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Wheat straw for biofuel production

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1. Abstract

Current commercial cultivars of wheat have been selected according to grain yield and quality, not straw yield or suitability for bioethanol production. There is a lack of data on the relative straw yield of different cultivars of wheat and whether there is variation in digestibility of straw for bioethanol production. It is not known whether the digestibility of wheat straw varies with cultivars, or if this is linked to lodging susceptibility (straw strength). Hence, the relationship between straw digestibility for bioethanol production and lodging resistance (straw strength) was investigated to identify traits with these important parameters with the effect of 'with' and 'without' plant growth regulators (PGRs) and to determine which could be used to select for more efficient bioethanol production. There were no significant differences between cultivars in total biomass production at harvest. However, there were differences in grain yield, straw yield, harvest index, straw glucose yield and straw digestibility. PGR application had no significant effect on total biomass or grain and straw yield; neither did PGRs affect straw glucose yield or straw digestibility but as expected, PGR application significantly reduced cultivar height. There was a negative relationship between cultivar height and straw digestibility which is hypothesised to be due to the greater stem:leaf ratio of taller cultivars. There was no relationship between straw digestibility vs. stem material strength and stem failure wind speed. Although straw digestibility had no relationship with stem failure wind speed, the actual glucose recovered and available for bioethanol production was positively related to stem failure wind speed which is a good indicator for growing dual purpose wheat crop (food and fuel). Moreover, potential bioethanol yield varied between cultivars in both years.

2. Introduction

Production of first generation liquid biofuels from starchy grains (such as wheat and maize) has been controversial due to the potential competition for land for growing food vs. fuel (IEA, 2009; FAO, 2010 and Erdei *et al*., 2010). Liquid biofuel production could displace food production in the use of land and could also affect the use of natural and agricultural resources (FAO, 2010). Many of the crops currently used as biofuel feedstock require high quality agricultural land and significant inputs of fertilisers, pesticides and water (UN, 2007; Demirbas *et al*., 2008). This has led to interest in second generation biofuels produced from lignocellulosic materials (*e.g. Miscanthus*, cereal straw, and other agricultural by-products) because of its low cost, availability and cellulosic content (Gnansounou *et al*., 2010; Sims *et al*., 2010). The second generation biofuel feedstock are rich in cellulose, but that cellulose is very well protected by hemicellulose and lignin and is not easily available for enzymatic digestion (Saha *et al*., 2005; Kumar and Stroeve, 2009).

In the UK, approximately 12.2 million tonnes of straw was produced from cereals and oilseeds in 2011 (Stoddart and Watts, AHDB 2012). Average harvestable straw yields for wheat, barley and oilseed rape in the UK are estimated to be 2.53 t ha^{-1}, 2.26 t ha^{-1} and 1.65 t ha^{-1}, respectively (Wilson *et al*., 2013). Wheat straw makes up 54% of this value and approximately 50% of wheat straw is chopped and incorporated into the soil, rather than being used for animal feed/bedding. Hence, there could be up to 3 million tonnes of wheat straw per annum available for bioenergy production in the UK alone. However, it is important to recognise that, when incorporated into the soil, straw has a nutrient value and also contributes to organic matter content and therefore soil quality (Punter and Woods, 2004; IEEP, 2012). Copeland and Turley (2008) estimated that the nutrient value of wheat straw was £17 per tonne of straw removed, which would rise with increasing fertiliser costs. The long term impacts of removing straw each year on soil quality have yet to be quantified.

Current commercial cultivars of wheat have been selected according to grain yield and quality, not straw yield or suitability for bioethanol production. There is a lack of data on the relative straw yield

of different cultivars of wheat and whether there is variation in digestibility of straw for bioethanol production and whether more digestible straw weaker, and therefore more prone to lodging?

The use of wheat straw for second generation bioethanol production will depend on a number of issues like straw availability, straw quality (lodging) and the economic feasibility of straw digestibility. The recalcitrant nature of lignocellulose is still the bottleneck of modern conversion processes (Himmel *et al*., 2007). Numerous factors contribute to the recalcitrance of wheat straw during pre-treatment and enzymatic saccharification. One of these factors is the histological variation between different plant tissues and organs. The wheat straw epidermis is thin, but has dense and thick-walled cells with an outer wall coated with a waxy film of cutin-cuticle. The vascular system has xylem tissue with dense lignified structures in the secondary wall, surrounded by a strong sheath of sclerenchyma cells, which have elongated thick lignified cell walls resistant to microbial degradation (Hansen *et al*., 2011).

Digestibility is not only an important characteristic of cereal straw for second generation biofuel production but also for animal feed. Early studies considering the digestibility of wheat straw were conducted for its use as an animal feed (Capper, 1989; Tolera *et al*., 2008). Studies revealed differences in straw digestibility between bread wheat cultivars (Knapp *et al*., 1983; Kernan *et al*., 1984; Habib *et al*., 1995). Habib *et al*. (1995) found a highly significant difference in straw digestibility of cultivars, with *in vitro* dry matter digestibility (IVDMD) ranging from 36.40% to 48.36%. Wagner Jensen *et al*. (2011) found significant differences in straw digestibility of 109 currently grown high yielding wheat cultivars. The cultivars exhibited much variation in straw degradability ranging from 258 g kg^{-1} to 407 g kg^{-1} of dry matter.

A large number of characteristics determine digestibility of lignocellulosic material, such as lignin content and cellulose crystallinity (Chang & Holtzapple, 2000). Different varieties vary in the proportion of their masses made up by the different components, *e.g.* the amount of stem and leaves, and these differ in their structure and composition and thus have different digestibility and this means there are differences in overall digestibility (Capper, 1988). Forages and crop residues

consist of a heterogeneous population of cell types each of which have degradation characteristics determined by their location within the plant, by their anatomical features and by the chemical composition of their walls (Travis *et al*., 1996). Detailed investigation of the relationship between the anatomy and digestibility of forages has demonstrated interactions between cell wall thickness, lignification and other anatomical features in determining the digestibility of different cell types (Minson & Wilson 1994; Travis *et al*., 1996).

Studies conducted by Kernan *et al*. (1984) observed that differences in the *in vitro* digestibility of organic matter in the leaf and stem fractions of wheat straw contributed more to overall digestibility than the actual proportions of leaf to stem in the straw. Ramanzin *et al*. (1986) observed the same relationship for dry matter degradability of barley straw. Leaves had the highest digestibility followed by chaff, nodes and internodes. However, Capper *et al*. (1989) argued that with a larger range of values, the stem to leaf ratio becomes a major contributor to variation in overall digestibility. Plant height was positively related to the content of cell wall components (Capper *et al*., 1989; Mathison *et al*., 1999) and negatively related to microbial degradation in the rumen (Colucci *et al*., 1992; Mathison *et al*., 1999). Degradation is closely related to the distribution of cell types (parenchyma, epidermis, and sclerenchyma cells) within leaf and stem, and the thickness of the walls of specific cell types (Goto *et al*., 1991). Recent studies conducted on wheat straw by Zhang *et al*. (2013) found that straw leaf and stem fractions differed in their compositional profiles and were found to behave differently under enzymatic digestion or saccharification. Pure leaf was hydrolysed significantly better than pure stem. In mixtures, higher leaf:stem ratios always gave a better sugar conversion rate after enzyme digestion or saccharification. Increased straw stiffness may be associated with modified anatomical features of the stems and changed chemical characteristics of the cell walls, which may be expected to decrease degradability of the straw (Travis *et al*., 1996).

Lodging is the permanent displacement of stems from the vertical and affects all cereal species. Lodging in plants is either due to failure of the stem (Neenan and Spencer-Smith, 1975; Thomas, 1982) or the root system (Crook and Ennos, 1993; Easson *et al*., 1993). Lodging is affected by

many factors including wind, rainfall, soil, and attributes of the plant as affected by variety, sowing date, seed rate, nitrogen supply, PGRs etc. The effect of these factors on lodging has been very difficult to quantify because of the complexity of the lodging process (Berry and Cameron, 2002).

The process of lodging in wheat in particular has been characterised and well modelled along with the plant characters involved in lodging resistance (Baker, Berry and Spink *et al*., 1998). The principal factors that are important in lodging in wheat are the leverage related parameters and the stem strength characters. Stem leverage force is determined by parameters such as height at the centre of gravity, ear area, and; natural frequency and shoot number. Stem strength characters includes stem diameter, wall width and material strength of the stem, and the root plate spread and depth.

The lodging model by Berry *et al*. (2003) further develops an existing lodging model by Baker *et al*. (1998) to predict the wind speed at which lodging will occur. The lodging model is based on more important parameters such as stem diameter, plant height and soil type. By using accurate values of drag coefficient and damping ratio, the model has been made more precise, making it easier to compare cultivar resistances and for farmers to select the most suitable cultivar with the lowest lodging risk.

This paper considers biomass production, partitioning to grain and straw, and lodging susceptibility of 15 UK winter wheat cultivars (introduced between 1968 and 2010). Lodging susceptibility and straw strength are assessed using a calibrated model of wheat lodging, as described by Berry *et al*. (2003). The relationship between straw digestibility for bioethanol production and straw strength/lodging resistance is examined.

3. Materials and methods

3.1. Management of the field experiment

Two field experiments were carried out during 2009/10 and 2010/11 at the University of Nottingham, Sutton Bonington Campus near Loughborough, UK. On 20 October 2009, winter wheat was sown at 250 seeds m^{-2}, using a Wintersteiger plot drill on a stony sandy loam soil (Dunington Heath series). The previous crop was winter oats. The experiment was a randomised block design with 14 cultivars of bread wheat grown in four replicate blocks. The plot size was 24 x 1.6 m with two plots per cultivar in each block (one for crop measurements and one for retaining large quantities of straw for further analysis).

On 13 October 2010, winter wheat was sown at 250 seeds m^{-2}, using a Wintersteiger plot drill, on a stony sandy loam soil (Dunington Heath series). The previous crop was, once again, winter oats. The same 14 cultivars were grown as in the previous experiment with the addition of Glasgow, a high biomass cultivar, all grown with or without plant growth regulators (PGRs). The experiment was arranged as a split plot with PGR on the main plot and cultivar on the sub plots. The plot size was 24 x 1.6 m with four replicate blocks.

Crop protection chemicals were used prophylactically to minimise weeds, pests and diseases in both years. And soil fertility levels were amended to ensure nutrient availability would not be limiting. The 15 UK winter wheat cultivars were selected to provide a wide range of material in terms of date of introduction, height, lodging resistance and nabim quality group (Table 1).

Table 1: Details of 15 winter wheat cultivars in the experiment with its selection criteria.

Cultivars	nabim Group	Resistance to lodging without PGR	Resistance to lodging with PGR	Height without PGR (cm)	Height with PGR (cm)	Year first listed
Hereward	1	8	9	88	-	1991
Xi 19	1	4	6	97	88	2002
Mascot	1	6	8	93	84	2006
Cordiale	2	8	9	82	76	2004
Battalion	2	7	8	88	82	2007
Sterling	2	6.7	8.3	80	-	2010
Riband	3	8	8	89	-	1989
Zebedee	3	6	6	87	84	2007
Invicta	3	7.2	7.5	93	86	2010
Istabraq	4	6	7	96	88	2004
Ambrosia	4	7	8	88	80	2005
Grafton	4	9	9	79	72	2009
Quartz	4	9	9	75	-	2009
Glasgow	4	6	8	85	74	2005
Maris Widgeon*	-	-	-	-	-	1968

Source: AHDB Recommended Lists for cereals and oilseeds 2009, 2010 and 2011

* limited information available on Maris Widgeon due to date of introduction

3.2. Lodging assessments

A full set of lodging associated measurements in 2009/10 and 2010/11 was taken so that the results could be put into the lodging model by Berry *et al*. (2003). The model allows the strength of the stem and root system to be calculated, along with the failure wind speed of each.

Ten plants were carefully removed from each plot on 1 July, 2010 and 6 July, 2011 when the plants were at Zadoks GS 75. The plants were placed in polythene bags and stored at 4°C until laboratory analysis was complete.

In the laboratory, the main shoot was isolated and the principal plant characters involved in stem lodging, as identified by Berry *et al*. (2000) were measured, including natural frequency, number of ears per plant, ear area, height at centre of gravity and length, diameter, wall width and breaking strength of the bottom two internodes (internodes 1 and 2). The detailed methodology for these measurements is described by Berry *et al*. (2000). Calculation of stem failure wind speed, stem material strength and stem leverage were done using calculations described in Berry *et al*. (2000).

