	0.57	0.65	0.68	0.65	0.66	0.35	0.78	0.84	1	0.8
LI	0.64	0.62	0.68	0.69	0.73	0.72	0.36	0.71	0.81	0.8	1

Figure 2. Correlogram of the correlation matrix computed form mean values of the stem characters from one hundred genotypes of tef. Color intensity of each box is proportional to the values of correlation coefficients and is indicated by the scale on the right side of the correlogram. **Abbreviations: NT:** Number of tillers, **NFT:** Number of fertile tillers, **L1stl:** Length of the 1^{st} basal internode (cm), **L2ndl:** Length of the 2nd basal internode (cm), **L3rdl:** Length of the 3rd basal internode (cm), **L4thl:** Length of the 4th basal internode (cm), **L5thl:** Length of the 5th basal internode (cm), **PedL:** Peduncle length (cm), **PanL:** Panicle length (cm), **PH:** Plant height (cm), **LI:** Lodging index (%).

Conclusions

Recent advances in cereal genomics have allowed the analysis of genes such as dwarfing genes in wheat and rice (Peng *et al.*, 1999; Monna *et al.*, 2002; Spielmeyer *et al.*, 2002) that are associated with key traits. Tef has joined the genomics era and its draft genome sequence reveals targets that can be exploited through breeding. In practice, breeding for short stature in tef has been a trade-off. On one hand, it is a success in developing high yielding and lodging tolerant dwarf/semi-dwarf varieties. On the other hand, it is reducing straw yield, which normally is used for animal feed, and housing both in rural and urban areas. How to balance this trade-off has remained one of the challenges in the tef breeder's dark toolbox. Hence, we suggest that, in addition to breeding for reduced plant height in general, the effect of other stem characters such as the length of basal internodes and peduncle length should be explored further. Moreover, given the scale of the present study more work needs to be done involving many genotypes and replications in years and locations.

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References

Assefa K, S Ketema, H Tefera, HT Nguyen, A Blum, M Ayele, G Bai, B Simane, and T Kefyalew. 1999. Diversity among germplasm lines of the Ethiopian cereal tef [*Eragrostis tef* (Zucc.) Trotter]. *Euphytica* 106(1): 87-97.

Assefa K, A Merker, and H Tefera. 2002a. Qualitative trait variation in Tef [*Eragrostis tef* (Zucc.) Trotter] germplasm from Western and Southern Ethiopia. *Euphytica* 127(3): 399-410.

Assefa K, H Tefera, and A Merker. 2002b. Variation and inter-relationships of quantitative traits in tef (*Eragrostis tef* (Zucc.) Trotter) germplasm from western and southern Ethiopia. *Hereditas* 136(2): 116-125.

Assefa K, H Tefera, A Merker, T Kefyalew, and F Hundera. 2001a. Quantitative trait diversity in tef *[Eragrostis tef* (Zucc.) Trotter] germplasm from Central and Northern Ethiopia. *Genetic Resources and Crop Evolution* 48(1): 53-61.

Assefa K, H Tefera, A Merker, T Kefyalew and F Hundera. 2001b. Variability, heritability and genetic advance in pheno-morphic and agronomic traits of tef [*Eragrostis tef* (Zucc.) Trotter] germplasm from eight regions of Ethiopia. *Hereditas* 134(2): 103-113.

Assefa K, JK Yu, M Zeid, G Belay, H Tefera, and ME Sorrells. 2011. Breeding tef [*Eragrostis tef* (Zucc.) trotter]: conventional and molecular approaches. *Plant Breeding* 130(1): 1-9.

Berry P M, M Sterling, JH Spink, CJ Baker, R Sylvester-Bradley, SJ Mooney, AR Tams, and AR Ennos. 2004. Understanding and reducing lodging in cereals. *Advances in Agronomy, Vol 84* 84: 217-271.

Chanyalew S. 2010. Genetic Analyses of Agronomic Traits of Tef *(Eragrostis tef*) Genotypes. *Research Journal of Agriculture and Biological Sciences* 6(6): 912-916.

Dalrymple D G. 1986. Development and spread of high-yielding rice varieties in developing countries. Washington, DC: Bureau for Science and Technology, Agency for International Development.

Debebe AS and H Tefera. 2014. Interrelationship and Path Coefficient Analysis of Yield Components in F4 Progenies of Tef (*Eragrostis tef*). *Pakistan Journal of Biological Sciences* 17(1): 92-97.

Evers JB and J Vos. 2013. Modeling branching in cereals. *Frontiers in Plant Science* 4.

Grausgruber H, H Bointner, R Tumpold, and P Ruckenbauer. 2002. Genetic improvement of agronomic and qualitative traits of spring barley. *Plant Breeding* 121(5): 411-416.

Hargrove TR and VL Cabanilla. 1979. Impact of Semi-Dwarf Varieties on Asian Rice-Breeding Programs. *Bioscience* 29(12): 731-735.

Hoshikawa KW. 1990. Studies on lodging in rice plants. *Japan Journal of Crop Science* 59(4): 809-814.

Hussien A, E Tavakol, DS Horner, M Munoz-Amatriain, GJ Muehlbauer, and L Rossini. 2014. Genetics of Tillering in Rice and Barley. *Plant Genome* 7(1).

Kefyalew T, H Tefera, K Assefa, and M Ayele. 2000. Phenotypic diversity for qualitative and phenologic characters in germplasm collections of tef *(Eragrostis tef*). *Genetic Resources and Crop Evolution* 47(1): 73-80.

Khush GS. 1999. Green revolution: preparing for the 21st century. *Genome* 42(4): 646-655.

Mewa DBG and E Bekele. 2013. Variability and trait association in culm and grain yield characteristics of recombinant inbred lines of Eragrostis tef × Eragrostis pilosa. *African Journal of Agricultural Research* 8(20): 2376-2384.

Monna L, N Kitazawa,R Yoshino, J Suzuki, H Masuda,Y Maehara, M Tanji, M Sato,S Nasu and Y Minobe. 2002. Positional cloning of rice semidwarfing gene, sd-1: rice "green revolution gene" encodes a mutant enzyme involved in gibberellin synthesis. *DNA Res* 9(1): 11-17.

Neenan M.1975. An analysis of the problem of lodging with particular reference to wheat and barley. *Journal of Agricultural Science* 85: 495-507.

Ookawa T and K Ishihara. 1993. Varietal Difference of the Cell-Wall Components Affecting the Bending Stress of the Culm in Relation to the Lodging Resistance in Paddy Rice. *Japanese Journal of Crop Science* 62(3): 378-384.

Peng JR. DE Richards, NM Hartley, GP Murphy, KM Devos, JE Flintham, J Beales, LJ Fish, AJ Worland, F Pelica, D Sudhakar, P Christou, JW Snape, MD Gale, and NP Harberd. 1999. 'Green revolution' genes encode mutant gibberellin response modulators. *Nature* 400(6741): 256-261.

Spielmeyer W, MH Ellis and PM Chandler. 2002. Semidwarf (sd-1), "green revolution" rice, contains a defective gibberellin 20-oxidase gene. *Proc Natl Acad Sci U S A* 99(13): 9043-9048.

Tefera H, K Assefa, F Hundera, T efyalew, and T Teferra. 2003. Heritability and genetic advance in recombinant inbred lines of tef (*Eragrostis tef*). *Euphytica* 131(1): 91-96.

Yates F. 1936. A new method of arranging variety trials involving a large number of varieties. *Journal of Agricultural Science* 26: 424-455.