3.2.1. Stem Leverage Characters

The height at the centre of gravity and main stem ear area, along with the natural frequency, are used to calculate stem leverage (Equation 3.1). The centre of gravity was determined by balancing the main stem on an extended finger, so that the point of balance could be determined. The height at the centre of gravity was recorded as the distance from the base of the stem to the balance point. Natural frequency was measured on the main stem, which was clamped at the base. The top of the shoot was displaced to a distance of approximately 10 cm from the vertical and then released, and time taken for three oscillations was recorded. Natural frequency (n) is then calculated as the number of oscillations per second. Ear area was measured using LI-COR leaf area meter. Stem leverage (B) is expressed by Equation 3.1.

Equation 3.1: Leverage on internode one (after Baker *et al*., 1998)

$$B = \frac{1}{2}\rho A C_D V_g^2 X\left(1 + \frac{g}{(2\pi n)^2 X}\right)\left(1 + e^{-\pi\delta}\frac{\sin\left(\pi/4\right)}{\pi/4}\right)$$

Where:

ρ = density of air (1.2 kg m^{-3})
A = main stem ear area (m^2)
C_D = drag coefficient (taken as 1)
V_g = wind gust speed (taken as 13 m s^{-1})
X = height at the centre of gravity (m)
g = acceleration due to gravity (9.81 m s^{-2})
n = natural frequency (Hz)
δ = damping ratio (taken as 0.08)

Leverage on internode two (B_2) was also calculated. This is defined by Equation 3.2.

Equation 3.2: Leverage on internode two (after Baker *et al*., 1998)

$$B_2 = B\left(\frac{X - h_1}{X}\right)$$

Where:

B = leverage on internode one
X = height at the centre of gravity (m)
h_1 = internode one length (m)

The stem failure wind speed (V_{gS}) can be calculated using stem leverage and stem failure moment values described in Equation 3.3.

Equation 3.3: Stem failure wind speed for internode one (after Berry *et al*., 2000)

$$V_{gS1} = \sqrt{\frac{2B_{S1}}{(\rho AC_D X)\left(1+\frac{g}{(2\pi n)^2 X}\right)\left(1+e^{-\pi\delta}\frac{\sin(\pi/4)}{\pi/4}\right)}}$$

Where:

V_{gS1} = stem failure wind speed (m s^{-1})

B_{S1} = internode one failure moment (Nm)

Internode two failure wind speed (V_{gS2}) is calculated using Equation 3.4.

Equation 3.4: Stem failure wind speed for internode two (after Berry *et al*., 2000)

$$V_{gS2} = \sqrt{\frac{2B_{S2}}{B\left(\frac{X-h_d}{X}\right)(\rho AC_D X)\left(1+\frac{g}{(2\pi n)^2 X}\right)\left(1+e^{-\pi\delta}\frac{\sin(\pi/4)}{\pi/4}\right)}}$$

Where:

B_{S2} = internode two failure moment (Nm)

3.2.2. Stem Strength Characters

The strength at the point of buckling of the internode may be described using the term internode failure moment, calculated from internode length and breaking strength. Internode material strength is calculated from internode failure moment, radius and wall width.

Internode breaking strength was measured by holding the internode against a Y–shaped brace that was clamped to the bench. The two nodes were supported by the metal prongs and a Weighmate digital scale (10 kg *x* 10 g: 1 kg = 9.81 Newtons) was pulled at an even rate to the point of internode failure. The force recorded just prior to the buckling of the internode was taken as its breaking strength. Internode length was measured from the mid-point of one node to the mid-point of the next node.

Internode failure moment (Equation 3.5) is the term of choice when describing stem strength, as this provides an estimate of internode strength that is independent of the length of the internode.

Equation 3.5: Internode one failure moment (after Baker *et al*., 1998)

$$B_{S1} = \left(\frac{h_1 F_{S1}}{4}\right)$$

Where:

B_{S1} = internode one failure moment (Nm)
h_1 = internode one length (m)
F_{S1} = internode one breaking strength (N)

Internode radius and wall width are used with the breaking strength to calculate internode material strength. The diameter was measured using digital callipers at the midpoint of each internode then divided by two to give the radius. The internode was cut transversely at the centre using a knife and the wall width was measured using digital callipers; the internode was then rotated 90° and the wall width were measured again. The mean of these two measurements was taken as the internode wall width. This method was employed due to high natural variability in this particular character. Internode material strength (σ) is calculated using Equation 3.6.

Equation 3.6: Internode material strength (after Berry *et al*., 2000)

$$\sigma = \frac{F_S h a}{\pi(a^4 - (a-t)^4)}$$

Where:

F_S = internode one breaking strength (N)
h = internode length (m)
a = internode radius (m)
t = internode wall width (m)

3.3. Assessment of biomass production and partitioning

When the crops were fully mature, a 0.5 x 0.5 m area was randomly sampled from each plot and cut at soil level with secateurs. The samples were removed to the laboratory for detailed analysis. The total biomass of the sample was determined by drying to constant mass, and then the ears were separated from the stems and threshed so that straw, grain and chaff weight could be

determined. Harvest index was determined as the proportion of total biomass in the grain and straw index as the proportion of total biomass in the straw.

3.4. Laboratory analysis of straw digestibility

Straw digestibility is expressed as the percentage of total available glucose in the residue released during enzyme hydrolysis. Straw digestibility consisted of four steps: milling, pre-treatment, acid hydrolysis and enzyme hydrolysis.

3.4.1. Milling

To obtain homogeneous samples, wheat straw comprising stem and leaf components was knife milled with a 1 mm mesh size (P15 mill, Fritsch Gmbh) generating particle sizes of 200–700 microns.

3.4.2. Pre-treatment of milled straw

One gram of milled wheat straw from each of the winter wheat cultivars was added to 10 ml of 1% H_2SO_4 (0.1M) and incubated for 20 minutes at 121°C using an autoclave. Samples were then brought to pH 4.5–4.8 by the addition of distilled H_2O then filtered through Whatman filter paper (110 mm Dia). The filtrate was discarded and the retained residue was dried overnight at 40°C in an oven.

3.4.3. Acid hydrolysis of pre-treated straw residue

Thirty milligrams of pre-treated dry wheat straw residue from each of the selected winter wheat cultivars were placed in a heat resistant screw cap tube and 1 ml of 12M H_2SO_4 was added and then incubated at 37°C for 1 hour. Samples were then diluted to 1M H_2SO_4 by the addition of 11 Eml distilled H_2O, and incubated at 100°C for a further 2 hours. After cooling under tap water, acid hydrolysed samples were then aliquoted and kept at -80°C until further high performance anion exchange chromatography (HPAEC) analysis.

3.4.4. Enzyme hydrolysis of pre-treated straw residue

Two hundred milligrams of cellulase enzyme (EC 3.2.1.4) from *Trichoderma reesei* ATCC 26921 (Sigma-Aldrich) was dissolved in 20 ml of 50 mM NaCitrate buffer (pH 4.8) and dialysed (molecular cut off: 12-14000 Daltons) overnight at 4°C with constant stirring in 2 litres of 50 mM NaCitrate buffer to remove any traces of sugars and other low molecular weight impurities.

Then, 200 mg of pre-treated dry wheat straw residue was added to 36 ml of the 50mM NaCitrate buffer (pH 4.8) in a screw cap falcon tube and 4 ml of the dialysed enzyme solution was added to give an enzyme activity equivalent to 40 FPU/g of biomass, at a concentration of 2 FPU/ml. Samples were then incubated at 50°C on an orbital shaker at 150 rpm for 72 hours. Aliquots of 1 ml were taken at time 0 (as soon as the enzyme was added) and then after 2, 4, 6, 24, 48 and 72 hours of incubation. To stop further enzyme activity, the sample was briefly centrifuged at 1000 rpm for 30 seconds and the supernatant was quickly frozen at -80°C until further HPAEC analysis.

3.4.5. Sugar analysis using High Performance Anion Exchange Chromatography (HPAEC)

Sugars were determined by high-performance anion exchange chromatography with pulsed amperometric detection (HPAEC-PAD) (DIONEX ICS - 3000, UK) using a CarboPac PA20 column with a 50 mM NaOH isocratic system and flow rate of 0.5 ml min^{-1} at 30°C. Glucose, xylose, arabinose and galactose were used as standards with mannitol as internal standard.

A standard curve was plotted for each sugar and the trend line equation was used to calculate the amount of sugar content and fermentable glucose yield in grams per litre for each straw sample. The best fitted line was calculated using Excel software. The linear equation obtained from the standard curve was used to find out the concentration of sample glucose in g L^{-1}. Then further the value was used to calculate mg of glucose per gram of straw.

3.5. Statistical analysis

Analysis of variance (ANOVA) procedures appropriate for the experimental design and regression analyses were carried out using GenStat for Windows, 15th Edition (Lawes Agricultural Trust). All data were converted to a per m^2 basis prior to statistical analysis.

4. Results

4.1. Biomass production and partitioning

Total biomass production was assessed in both years. There were no significant differences between cultivars in total biomass production in 2010 and 2011 (Tables 2 and 3). However, there were significant differences in grain yield in 2010 (P=0.047) and 2011 (P<0.001) with Cordiale producing the highest grain yield in 2010, Glasgow producing the highest grain yield in 2011 and Maris Widgeon produced the lowest yield in both years (Tables 2 and 3). There were large differences between cultivars in straw yield in 2010 (P=0.005) and 2011 (P<0.001) with Maris Widgeon, the only non-semi dwarf, produced the most straw in both years (Tables 2 and 3). Cultivars differed significantly in the quantity of chaff produced in 2010 (P=0.022; Table 2) and 2011 (P=0.002; Table 3). PGR application had no significant effect on total biomass, grain yield, straw yield or chaff biomass and there were no significant interactions between cultivar and PGR in 2011.

With the exception of Maris Widgeon, all cultivars had a harvest index above 0.53, the highest being 0.57 in 2010 (P<0.001) (Cordiale, Grafton Mascot and Quartz; Table 2) and 0.59 in 2011 (P<0.001) (Grafton and Riband; Table 3). Considering straw yield as a proportion of total biomass (straw index), as expected, Maris Widgeon had the highest straw index (0.48 in 2010 and 0.46 in 2011) and Cordiale (0.29 in 2010 and 2011) the lowest in both years (Tables 2 and 3) and with other cultivars ranging from 0.30-0.33 (P<0.001; Tables 2 and 3). PGR application had no significant effect on harvest index and straw index and there were no significant interactions between cultivar and PGR in 2011.

Table 2: Total biomass production and yield components of 14 winter wheat cultivars in 2010.

Cultivars	Total Biomass ($g\ m^{-2}$) (2010)	Grain Yield ($g\ m^{-2}$) (2010)	Straw Yield ($g\ m^{-2}$) (2010)	Chaff Biomass ($g\ m^{-2}$) (2010)	Harvest Index (2010)	Straw Index (2010)
Ambrosia	1564	877	505	154	0.56	0.32
Battalion	1565	872	511	164	0.55	0.32
Cordiale	1846	1061	553	201	0.57	0.29
Grafton	1378	788	422	152	0.57	0.30
Glasgow	-	-	-	-	-	-
Hereward	1540	829	506	176	0.53	0.32
Invicta	1540	816	537	160	0.52	0.35
Istabraq	1492	829	486	152	0.55	0.32
Maris Widgeon	1452	596	709	139	0.41	0.48
Mascot	1492	863	473	152	0.57	0.31
Quartz	1411	813	424	160	0.57	0.30
Riband	1703	964	551	174	0.56	0.32
Sterling	1391	767	441	156	0.54	0.32
Xi 19	1779	987	581	198	0.55	0.32
Zebedee	1407	797	439	149	0.56	0.31
Mean	1540	847	510	163	0.54	0.33
P	0.265	0.047	0.005	0.022	<0.001	<0.001
SED	181.3	110.5	63.2	17.29	0.0155	0.0130
df	39	39	39	39	39	39

Table 3: Total biomass production and yield components of 15 winter wheat cultivars in 2011.

Cultivars	Total Biomass ($g\ m^{-2}$) (2011)	Grain Yield ($g\ m^{-2}$) (2011)	Straw Yield ($g\ m^{-2}$) (2011)	Chaff Biomass ($g\ m^{-2}$) (2011)	Harvest Index (2011)	Straw Index (2011)
Ambrosia	1747	1005	559	177	0.57	0.31
Battalion	1585	893	513	172	0.56	0.32
Cordiale	1503	878	446	172	0.58	0.29
Grafton	1573	929	469	169	0.59	0.29
Glasgow	1788	1048	522	207	0.58	0.29
Hereward	1653	880	556	209	0.53	0.33
Invicta	1686	938	556	176	0.55	0.33
Istabraq	1759	977	578	194	0.55	0.32
Maris Widgeon	1589	670	743	165	0.42	0.46
Mascot	1657	923	545	178	0.55	0.32
Quartz	1507	861	459	169	0.57	0.30
Riband	1614	956	494	160	0.59	0.30
Sterling	1434	820	446	157	0.57	0.31
Xi 19	1618	907	520	185	0.55	0.32
Zebedee	1635	946	508	172	0.57	0.31
Mean	1623	909	528	178	0.56	0.32
P	0.23	<0.001	<0.001	0.002	<0.001	<0.001
SED	121.8	68.3	44.08	12.42	0.0078	0.0070
df	56	56	56	56	56	56

4.2. Straw glucose yield and straw digestibility

Straw glucose yield differed significantly between cultivars with Quartz recording the highest glucose yield and Maris Widgeon the least in both years (P<0.001; Table 4). Straw digestibility is expressed as the percentage of total available glucose in the residue released during enzyme hydrolysis. Moreover, straw digestibility also differed significantly between cultivars in 2010 and 2011 (*P*<0.001; Table 5) with Quartz recording the highest straw digestibility in 2010 (60.32%) and Cordiale the highest in 2011 (67.46%) and with Maris Widgeon recording the lowest digestibility in both years (Table 5). PGR application had no significant effect on straw glucose yield and straw digestibility and there were no significant interactions between cultivar and PGR in 2011.

Table 4: Glucose yield of 6 winter wheat cultivars in 2010 and 7 winter wheat cultivars in 2011.

Cultivars	Glucose Yield (mg gm^{-1}) (2010)	Glucose Yield (mg gm^{-1}) (2011)
Cordiale	344	390
Hereward	324	375
Istabraq	-	369
Maris Widgeon	244	315
Quartz	374	404
Riband	336	380
Zebedee	339	380
Mean	327	373
P	<0.001	<0.001
SED	9.71	10.72
df	15	24

Table 5: Straw digestibility of 6 winter wheat cultivars in 2010 and 7 winter wheat cultivars in 2011.

Cultivars	Straw Digestibility (%) (2010)	Straw Digestibility (%) (2011)
Cordiale	54.02	67.46
Hereward	50.63	65.98
Istabraq	-	62.74
Maris Widgeon	38.65	54.13
Quartz	60.32	67.15
Riband	53.08	63.95
Zebedee	53.99	65.95
Mean	51.78	63.91
P	<0.001	<0.001
SED	1.767	2.516
df	15	24

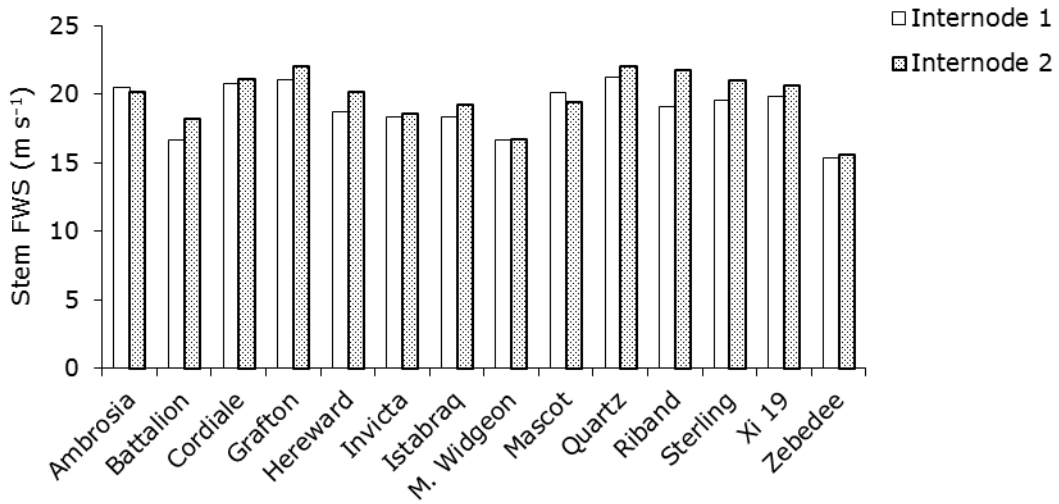
4.3. Lodging assessments

The lodging model (Berry *et al*., 2000) uses crop measurements to predict the wind speed at which lodging will occur. Cultivars differed significantly for stem failure wind speed for internode 1 and 2 in 2010 (P<0.001; Figure 1 (a)) with cultivars ranking similarly for internode 2 in 2011 (Figure 1 (b)). Stem failure wind speed values were lower overall with significant differences for internode 1 in 2011 (P<0.001; Figure 1 (b)).

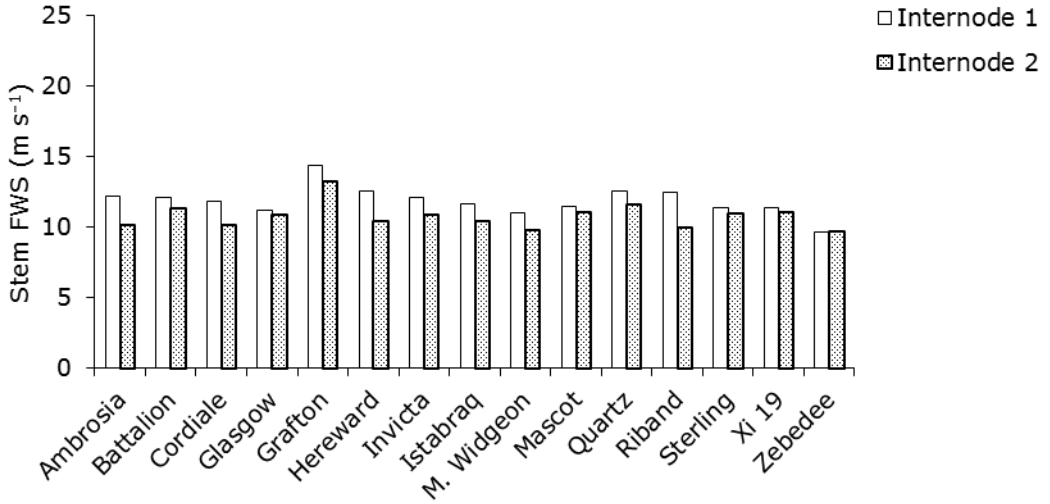
The cultivars most prone to stem lodging were Zebedee, followed by Battalion and Maris Widgeon in 2010 (Figure 1 (a)). The most resistant was Quartz in 2010 (Figure 1 (a)) and Grafton in 2010 and 2011 (Figure 1 (a) and (b)). There was a trend for PGR to increase stem failure wind speed for both internodes, but the differences were not significant and there were no significant interactions between cultivar and PGR for either internode in 2011 (Figure 1 (c) and (d)).

The component of stem failure wind speed most likely to be related to digestibility of the stem is the stem material strength (Figure 2). Differences between cultivars in stem material strength were not significant for internode 1 and 2 in 2010 (Figure 2 (a)). Cultivars ranked similarly in terms of stem material strength for internode 2 (Figure 2 (b)) but significantly differed for internode 1 in 2011 (P=0.002; Figure 2 (b)). PGR had an increasing and decreasing effect and had no significant effect on stem material strength for both internodes and there were no significant interactions between cultivar and PGR for either internode (Figure 2 (c) and (d)).

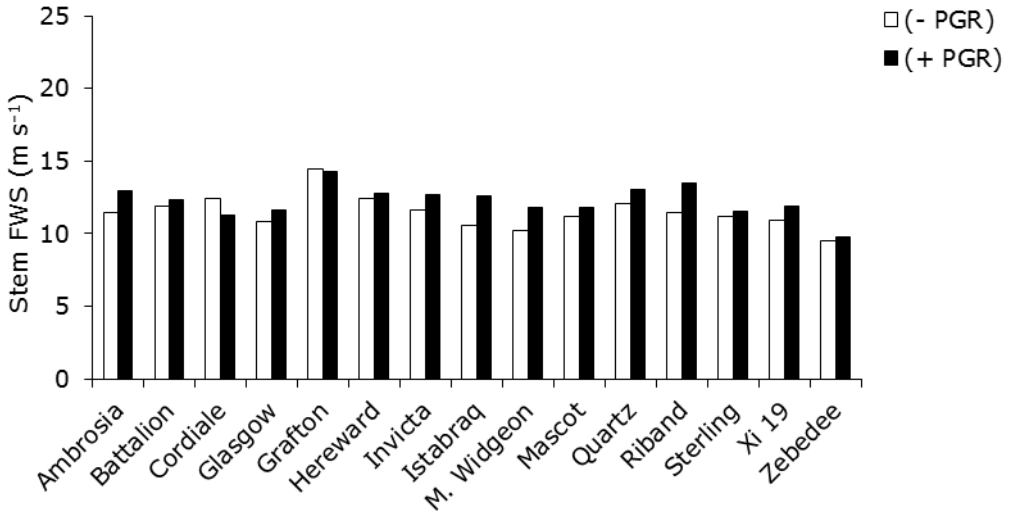
(a)


Internode 1
Internode 2
Stem FWS (m s-1)
25
20
15
10
5
0
Ambrosia
Battalion
Cordiale
Grafton
Hereward
Invicta
Istabraq
M. Widgeon
Mascot
Quartz
Riband
Sterling
Xi 19
Zebedee

(b)


Internode 1
Internode 2
Stem FWS (m s-1)
25
20
15
10
5
0
Ambrosia
Battalion
Cordiale
Glasgow
Grafton
Hereward
Invicta
Istabraq
M. Widgeon
Mascot
Quartz
Riband
Sterling
Xi 19
Zebedee

(c)



(d)

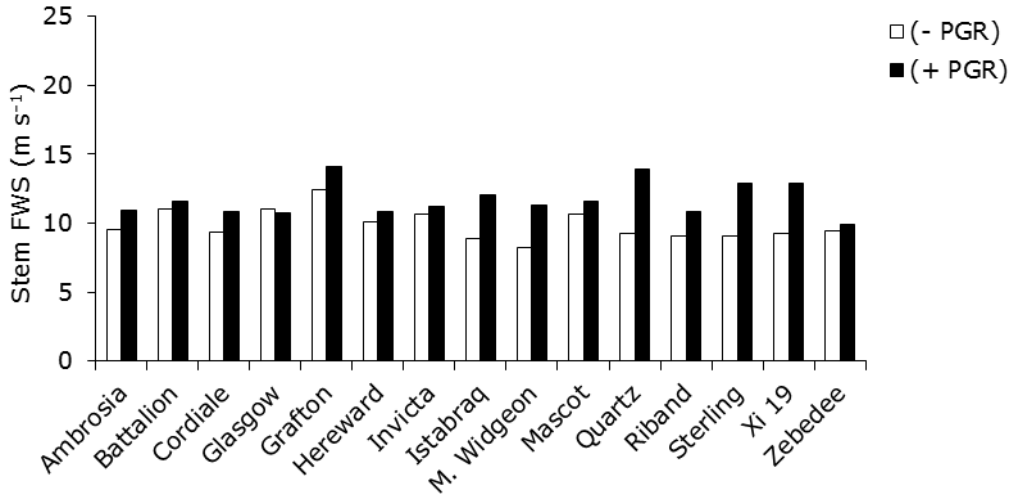
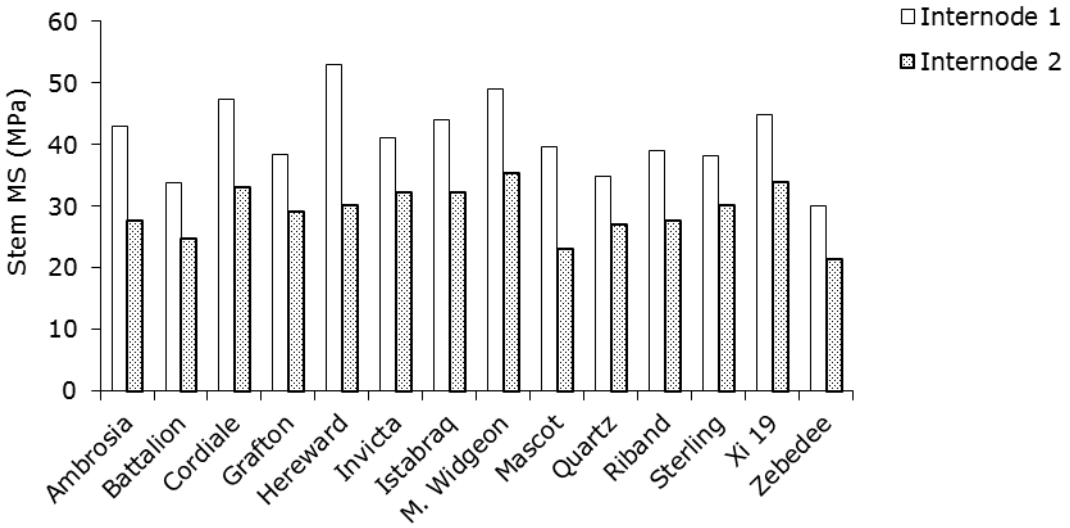
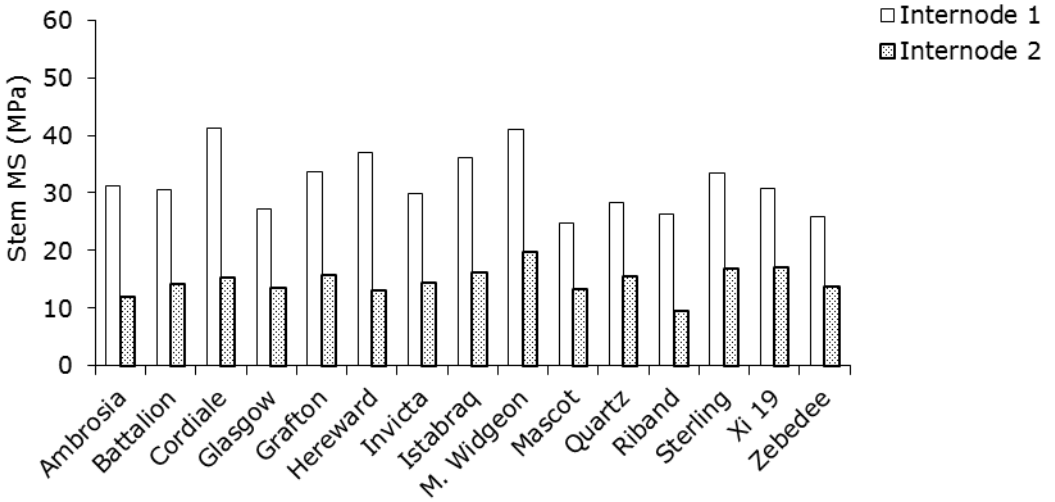


Figure 1: (a) Internode 1 stem failure wind speed (SED=1.214, df=39) and internode 2 stem failure wind speed (SED=1.402, df=39) of 14 winter wheat cultivars in 2010. (b) Effect of cultivar on internode 1 stem failure wind speed (SED=0.752, df=56) and internode 2 stem failure wind speed (SED=0.93, df=56) of 15 winter wheat cultivars in 2011. (c) Effect of cultivar and PGR on internode 1 stem failure wind speed (SED=1.056, df=57.46) of 15 winter wheat cultivars in 2011. (d) Effect of cultivar and PGR on internode 2 stem failure wind speed (SED=1.346, df=49.77) of 15 winter wheat cultivars in 2011.

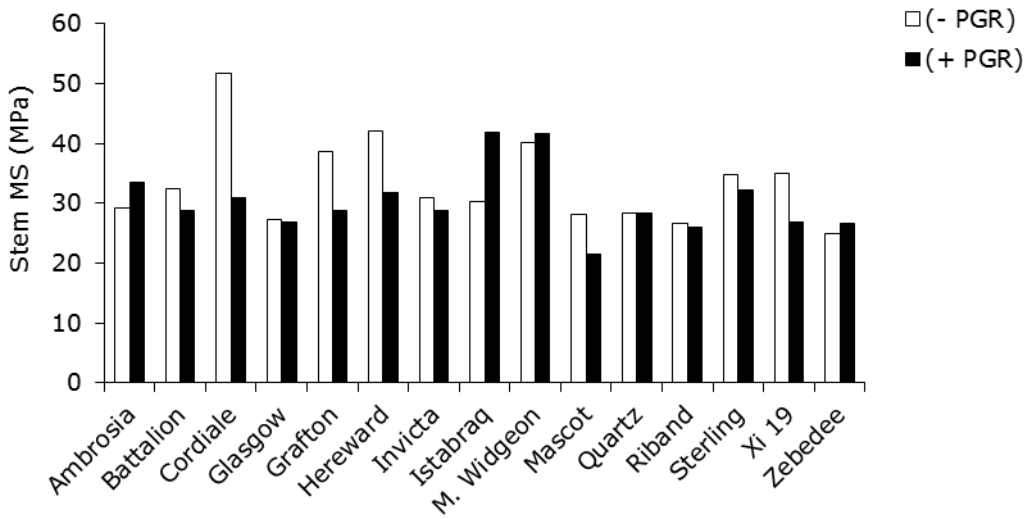
(a)


Internode 1
Internode 2
Stem MS (MPa)
60
50
40
30
20
10
0
Ambrosia
Battalion
Cordiale
Grafton
Hereward
Invicta
Istabraq
M. Widgeon
Mascot
Quartz
Riband
Sterling
Xi 19
Zebedee

(b)


Internode 1
Internode 2
Stem MS (MPa)
60
50
40
30
20
10
0
Ambrosia
Battalion
Cordiale
Glasgow
Grafton
Hereward
Invicta
Istabraq
M. Widgeon
Mascot
Quartz
Riband
Sterling
Xi 19
Zebedee

(c)



(d)

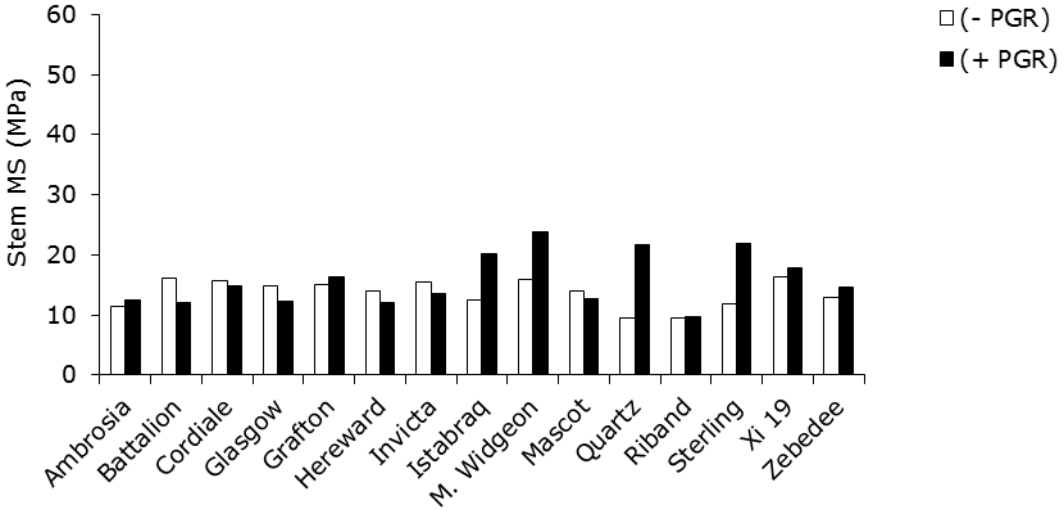


Figure 2: (a) Internode 1 stem material strength (SED=7.83, df=39) and internode 2 stem material strength (SED=4.27, df=39) of 14 winter wheat cultivars in 2010. (b) Effect of cultivar on internode 1 stem material strength (SED=4.33, df=56) and internode 2 stem material strength (SED=3.11, df=56) of 15 winter wheat cultivars in 2011. (c) Effect of cultivar and PGR on internode 1 stem material strength (SED=5.99, df=57.87) of 15 winter wheat cultivars in 2011. (d) Effect of cultivar and PGR on internode 2 stem material strength (SED=4.56, df=44.97) of 15 winter wheat cultivars in 2011.

4.4. Relationship between straw digestibility and lodging resistance

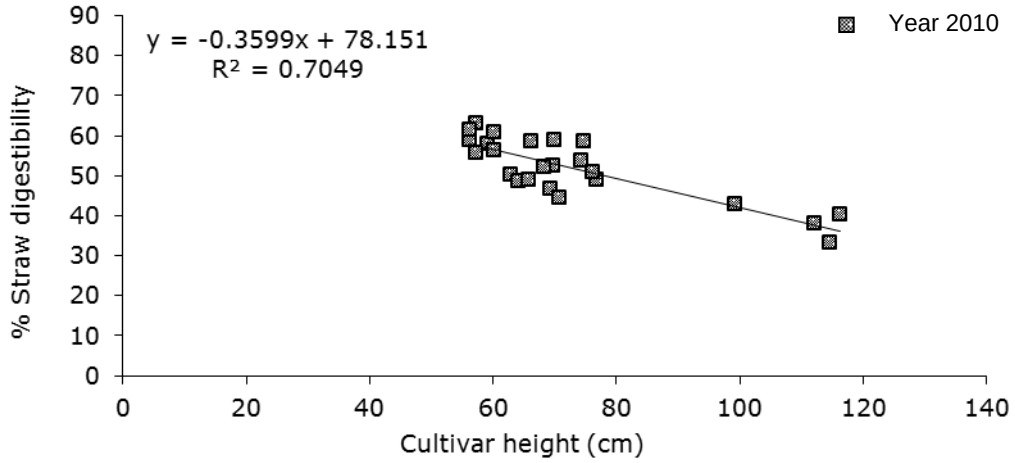
When straw digestibility was regressed against stem material strength, there was no significant relationship for either internode in 2010 or 2011 analysed alone. PGR application had no significant effect on the relationship in 2011. Stem material strength is not the only determinant of lodging susceptibility as the leverage force on the stem also needs to be considered.

A key component of leverage force is cultivar height. When cultivar height was regressed against straw digestibility, a significant negative relationship was detected in both years (P<0.001, R^2=0.7049; Figure 3 (a)) and (P<0.001, R^2=0.373; Figure 3 (b)). PGR application had no significant effect on the relationship in 2011 (Figure 3 (b)).

Stem strength and leverage force are used to calculate stem failure wind speed (the wind speed at which the stem is predicted to fail). When straw digestibility was regressed against stem failure wind speed, there was no significant relationship for either internode in 2010 or 2011 analysed alone. PGR application had no significant effect on the relationship in 2011.

When glucose yield was regressed against stem failure wind speed, a significant weak linear relationship was detected for internode 1 (P=0.022, R^2=0.216; Figure 4 (a)) in 2010 but there were no relationship for internode 2 in 2010 and for either internode in 2011. PGR application had no significant effect on the relationship in 2011.

(a)



(b)

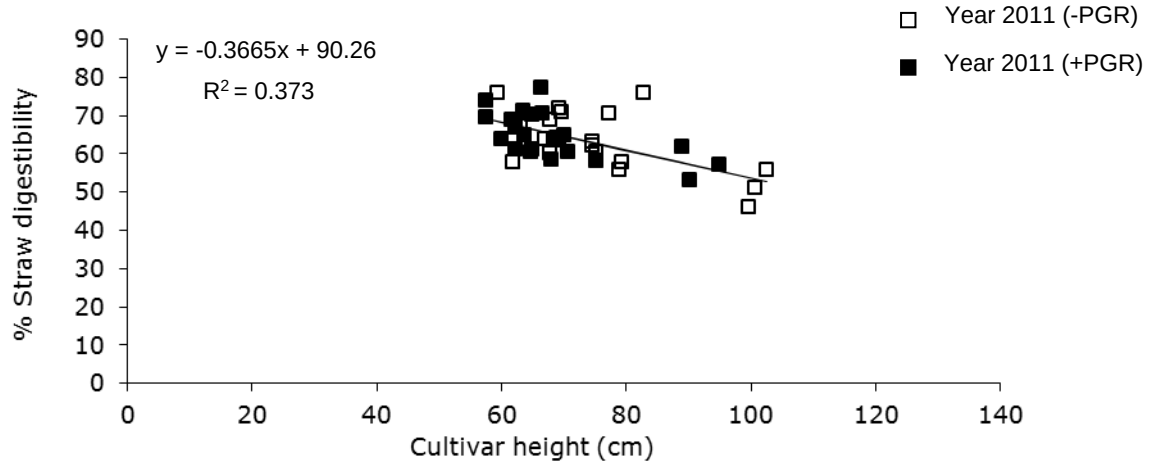


Figure 3: (a) Relationship between cultivar height and % straw digestibility of 6 winter wheat cultivars in 2010. (b) Relationship between cultivar height and % straw digestibility of 7 winter wheat cultivars in 2011.

(a)

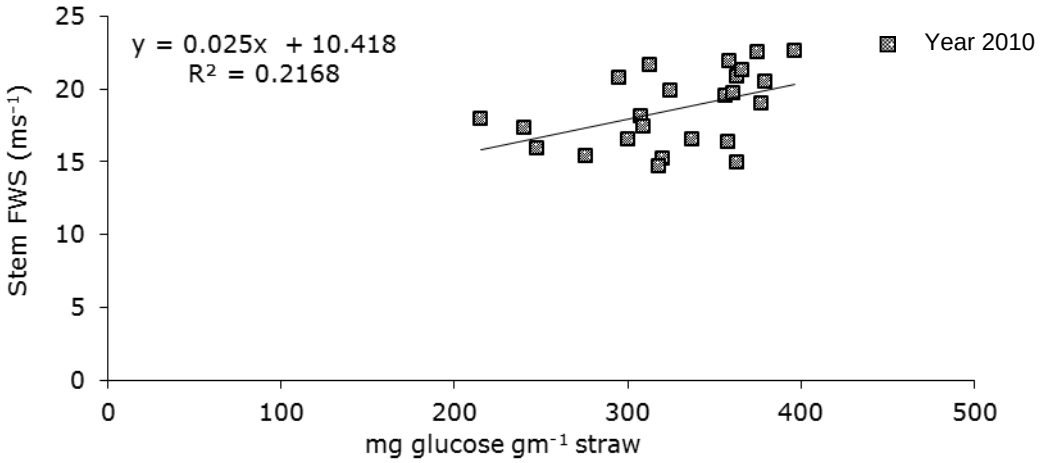


Figure 4: (a) Relationship between glucose yield and internode 1 stem failure wind speed of 6 winter wheat cultivars in 2010.

5. Discussion

The 15 cultivars selected produced similar amounts of biomass per unit area but contrasted for partitioning of that biomass to grain, straw and chaff and therefore had significantly different grain and straw yields. This is not surprising as several reviews of yield progress in wheat have shown that recent improvements in yield have come mainly from increases in harvest index rather than total biomass production (*e.g.* Shearman *et al*., 2005). Maris Widgeon, the only non-semi-dwarf cultivar in the experiment, produced similar amounts of biomass as the other cultivars but, as expected, had a smaller harvest index and hence less grain yield and greater straw yield than the other cultivars.

Pre-treatment was selected to achieve 50% subsequent saccharification of glucose from a standard wheat cultivar. This was to identify variations in digestibility between cultivars. Glucose yield from pre-treated straw residue after enzyme hydrolysis varied between cultivars in both years. This is a similar finding to Knapp *et al*. (1983) who reported significant differences between cultivars of winter wheat in the amount of reducing sugars released by enzyme saccharification with *Trichoderma reesei*. In contrast, Larsen *et al*. (2012) found no significant cultivar differences with enzyme saccharification either in terms of glucose, xylose nor total sugar released from straw. With similar level of glucose content from straw residue, Quartz had the highest glucose yield and Maris Widgeon the least from pre-treated straw residue after enzyme hydrolysis in both years. Lindedam *et al*. (2012) reported a similar range of C6 sugar (glucose) release ranging from 0.21-0.22 g g^{-1} of straw from twenty wheat cultivars. Saha *et al*. (2005) reported a maximum value of 550 mg g^{-1}.

Straw digestibility is expressed as the percentage glucose released by enzymes. Straw digestibility varied between cultivars in both years and PGR application had no effect on straw digestibility in 2011. Average straw digestibility was higher in 2011 (63.91%) than 2010 (51.78%). Jensen *et al*. (2011) identified differences between winter wheat cultivars with respect to degradability of straws from 106 winter wheat cultivars which exhibited differences in degradability ranging from 258 g kg^{-1} to 407 g kg^{-1} of dry matter by using *in vitro* enzymatic solubility (EFOS) assay which was been

developed to assess feed value. EFOS assay correlates with other assays such as the recently developed high-throughput pre-treatment and enzymatic saccharification developed by Selig *at al*. (2010). White *et al*. (1981) previously also found significant differences in degradability in a set of 25 winter wheat cultivars.

Quartz consistently had higher glucose yield with the highest straw digestibility with 60.32% followed by Cordiale (54.02%) in 2010. But surprisingly, Cordiale had the highest straw digestibility with 67.46% followed by Quartz (67.15%) in 2011. But moreover, Cordiale also had the highest glucose yield after Quartz in both years. However, Habib *et al*. (1995) also found a highly significant difference in digestibility by using *in vitro* dry matter digestibility (IVDMD) by 48 h *in vitro* fermentation technique developed by Tilley and Terry (1963) ranging from 36.40% to 48.36% in 15 wheat cultivars. Interestingly, Maris Widgeon the only non-semi-dwarf with high straw yield had the least straw digestibility (38.65% and 54.13% in 2010 and 2011, respectively) in both years as well had the least glucose yield in both years. This was in agreement with Capper (1988) who suggested that taller cultivars would have more stem than shorter cultivars and this would theoretically result in lower digestibility. Tolera *et al*. (2008) also reported that there were differences in digestibility caused by cultural practice. Cordiale and Quartz both a semi-dwarf with the greatest grain yield along with greatest straw yield had the highest straw digestibility in both years. Keman *et al*. (1984) and Tolera *et al*. (2008) reported that the digestibility of different parts or components of the plant varies and part of the reason for the difference in digestibility of the different cultivars may be due to different ratios of the parts of the plants (leaves vs. stem). Travis *et al*. (1996) who also reported that increased straw stiffness may be associated with modified anatomical features of the stems and changed chemical characteristics of the cell walls, which may be expected to decrease degradability of the straw.

There was no evidence that straw digestibility was related to lodging susceptibility. When data from 2010 or 2011 were analysed separately, no relationship was found between straw digestibility and stem material strength. However, suggests that cultivars with the highest straw digestibility are not necessarily with more stem material strength and may less likely to get lodged. Baker *et al*.

(1998) reported that stem lodging risk increases significantly if the stem material strength falls below 20 MPa. Travis *et al*. (1996) found that wheat and barley varieties that were more resistant to lodging had higher *in vitro* degradability of the basal internode than susceptible varieties.

Stem material strength is only one component of overall stem strength which is also dependent on factors such as internode length. Stem failure wind speed is the force of wind required to cause the internode to lodge and is hence a better indicator of lodging risk than stem material strength. There was no evidence that straw digestibility was related to stem failure wind speed, *i.e.* lodging susceptibility, for either internode in 2010 or 2011 when analysed alone. Berry *et al*. (2000) reported that stem lodging risk increases significantly if the stem failure wind speed falls below 20–25 m s^{-1} and the wheat must withstand wind gusts of up to 40 m s^{-1}.

Although, straw digestibility had no relationship between stem failure wind speed but the actual glucose recovered and available for bioethanol production was positively related to stem failure wind speed for internode 1 in 2010. Moreover, PGR had no significant effect on the relationship in 2011.

A key component of leverage force is cultivar height. When regressed against straw digestibility, a negative relationship was detected in both years. This agrees with Jensen *et al*. (2011) who reported that degradability of straw decreased with height as more degradable leaves constitute a larger part of the straw in shorter cultivars. Thus, this indicates that taller wheat cultivars are less digestible. Lindedam *et al*. (2012) suggested that cultivar-specific relationships of leaf and stem sugar yield is more important in predicting the overall sugar yield than the leaf-to-stem ratio. Taller plants had a preferred structure for pre-treatment and enzymatic hydrolysis, which impact conversion to sugar positively compared to shorter plants.

These results are promising as they indicate that it should be possible to identify wheat cultivars that are suitable for dual purpose use (grain for food, straw for bioethanol) and that these are not likely to be more susceptible to lodging. There was some variation in straw digestibility between

cultivars but there was no evidence that higher digestibility leads to weaker stem and subsequently increases lodging risk. PGRs reduced plant height and therefore lodging risk without reducing straw yield so had no impact on potential bioethanol yield.

6. References

Acevedo E, Silva P and Silva H. (2002) Wheat growth and physiology, Curtis BC, Rajaram S, Gómez MH (eds.) Bread wheat: Improvement and production. FAO, Plant Production and Protection Series.

Agriculture Development and Advisory Service (ADAS, 2008) Growing Wheat for Alcohol and Bioethanol Production in the North East.

Antongiovanni M and Sargentini C. (1991) Variability in chemical composition of straws. CIHEAM – *Options Mediterraneennes*, **16**: 49-53.

Aspinal GO. (1959) Structural chemistry of the hemicelluloses. *Advances in carbohydrate chemistry*, Vol. **14**: 429-468, Academic Press, New York and London.

Austin RB, Bingham J, Blackwell RD, Evans LT, Ford MA, Morgan CL and Taylor M. (1980A) Genetic Improvements in Winter Wheat Yields Since 1990 and Associated Physiological Changes. *Journal of Agricultural Science*, **94**: 675-689.

Austin RB. (1980) Physiological limitations to cereal yields and ways of reducing them by breeding: Opportunities for Increasing Crop Yields. *Association of Applied Biology*, 3-19 (Ed. Hurd RG, Biscoe PV and Dennis C.). Boston; London, Pitman.

Austin RB, Ford A and Morgan CL. (1989) Genetic improvement in the yield of winter wheat: a further evaluation. *Journal of Agricultural Science* (*Cambridge*), **112**: 295-301.

Austin RB, Edrich JA, Ford MA and Blackwell RD. (1977) The fate of the dry matter, carbohydrates and ^{14}C (carbon isotope) lost from the leaves and the stems of wheat during grain filling. *Annals of Botany*, **41**: 1309-1321.

Azam-Ali S, Aguilar-Manjarrez J and Bannayan-Avval M. (2001) A Global Mapping System for Bambara Groundnut Production. FAO, Agricultural Information Management Series. Food and Agriculture Organization of the United Nations, Rome.

Azam-Ali SN and Squire GR. (2002) Principles of Tropical Agronomy. CABI Publishing, Wallingford, UK.

Baker CJ, Berry PM, Spink JH, Sylvester-Bradley R, Griffin JM, Scott RK and Clare RW. (1998) A method for the assessment of the risk of wheat lodging. *Journal of Theoretical Biology,* **194**: 587-603.

Baker CJ. (1995) The development of a theoretical model for the wind throw of plants. *Journal of Theoretical Biology*, **175**: 355-372.

Berndes G, Hansson J, Egeskog A and Johnsson F. (2009) Strategies for 2nd generation biofuels in EU–Co-firing to stimulate feedstock supply development and process integration to improve energy efficiency and economic competitiveness. *Biomass and Bioenergy*, **30**: 1-10.

Berry PM, Sterling M, Baker CJ, Spink J and Sparkes DL. (2003) A calibrated model of wheat lodging compared with field measurements. *Agricultural and Forest Meteorology*, **119**: 167-180.

Berry PM, Sylvester-Bradley R and Berry S. (2007) Ideotype design for lodging-resistant wheat. *Euphytica*, **154**: 165-179.

Berry PM, Griffin JM, Sylvester-Bradley R, Scott RK, Spink JH, Baker CJ and Clare RW. (2000) Controlling plant form through husbandry to minimize lodging in wheat. *Field Crops Research,* **67**: 59-81.

Berry PM, Spink J, Sylvester-Bradley R, Pickett A, Sterling M, Baker C and Cameron N. (2002) Lodging control through variety choice and management. HGCA Conference 2002, Agronomic intelligence: the basis for profitable production.

Berry PM, Spink JH, Griffin JM, Sylvester-Bradley R, Baker CJ, Scott RK and Clare RW. (1998) Research to understand, predict and control factors affecting lodging in wheat. In Home Grown Cereals Authority Research, Project No. 169, p. 131. London, UK: AHDB.

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

Bothast RJ and Schlicher MA. (2005) Biotechnological processes for conversion of corn into ethanol. *Applied Microbiology Biotechnology*, **67**: 19–25.

Brander M, Hutchison C, Sherrington C, Ballinger A and Beswick C. (2009) Methodology and Evidence Base on the Indirect Greenhouse Gas Effects of Using Wastes, Residues, and By-products for Biofuels and Bioenergy: Report to the Renewable Fuels Agency and the Department for Energy and Climate Change. Ecometrica, Eunomia, Imperial College London.

British Petroleium (BP, June 2006) BP Statistical Review of World Energy.

Brancourt-Hulmel M, Doussinault G, Lecomte C, Berard P, Le Buanec B and Trottet M. (2003) Genetic improvement of agronomic traits of winter wheat cultivars released in France from 1946 to 1992. *Crop Science*, **43**: 37-45.

Butler JD, Byrne PF, Mohammadi V, Chapman PL and Haly SD. (2005) Agronomic performance of *Rht* alleles in a spring wheat population across a range of moisture levels. *Crop Science*, **45**: 939-947.

Calderini DF, Dreccer MF and Slafer GA. (1997) Consequences of breeding on biomass, radiation interception and radiation-use efficiency in wheat. *Field Crops Research,* **52**: 271-281.

Campbell JE, Lobell DB, Genova RC and Field CB. (2008) The Global Potential of Bioenergy on Abandoned Agriculture Lands. *Environmental Science and Technology*, **42**(15), 5791-5794.

Capper BS, Thomson EF and Rihawi S. (1989) voluntary intake and digestibility of barley straw as influenced by variety and supplementation with either barley grain or cotton seed cake. *Animal Feed Science Technology*, **26**: 105-118.

Capper BS. (1988) genetic variation in the feeding value of cereal straw. *Animal Feed Science Technology*, **21**: 127-140.

Carrasco JE, Saiz MAC, Navarro A, Soriano P, Saez F and Martinez JM. (1994) Effects of Dilute Acid and Steam Explosion Pretreatments on the Cellulose Structure and Kinetics of Cellulosic Fraction Hydrolysis by Dilute Acids in Lignocellulosic Materials. *Applied Biochemistry and Biotechnology*, Vol. **45/46**, 23-34.

Chandler PM, Poll AM and Gubler F. (2002) Mutants at the slender 1 locus of barley cv. Himalaya. Molecular and physiological characterization. *Plant Physiology*, **129**: 181-190.

Chakrabortty A. (July, 2008) Secret report: Biofuel caused food crisis. Internal World Bank study delivers blow to plant energy drive.

Chisti Y. (2007) Biodiesel from microalgae. *Biotechnology Advances*, **25**: 294-306.

Charles C. (April 2012) Should we be concerned about competition between Food and Fuel? Analysis of biofuel consumption mandates in the European Union and the United States. Report prepared for the International Institute for Sustainable Development.

Chang VS and Holtzapple MT. (2000) Fundamental factors affecting biomass enzymatic reactivity. *Applied Biochemistry and Biotechnology*, **84**: 5-37.

Clarke S, Kindred D, Weightman R, Dyer C and Sylvester-Bradley R. (2008) Growing Wheat for Alcohol and Bioethanol Production in the North East. ADAS, Version 1.8.

Clarke SM, Sylvester-Bradley R, Foulkes MJ, Ginsburg D, Gaju O, Werner P, Jack P, Flatman E and Smith-Reeve L. (2012) Adapting wheat to global warming. Project report for AHDB Cereals & Oilseeds project 3214. Stoneleigh, Warwickshire, UK: AHDB.

Clark TA and Mackie KE. (1984) Fermentation inhibitors in wood hydrolysates derived from the softwood *Pinus radiata*. *Journal of Chemical Technology and Biotechnology*, 34B:101.

Copeland J and Turley D. (2008) National and regional supply/demand balance for agricultural straw in Great Britain. Report prepared for The National Non-Food Crops Centre.

Cox TS, Shroyer JP, Ben-Hui L, Sears RG and Martin J. (1988) Genetic improvement in agronomic traits of hard red winter wheat cultivars from 1919 to 1987. *Crop Science*, **28**: 756-760.

Cottrill B, Smith C, Berry P, Weightman R, Wiseman J, White G and Temple M. (2007) Opportunities and implications of using the co-products from biofuel production as feeds for livestock. In *Research Review* 66 London: AHDB.

Colucci PE, Falk D, Macleod GK and Grieve DG. (1992) In situ organic matter degradability of untreated and urea-treated varieties of spring barley and oat straws and of untreated varieties of winter wheat straws. *Animal Feed Science Technology*, **37**: 73-84.

Cruz-Aguado JA, Rodes R, Perez IP and Dorado M. (2000) Morphological characteristics and yield components associated with accumulation and loss of dry mass in the internodes of wheat. *Field Crops Research*, **66**: 129-139.

Crook MJ and Ennos AR. (1993) The mechanics of root lodging in winter wheat (*Triticum aestivum L.*). *Journal of Experimental Botany*, **44**: 1219-1224.

Davies M, Campbell M and Henry R. (2010) The role of plant biotechnology in bio-energy production. *Plant Biotechnology Journal*, **8**:243

Demirbas A. (2008) Economic and environmental impacts of the liquid biofuels. Energy Edu Sci Technol **22**:37–58.

Deng M and Coleman JR. (1999) Ethanol Synthesis by Genetic Engineering in Cyanobacteria. *Applied and Environmental Microbiology*, Vol. **65(2)**, 523-528.

Decker SR, Brunecky R, Tucker MP, Himmel ME and Selig MJ. (Dec, 2009) High-Throughput Screening Techniques for Biomass Conversion. *Bioenergy Research,* Vol. **2**, 179-192.

Deckerd EL, Busch RH and Kofoid KD. (1985) Physiological aspects of spring wheat improvement: Exploitation of Physiological and Genetic Variability to Enhance Crop Productivity, 45-54 (Ed. Hasper J, Scrader L and Howel R.). *American Society of Plant Physiologists*, Rockland MD.

Demirbas A. (2008) Biofuels sources, biofuel policy, biofuel economy and global biofuel projections. *Energy Conversion and Management,* **49**: 2106-2116.

Delgenes JP, Moletta R and Navarro JM. (1996) Effects of lignocellulose degradation products on ethanol fermentations of glucose and xylose by *Saccharomyces cerevisiae, Zymomonas mobilis, Pichia stipites* and *Candida shehatae*. *Enzyme Microbial Technology*, Vo.19, pp. 220-225.

Dey PM and Brinson K. (1984) Plant cell walls. *Advances in Carbohydrate Chemistry and Biochemistry*, **42**: 265-382.

Difiglio C. (1997) Using advanced technologies to reduce motor vehicle greenhouse gas emissions. *Energy Policy*, **25**:1173–1178.

Dubois M, Gilles KA, Hamilton JK, Rebers PA and Smith F. (March, 1956) Colorimetric Method for Determination of Sugars and Related Substances. *Analytical Chemistry*, Vol. **28**, No. **3**, 350-356.

Easson DL, White EM and Pickles SJ. (1993) The effects of weather, seed rate and cultivar on lodging and yield in winter wheat. *Journal of Agricultural Science*, **121**: 145-156.

Edwards V, Goktepe I, Milford B, Isikhuemhen OS, Yu J and Ahmedna M. (2005) Inhibitory activity of tiger milk mushroom on cancer cells. *IFT annual meeting*. New Orleans, Lousiana.

Ellis CM, Nagpal P, Young JC, Hagen G, Guilfoyle TJ and Reed JW. (2005) Auxin response factor 1 and auxin response factor 2 regulate senescence and floral organ abscission in *Arabidopsis thaliana*. *Development*, **132**: 4563-4574.

Ellis MH, Rebetzke GJ, Azanza F, Richards RA and Spielmeyer W. (2005) Molecular mapping of gibberellin-responsive dwarfing genes in bread wheat. *Theoretical Applied Genetics*, **111**: 423-430.

Engelman R. (2009) Population and Sustainability: Can we avoid limiting the number of people?. *Scientific American*.

Erdei B, Barta Z, Sipos B, Reczey K, Galbe M and Zacchi G. (2010) Ethanol production from mixtures of wheat straw and wheat meal. *Biotechnology for Biofuels,* **3**: 16.

Ericsson K, Rosenqvist H and Nilsson LJ. (2009) Energy crop production costs in the EU. *Biomass and Bioenergy*, **33**: 1577-1586.

Evans LT. (1998) *Feeding the Ten Billion:* Plant Population Growth. Cambridge University Press, Cambridge, UK.

Evenson RE and Gollin D. (2003) Crop Variety Improvement and its Effect on Productivity: *The Impact of International Research*. Wallingford: CABI Publishing.

Fargione J, Hill J, Tilman D, Polasky S and Hawthrone P. (2008) Land Clearing and the Biofuel Carbon Debt. *Science*, Vol. **319**, 1235-1237.

Fan LT, Lee YH and Gharpuray MM. (1982) The nature of lignocellulosics and their pretreatments for enzymatic hydrolysis. *Advances in Biochemical Engineering*, **23**: 157-187.

Fengel D and Wegener G. (1989) Wood: Chemistry, Ultrastructure, Reactions. Walter de Gruyter, Berlin.

Fischer RA and Stockman YM. (1986) Increased kernel number in Norin 10-derived dwarf wheat: Evaluation of the cause. *Australian Journal of Plant Physiology*, **13**: 767-784.

Fischer RA. (1985) Number of kernels in wheat crops and the influence of solar radiation and temperature. *Journal of Agricultural Science* (Cambridge), **105**: 447-461.

Fischer RA and Stapper M. (1987) Lodging effects on high yielding crops of irrigated semi-dwarf wheat. *Field Crops Research*, **17**: 245-258.

Foulkes MJ, Reynolds MP and Sylvester-Bradley R. (2009) Genetic Improvement of Grain Crops: Yield Potential. Sadras V and Calderini D (eds.), *Crop Physiology*. Oxford: Elsevier.

Foulkes MJ, Sylvester-Bradley R and Scott RK. (2002) The ability of wheat cultivars to withstand UK drought: formation of grain yield. *Journal of Agricultural Science*, Cambridge, **138**: 153-169.

Food and Agriculture Organization (FAO, 2012) Food Outlook. Global Market Analysis.

Food and Agriculture Organization (FAO, 2010) Bioenergy and Food Security, Rome.

Food and Agriculture Organization (FAO, 2011) Statistics Database.

Food and Agriculture Organization (FAO, 2009) Sustainable Production of Second-Generation Biofuels.

Frederick JR and Camberato JJ. (1995b) Water and nitrogen effects on winter wheat in the southeastern coastal plain: II-physiological responses. *Agron. Journal*, **4**: 241-248.

Fry CS. (1987) The growing plant cell wall: chemical and metabolic analysis. Longman, UK. pp. 1-15.

Gahukar RT. (2009) Food Security: The challenges of climate change and bioenergy. *Current Science*, **96**(1), 26-28.

Gale MD and Youssefian S. (1985) Dwarfing genes in wheat. *In Progress in Plant Breeding*, Russell GE (ed.), Butterworths, London, pp. 1-35.

Galbe M and Zacchi G. (2002) A review of the production of ethanol from softwood. *Applied Microbiological Biotechnology*, **59**: 618-628.

Gent MPN and Kiyomoto RK. (1998) Physiological and agronomic consequences in *Rht* genes in wheat. Journal of Crop Production, **1**: 27-46.

Gebbing T, Schnyder H and Kuhbauch W. (1999) The utilization of pre-anthesis reserves in grain filling of wheat. Assessment by steady-state (CO_2)-C-13/(CO_2)-C-12 labelling. *Plant Cell and Environment*. **22**: 851-858.

Ghose TK. (1987) Measurement of cellulase activities. *Pure and Applied Chemistry*, **59**: 257-268.

Gibson L and Benson G. (2002) Origin, History and uses of Oat (*Avena sativa*) and Wheat (*Triticum aestivum*). Iowa State University, Department of Agronomy.

Gifford RM, Thorne JH, Hitz WD and Giaquinta RT. (1984) Crop Productivity and Photo-assimilate Partitioning. *Science*, **225**: 801-808.

Gnansounou E. (2010) Production and use of lignocellulosic of bioethanol in Europe: Current situation and perspectives. *Bioresource Technology*, **101**: 4842-4850.

Golik SI, Chidichimo HO and Sarandon SJ. (2005) Biomass production, nitrogen accumulation and yield in wheat under two tillage systems and nitrogen supply in the Argentine Rolling Pampa. *World Journal of Agricultural Sciences*, **1**: 36-41.

Goto M, Morita O and Chesson A. (1991) Morphological and anatomical variations among barley cultivars influence straw degradability. *Crop Science*, **31**: 1536-1541.

Gregory PJ, Tennant D and Belford RK. (1992) Root and shoot growth and water and light use efficiency of barley and wheat crops grown on a shallow duplex soil in a Mediterranean type environment. *Australian Journal of Agricultural Research*, **43**: 555-573.

Habib G, Shah SBA and Inayat K. (1995) Genetic variation in morphological characteristics, chemical composition and in vitro digestibility of straw from different wheat cultivars. *Animal Feed Science Technology,* **55**: 263-274.

Hamdi QA, Harris D and Clark JA. (Aug, 1987) Saturation deficit, canopy formation and function in *Sorghum bicolour*. *Journal of Experimental Botany,* Vol. **38**, No. **193**, 1271-1283.

Hamelinck CN, Van Hooijdonk G and Faaij PC. (2005) Ethanol from lignocellulosic biomass: techno-economic performance in short, middle and long term. *Biomass and Bioenergy*, Vol. **28(4)**, 384-410.

Hamilton R. (2009) Agriculture's Sustainable Future: Breeding Better Crops. *Scientific American*.

Hansen MAT, Kristensen JB, Felby C and Jorgensen H. (2011) Pretreatment and enzymatic hydrolysis of wheat straw (Triticum aestivumL.)-The impact of lignin relocation and plant tissues on enzymatic accessibility. *Bioresource Technology*, **102**: 2804-2811.

Hatfield R and Fukushima RS. (2005) Can Lignin Be Accurately Measured? *Crop Science,* Vol. **45**, 832-839.

Harlan JR. (1992) Crops and Man. American Society of Agronomy, Crop Science Society of America, Madison, Wisconsin, USA.

Hawkes JG. (1995) Centers of origin for agricultural diversity in the Mediterranean: from Vavilov to the present day. *Diversity*, **11**: 109-111.

Hay KMR and Poter JR. (2006) The physiology of crop yields. Second Edition, Blackwell Publishing Limited, UK.

Harris JH. (1990) Plant cell wall structure and development. In: Microbial and plant opportunities to improve lignocellulose utilization by ruminants. Editor: Akin DE, Ljungdahl LG, Wilson JR, Harris PJ. London, pp. 71-90.

Harris EK. (1949) Wood saccharification. Advances in carbohydrate chemistry and biochemistry, **4**: 153-188.

Harkin JM. (1973) Lignin. In: Chemistry and Biochemistry of Herbage. Vol.1 (eds: Butler GW and Bailey RW, Academic press New York, pp. 3232-3373.

Hedden P. (2010) Green Revolution Genes: The Green Revolution. Essay 20.3, Plant Physiology, 5th Edition.

Herbert CD. (1982) Growth regulation in cereals-chance or design? In *Chemical Manipulation of Crop Growth and Development*, McLaren JS (ed.). London:Butterworth Scientific. p. 315-327.

Himmel ME, Ding S, Johnson DK, Adney WS, Nimlos MR, Brady JW and Foust TD. (2007) Biomass recalcitrance: Engineering plants and enzymes for biofuels production. *Science*, **315**(5813): 804-807.

Hobbs PR, Sayre KD and Ortiz-Monasterio JI. (1998) Incereasing wheat yields sustainably through agronomic means. NRG Paper 98-01. Mexico, DF, CIMMYT.

AHDB (AHDB, 2010) Growing wheat for alcohol/bioethanol production.

AHDB (AHDB, 2009) Feasibility of co-producing arabinoxylans and ethanol in a wheat biorefinery: Fractionation studies on UK wheat.

International Energy Agency (IEA, 2008) World Energy Outlook, London.

International Energy Agency (IEA, 2009) World Energy Outlook, London.

International Energy Agency (IEA, 2011) World Energy Outlook, London.

Institute for European Environmental Policy (IEEP, 2012) The role of bioenergy in Europe's energy future.

International Institute for Sustainable Development (IISD, 2012) Cultivating Governance: Cautionary tales for biofuel policy reformers.

Jakobsson E. (2002) *Master's thesis*: Optimization of the pretreatment of wheat straw for production of bioethanol.

Jensen JW, Magid J, Hansen-Møller J, Anderson SB and Bruun S. (2011) Genetic variation in degradability of wheat straw and potential for improvement through plant breeding. *Biomass and Bioenergy*, **35**: 1114-1120.

Jordan N, Boody G, Broussard W, Glover JD, Keeney D, Mccown BH, Mcisaac G, Muller M, Murray H, Neal J, Pansing C, Turner RE, Warner K and Wyse D. (2007) Environment-Sustainable development of the agricultural bio-economy. *Science*, **316**(5831), 1570-1571.

Jung HG and Himmelsbach DS. (1989) Isolation and Characterization of Wheat Straw Lignin. *Journal of Agricultural and Food Chemistry*, Vol. **37,** 81-87.

Jung HG and Fahey GC. (1983) Nutritional implications of phenolic monomers and lignin: a review. *Journal of Animal Sciences*, **57**: 206-219.

Kernan JA, Coxworth EC, Crowle WL and Spurr DT. (1984) The nutritional value of crop residue components from several wheat cultivars grown at different fertilizer levels. *Animal Feed Science Technology,* **11**: 301-311.

Kemanian AR, Stockle CO, Huggins DR. (2004) Variability of barley radiation-use efficiency. *Crop Science*, **44**: 1662-1672.

Kim S and Dale BE. (2004) Global potential bioethanol production from wasted crops and crop residues. *Biomass Bioenergy*, **4**: 361-375.

Kindred DR, Smith TC, Sylvester-Bradley R, Ginsberg D and Dyer CJ. (2007) Optimizing nitrogen applications for wheat grown for the biofuels market. AHDB Cereals & Oilseeds Project Report 417.

Kiniry JR. (1993) Nonstructural carbohydrate utilization by wheat shaded during growth. *Agronomy Journal*, **85**: 844-849.

Kiniry JR, Jones CA, O'toole JC, Blanchet R, Cabelguenne and Spanel DA. (1989) Radiation use efficiency in biomass accumulation prior to grain filling for five grain crops species. *Field Crops Research*, **20**: 51-64.

Knapp JS, Parton JH and Walton NI. (1983) Enzyme scarification of wheat straw – differences in the degradability of straw derived from different cultivars of winter wheat. *Journal of the Science of Food and Agriculture,* **34**: 433-439.

Knight J. (2003) Crop Improvement: A Dying Breed. *Nature*, **421**: 568-570.

Kristensen JB, Thygesen LG, Felby C, Jorgensen H and Elder T. (16TH April, 2008) Cell-wall structure changes in wheat straw pretreated for bioethanol production. *Biotechnology for Biofuels,* **1**: 1-5.

Kretschmer B, Allen B and Hart K. (2012) Mobilizing cereal straw in the EU to feed advanced biofuel production. *Institute for European Environmental Policy: London.*

Kumar P, Barrett DM, Delwiche MJ and Stroeve P. (2009) Methods of pretreatment of lignocellulosic biomass for efficient hydrolysis and biofuel production. *American Chemical Society*, Vol. **48**, 3713-3729.

Kumar R and Wyman CE. (2009) Effect of xylanase supplementation of cellulase on digestion of corn stover solids prepared by leading pretreatment technologies. *Bioresource Technology*, **100**: 4203-4213.

Lawther JM, Sun R and Banks WB. (1995) Extraction, Fractionation and Characterization of Structural Polysaccharides from Wheat Straw. *Journal of Agricultural and Food Chemistry*, Vol. **43**, 667-675.

Larsen SU, Bruun S and Lindedam J. (2012) Straw yield and scarification potential for ethanol in cereal species and wheat cultivars. *Biomass and Bioenergy*, Vol. **45**, 239-250.

Lee J. (1997) Biological conversion of lignocellulosic biomass to ethanol. *Journal of Biotechnology*, **56**(1): 1-24.

Li Q, Liu M, Zhang J, Dong B and Bai Q. (2009) Biomass accumulation and radiation use efficiency of winter wheat under deficit irrigation regimes. *Plant, Soil and Environment*, **55**: 85–91.

Lopes MS and Reynolds MP. (2012) Stay-green in spring wheat can be determined by spectral reflectance measurements (normalized difference vegetation index) independently from phenology. *Journal of Experimental Botany*, Vol. **63**(10): 3789-3798.

Lutz W, Sanderson W and Scherbov S. (2001) The end of world population growth. *Nature*, **412**(6846): 543-545.

Luo MC, Yang ZL, You FM, Kawahara T, Waines JG and Dvorak J (2007) The structure of wild and domesticated emmer wheat populations, gene flow between them and the site of emmer domestication. *Theoretical and Applied Genetics*, **114**: 947-959.

Marzola DL and Bartholomew DP. (10TH Aug, 1979) Photosynthetic pathway and biomass energy production. *Science*, Vol. **205**, 555-559.

Mathison GW, Soofi-Siawash R, Okine EK and Sedwick G. (1999) Degradability of alfalfa saponins in the digestive tract of sheep and their rate of accumulation in rumen fluid. *Canadian Journal of Animal Science*, **79**: 315-319.

Mann DGJ, Labbe N, Sykes RW, Gracom K, Kline L, Swamidoss IM, Burris JN, Davis M and Stewart Jr. CN. (OCT, 2009) Rapid Assessment of Lignin Content and Structure in Switch grass (*Panicum virgatum L.*) Grown Under Different Environmental Conditions. *Bioenergy Research,* Vol. **2**, 246-256.

McCann MC and Carpita NC. (2008) Designing the deconstruction of plant cell walls. *Current Opinion in Plant Biology*, Vol. **11**, 314-320.

McIntosh S and Vancov T. (2010) Enhanced enzyme saccharification of Sorghum bicolor straw using dilute alkali pre-treatment. *Bioresource Technology*, **101**: 6718-6727.

McKendry P. (2002) Energy production from biomass (part 1): overview of biomass. *Bioresource Technology*, **83**: 37-46.

Miralles DJ, Katz SD, Colloca A and Salfer GA. (1998) Floret development in near isogenic wheat lines differing in plant height. *Field Crop Research*, **59**: 21-30.

Minson DJ and Wilson JR. (1994) Prediction of intake as an element of forage quality. Fahey GC. (ed.), Forage quality, evaluation and utilization. *American Society of Agronomy*, Madison, WI, 533-563.

Monteith JL. (1977) Climate and efficiency of crop production in Britain. *Philosophical Transactions of the Royal Society*. London. B, **281**: 277-294.10.1002/jsfa.4442.

Mosier N, Wyman CE, Dale BE, Elander RT, Lee YY Holtzapple M, Ladisch M.(2005) Features of promising technologies for pretreatment of lignocellulosic biomass. *Bioresource Technology*, **96**: 673-686.

Muurinen S and Peltonen-Sainio P. (2006) Radiation-use efficiency of modern and old spring cereal cultivars and its response to nitrogen in northern growing conditions. *Field Crops Research*, **96**: 363–373.

nabim wheat guide 2009, 2010 and 2011 (*cereals.ahdb.org.uk*).

Nakajima T, Yoshida M and Tomimura K. (2008) Effect of lodging on the level of mycotoxins in wheat, barley and rice infected with the *Fusarium graminearum* species complex. *Journal of General Plant Pathology*, **74**: 289-295.

Nevo E, Korol AB, Beiles A and Fahima T. (2002) Evolution of Wild Emmer and Wheat Improvement. Population Genetics, Genetic Resources, and Genome Organization of Wheat's Progenitor, *Triticum dicoccoides*. Springler-Verlag Berlin Heidelberg, Germany.

Neenan M and Spencer-Smith JL. (1975) An analysis of the problem of lodging with particular reference to wheat and barley. *Journal of Agricultural Science*, Cambridge, **85**: 495-507.

Neryssa JG, Ramsden SJ and Wilson P. (2013) Barriers and incentives for cereal straw based bioethanol: a farm business perspective. *Energy Policy*, **59**: 161-171.

Neryssa JG, Wilson P and Ramsden SJ. (2013) Straw use and availability for second generation biofuels in England. *Biomass and Bioenergy*, **55**: 311-321.

Ortiz R, Braun HJ, Crossa J, Jonathan H, Crouch JH, Davenport G, Dixon J, Dreisigacker S, Duveiller E, He Z, Huerta J, Joshi AK, Kishii M, Kosina P, Manes Y, Mezzalama M, Morgounov A, Murakami J, Nicol J, Ferrara GO, Ortiz-Monasterio JI, Payne TS, Pena RJ, Reynolds MP, Sayre KD, Sharma RC, Singh RP, Wang J, Warburton M, Wu H and Iwanaga M. (2008) Wheat genetic resources enhancement by the International Maize and Wheat Improvement Center (CIMMYT). *Genetic Resources and Crop Evolution*, **55**: 1095-1140.

Organisation for Economic Co-Operation and Development (OECD, 2008) Annual Report.

Ornston LN, Balows A and Baumann P. (1987) Annual review of microbiology. Annual review of microbiology, **41**: 465-505.

Osei AM. (2010) *Master's thesis*: Exploiting resource use efficiency and resilience in ancient wheat species.

O'sullivan A. (1997) Cellulose: the structure slowly unravels. *Cellulose*, **4**: 173-207.

Pauly M and Keegstra K. (2008) Cell-wall carbohydrates and their modification as a resource for biofuels. *The Plant Journal,* **54**: 559-568.

Passioura JB. (1977) grain yield, harvest index and water use of wheat. *Journal of the Australian Institute of Agricultural Science*, **43**: 117-120.

Pinthus MJ. (1973) Lodging in wheat, barley and oats: the phenomenon, its causes and preventative measures. *Advances in Agronomy,* **25**: 209-263.

Powlson DS, Whitmore AP and Goulding WT. (2011) Soil carbon sequestration to mitigate climate change: a critical re-examination to identify the true and the false. *European Journal of Soil Science*, **62**: 42-55.

Prasad S, Singh A and Joshi HC. (2007) Ethanol as an alternative fuel from agricultural industrial and urban residues. *Resources, Conversion and Recycling*, **50**: 1-39.

Punter G, Rickeard D, Larive J-F, Edwards R, Mortimer N, Horne R, Bauen A and Woods J. (2004) Well-to-Wheel Evaluation for Production of Ethanol from Wheat. A report by the Low CVP Fuels Working Group. WTW Sub-Group. pp 40. Low Carbon Vehicle Partnership (LCVP).

Puls J and Schuseil J. (1993) Chemistry of hemicelluloses: relationship between hemicellulose structure and enzymes required for hydrolysis. *Portland Press Research Monograph 4: Hemicellulose and Hemicellulases* (eds Coughlan MP and Hazlewood GP), pp. 1-27. Portland Press, London.

Raun WR, Solie JB, Johnson GV, Stone ML, Mullen RW, Freeman KW, Thomason WE and Lukina EV. (2002) Improving Nitrogen Use Efficiency in Cereal Grain Production with Optical Sensing and Variable Rate Application. *Agronomy Journal*, **94**: 815-820.

Rajbhandari BP. (2004) Eco-Physiological Aspects of Common Buckwheat. *Proceedings of the 9th International Symposium on Buckwheat, Prague, 2004.*

Rademacher W, Temple-Smith KE, Griggs DL and Hedden P. (1992) The mode of action of acyclohexanediones-a new type of growth retardant. In: *Progress in Plant Growth Regulation*. Proceedings of the 14th International Conference on Plant Growth Substances. Karssen C, Van Loon L and Vreugdenhill D. (eds.) Dordrecht: Kluwer Academic Publishers, p. 571-577.

Ramanzin M, Orskov ER and Tuah AK. (1986) Rumen degradation of straw. Botanical fractions of straw from two barley cultivars. *Animal Production*, **43**: 271-278.

Reddy N and Yang Y. (2005) Bio fibers from agricultural byproducts for industrial applications. *TRENDS in Biotechnology*, Vol. **23**, 22-27.

Reynolds MP and Borlaug NE. (2006) Applying innovations and new technologies for international collaborative wheat improvement. *Journal of Agricultural Science*. Centenary Review, 1-16.

Reynolds MP, Van Ginkel M and Ribaut JM. (2000) Avenues for genetic modification of radiation use efficiency in wheat. *Journal of Experimental Botany*, **51**: 459-473.

Rosillo-Calle F and Walter A. (2006) A global market for Bioethanol: Historical trends and future prospects, *Energy Sustainable Development*, Pages:20-32.

Ruuska SA, Rebetzke GJ, Herwaarden AF, Richards RA, Fettell NA, Tabe L and Jenkins CLD. (2006) Genotypic variation in water-soluble carbohydrate accumulation in wheat. *Functional Plant Biology*, **33**: 799-809.

Sands RD and Leimbach M. (2003) Modeling Agriculture and Land Use in an Integrated Assessment Framework. *Climatic Change*, **56**(1), 185-210.

Sarkar P, Bosneaga E and Auer M. (2009) Plant cell walls throughout evolution: towards a molecular understanding of their design principles. *Journal of Experimental Botany*, **60**: 3615-3635.

Saha BC, Iten LB, Cotta MA and Wu YV. (2005) Dilute acid pretreatment, enzymatic saccharification and fermentation of wheat straw to ethanol. *Process Biochemistry,* **40**: 3693-3700.

Saeman JF, Moore WE and Millett MA. (1963) Hydrolysis and quantitative paper chromatography. In: Whistler RL (Ed.) *Methods in Carbohydrate Chemistry*. Vol. **III**, pp 54-69. Academic Press, New York.

Salamini F, Ozkan H, Brandolini A, Schafer-Preg R and Martin W. (2002) Genetics and geography of wild cereal domestication in the near east. *Nature reviews Genetics*, **3**: 429-411.

Sayre KD, Rajaram S and Fischer RA. (1997) Yield potential progress in short bread wheats in northwest Mexico. *Crop Science*, **37**: 36-42.

Schnyder H. (1993) The role of carbohydrate storage and redistribution in the source-sink relations of wheat and barley during grain filling. *New Physiologist*, **123**: 233-245.

Scudamore KA and Patel S. (2000) Survey for aflatoxins, ochratoxin A, zearalenone and fumonisins in maize imported into the United Kingdom. *Food Additives and Contaminants*: Part A, **17**(5): 407-416.

Shearman VJ, Sylvester-Bradley R, Scott RK and Foulkes MJ. (2005) Physiological processes associated with wheat yield progress in the UK. *Crop Science Society of America*, Vol. **45**, 175-185.

Sharma HSS, Faughey G, Chambers J, Lyons G and Sturgeon S. (2000) Assessment of winter wheat cultivars for changes in straw composition and digestibility in response to fungicide and growth regulator treatments. *Annals of Applied Biology*, **137**: 297-303.

Shen H, Fu C, Xiao X, Ray T, Tang Y, Wang Z and Chen F. (OCT, 2009) Developmental Control of Lignification in Stems of Lowland Switch grass Variety Alamo and the Effects on Scarification Efficiency. *Bioenergy Research,* Vol. **2**, 233-245.

Sims REH, Mabee W, Saddler JN and Taylor M. (2010) An overview of second generation biofuel technologies. *Bioresource Technology*, **101**: 1570-1580.

Singels A and Smit MA. (2002) The effect of row spacing on an irrigated plant crop of sugarcane variety NCO376. *Proceedings of South African Sugar Technology Association,* **76**: 94-105.

Simons KJ, Fellers JP, Trick HN, Zhang Z, Tai Y-S and Gill BS. (2006) Molecular Characterization of the Major Wheat Domestication Gene Q. *Genetics*, **172**: 547-555.

Simmons SR. (1987) Growth development and physiology. In: Wheat and Wheat Improvement. Pp 77-113 (Ed. Heyne E. G). Agronomy Series No. 13, Second Edition, *American Society of Agronomy*, Madison, WI.

Siddique KHM, Belford RK, Perry MW and Tennant D. (1989) Growth, development and light interception of old and modern wheat cultivars in a Mediterranean type environment. *Australian Journal of Agricultural Research*, **40**: 473-487.

Sjostrom E. (1981) *Wood Chemistry: Fundamentals and Applications*, Academic Press, New York, 169-189.

Slafer GA and Andrade FH. (1989) Genetic improvement in bread wheat (*Triticum aestivum*, L.) yield in Argentina. *Field Crops Research*, **21**: 289-296.

Slafer GA and Andrade FH. (1991) Changes in physiological attributes of the dry matter economy of bread wheat (*Triticum aestivum L.*) through genetic improvement of grain yield potential at different regions of the world. A review. *Euphytica*, 58: 37-49.

Slafer GA, Satorre EH and Andrade FH. (1994) Increases in grain yield in bread wheat from breeding and associated physiological changes: *Genetic Improvement of Field Crops*, 1-68 (Ed. Slafer GA). Marcel Dekker Inc.: New York.

Slafer GA and Savin R. (1991) Development base temperature in different phonological phases of wheat (*Triticum aestivum*). *Journal of Experimental Botany*, **42**: 1077-1082.

Smith TC, Kindred DR, Brosnsn JM, Weightman RM, Shepherd M and Sylvester-Bradley R. (2006) Wheat as a feedstock for alcohol production. AHDB.

Spink JH, Semere T, Sparkes DL, Whaley JM, Foulkes MJ, Clare RW and Scott RK. (2000) Effect of sowing date on the optimum plant density of winter wheat. *Annals of Applied Biology*, **137**: 179-188.

Sparkes DL. (2003) Field Crops. GROWTH AND DEVELOPMENT/Field Crops: 595-600.

Sun R, Lawther JM and Banks WB. (1995) Influence of alkaline pre-treatments on the cell wall components of wheat straw. *Industrial Crops and Products*, **4**: 127-145.

Swaminathan MS. (2007) Can science and technology feed the world in 2025?. *Field Crops Research*, **104**(1-3), 3-9.

Szwarc A. (2004) The use of bio-fuels in Brazil. In United Nations Framework Convention on Climate Change - In session workshop on mitigation SBSTA21/COP10, Buenos Aires.

Tabka MJ, Herpoel-Gimbert I, Monod F, Asther M and Sigoillot JC. (2006) Enzymatic saccharification of wheat straw for bioethanol production by a combined cellulase xylanase and feruloyl esterase treatment. *Enzyme and Microbial Technology*, **39**: 897-902.

Taherzadeh MJ and Karimi K. (2007) Process for ethanol from lignocellulosic materials. Acid based hydrolysis processes. *Bioresources*, **2**(3): 472-499.

Takahashi T and Nakaseko K. (1990) Seasonal change of photosynthetically active radiation intercepted by spring wheat canopy and its relation to dry matter production*. Japanese Journal of Crop Science,* **59**: 778-784.

Talebnia F, Karakashev D and Angelidaki I. (2010) Production of bioethanol from wheat straw: An overview on pre-treatment, hydrolysis and fermentation. *Bioresource Technology*, **101**: 4744-4753.

Thomas H. (1982) Leaf senescence in a non-yellowing mutant of *Festuca pratensis I*. chloroplast membrane polypeptides. *Planta*, **154**: 212-218.

Timell TE. (1964) Wood hemicelluloses: Part one. *Advances in Carbohydrates Chemistry and Biochemistry*, **19**: 247-302.

Timell TE. (1965) Wood hemicelluloses: Part TWO. *Advances in Carbohydrates Chemistry and Biochemistry*, **20**: 409:483.

Tolera A, Tsegaye B and Berg T. (2008) Effects of variety, cropping year, location and fertilizer application on nutritive value of durum wheat straw. *Journal of Animal Physiology and Animal Nutrition*, Vol. **92**(2): 121-130.

Travis AJ, Murison SD, Hirst DJ, Walker KC and Chesson A. (1996) Comparison of the anatomy and degradability of straw from varieties of wheat and barley that differ in susceptibility to lodging. *Journal of Agricultural Science*, **127**: 1-10.

Tripathi SC, Sayre KD. (2003) Growth and Morphology of spring wheat (Triticum aestivum L.) culms and their association with lodging:effects of genotypes, N levels and ethephon. *Field Crops Research*, Vol. **84**, 271-290.

United Nation (UN, 2007) The State of Food and Agriculture 2008 – Biofuels: prospects, risks and opportunities.

United Nation (UN, 2008) Investing in Renewable Energy: The GEF Experience.

Waddington SR, Osmanzai M, Yoshida S and Ransom JK. (1987) The Yield of Durum Wheat Released in Mexico Between 1960 and 1984. *Journal of Agricultural Science*, **108**(2), 469-477.

Wang J, Zhu JM, Lin QQ, Li XJ, Teng NJ, Li ZS, Li B, Zhang AM and Lin JX. (2006) Effects of culm structure and chemical component in the cell walls on compressive strength. *Chinese Science Bulletin*, **51**: 1-7.

Wheals AE, Basso LC, AlvesanD DMG and Amorim HV. (1999) Fuel ethanol after 25 years. *Trends in Biotechnology*, **17**: 482-487.

Whaley JM, Sparkes DL, Foulkes MJ, Spink JH, Semere T and Scott RK. (Sept, 2000) The physiological response of winter wheat to reduction in plant density. *Annals of Applied Biology*, Vol. **137**, 165-177.

Wilkie KCB. (1979) The hemicellulose of grasses and cereals. *Advances in Carbohydrate Chemistry and Biochemistry*, **36**: 215-264.

World Resources Institute (WRI, 2005) World Resources 2005 – The Wealth of the Poor.

Wu X, Zhao R, Bean SR, Seib PA, McLaren JS, Madl RL, Tuinstra M, Lenz MC and Wang D. (2007) Factors impacting ethanol production from grain sorghum in the dry-grind process. *Cereal Chemistry*, **84**: 130-136.

Yang J, Worley E, Wang M, Lahner B, Salt DE, Saha M and Udvardi M. (Oct, 2009) Natural Variation for Nutrient Use Remobilization Efficiencies of Switch grass. *Bioenergy Research,* Vol. **2**, 257-266.

Yang B and Wyman CE. (2008) Pre-treatment: the key to unlocking low-cost cellulosic ethanol. *Biofuels, Bio-products and Bio-refining*, Vol. **2**, 26-40.

Yu Q, Zhuang X, Yuan Z, Wang Q, Qi W, Wang W, Zhang Y, Xu J and Xu H. (2010) Two-step liquid hot water pre-treatment of *Eucalyptus grandis* to enhance sugar recovery and enzymatic digestibility of cellulose. *Bioresource Technology*, **101**: 4895-4899.

Yu G, Yano S, Inoue H, Inoue S, Endo T and Sawayama S. (2010) Pre-treatment of Rice Straw by Hot-Compressed Water Process for Enzymatic Hydrolysis. *Applied Biochemical Biotechnol*, **160**: 539-551.

Zhang H, Oweis TY, Garabet S and Pala M. (1998) Water-use efficiency and transpiration efficiency of wheat under rain-fed conditions and supplemental irrigation in a Mediterranean-type environment. *Plant and Soil,* **201**: 295–305.

Zhang H, Fangel JU, Willats WGT, Selig MJ, Lindedam J, Jorgensen H and Felby C. (2013) Assessment of leaf/stem ration in wheat straw feedstock and impact on enzymatic conversion. *GCB Bioenergy*, 1-7.

Zhao R, Wu X, Seabourn BW, Bean SR, Guan L, Shi YC, Wilson JD, Madl R and Wang D. (2009) Comparison of waxy vs nonwaxy wheats in fuel ethanol fermentation. *Cereal Chemistry*, **86**(2): 145-156.