Late summer planting of winter wheat (Triticum aestivum L.) into tilled fallow is necessary for production of maximum yield in many areas of the low precipitation (<30 cm, annual) zone of the inland Pacific Northwest region of the United States. Farmers plant deep to reach moisture adequate for germination and emergence. The coleoptile of deep-planted wheat remains underground. The first leaf protrudes through the tip of the coleoptile and usually emerges about 10 to 12 d after planting. Emergence may be jeopardized by below-surface buckling of the first leaf. Buckling of the first leaf occurs when its exerted force cannot overcome the density or strength of overlying soil. Small, single-point load cells were used to measure force exerted by the first leaf of one semidwarf cultivar (‘Norwest 553’) and two standard-height cultivars (‘Farnum’ and ‘Finley’) as they emerged from a deep planting depth (100 mm) in a small containerized volume of soil. The average maximum before-buckling emergence force (BBEF) of Norwest 553 and Finley was 12.2 and 11.6 g, respectively. The corresponding value for Farnum (10.9 g) was statistically similar to the BBEF of Finley and less than that of Norwest 553. The measured difference between Farnum and Norwest 553 may be a consequence of variation in coleoptile diameter. Maximum diameter measurements of 1.6 to 1.7 mm were made near the base and in the middle of the Norwest 553 coleoptile. New knowledge generated from this research can be used to make decisions about the focus of future investigations that deal with poorly understood mechanisms responsible for emergence of wheat from deep planting depths.
semidwarf cultivars (Vogel et al., 1956, 1966; Morrison and Vogel, 1962; Vogel, 1964; Vogel and Peterson, 1974). These short-statured cultivars responded to increased rates of N fertilizer, resisted lodging, and set new grain yield records, but farmers in the low precipitation zone were unable to take full advantage of them because they did not emerge well from deep planting depths. Poor emergence was the result of a pleiotropic effect between reduced plant height and shortened coleoptiles. Wheat breeders now use a coleoptile length screening protocol to evaluate germplasm of predominantly tall lines targeted for the low precipitation zone. There is a limit to what can be accomplished from this kind of protocol, however, as coleoptile length accounts for only 28% of the variation in emergence from deep planting depths (Mohan et al., 2013).

Successful emergence is presumed to be a function of force. The force exerted by emerging seedlings was studied in the 1950s (Williams, 1956), 1960s (Williams, 1963; Arndt, 1965), and again in the 1980s (Gerard, 1980), but this work focused on methodology and/or crops such as cotton (Gossypium hirsutum L.), alfalfa (Medicago sativa L.), crimson clover (Trifolium incarnatum L.), red clover (Trifolium pratense L.), guar bean (Cyamopsis tetragonoloba (L.) Taubert), and peanut (Arachis hypogaea L.). A study on the force exerted by the emerging coleoptile of wheat, planted at a “normal” (shallow) planting depth, was described in the literature in 1990 (Bouaziz et al., 1990). The objective of this research was to conduct a preliminary test of our hypothesis, and a “widely held belief,” that the first leaf of taller (standard-height) cultivars emerges with greater force than the first leaf of semidwarf cultivars.

MATERIALS AND METHODS

Overview
Collection of emergence force data was initiated in 2014, after trial-and-error development of a suitable testing protocol, and continued into 2015. Load cells were used to measure force exerted by first leaves as they emerged from a deep planting depth in a small containerized volume of soil. Coleoptile diameter, evaluated in a separate investigation conducted in 2016, was determined because we believed this morphological characteristic might affect emergence force. It was not our intent to describe this effect. We wanted to know if there were differences among cultivars used in our experiment.

Germplasm and Seed Selection
Cultivars were selected because they “cover” a broad range of coleoptile lengths (Table 1), and they are part of a valuable germplasm resource for Pacific Northwest wheat breeders. Seed was harvested from plots in one block (15 × 30 m²) of a 2013 field experiment in Morrow County, Oregon (45.58° N, 119.59° W). The three cultivars were ‘Farnum’ (Cavalieri, 2008), ‘Finley’ (Donaldson et al., 2000), and ‘Norwest 553’ (Flowers et al., 2008). Farnum and Finley are tall (standard-height) cultivars. Norwest 553 is a much shorter (semidwarf) cultivar. The short stature of Norwest 553 is a consequence of an intended mutation in the Rht-B1 gene that interferes with the action or production of a plant growth hormone known as gibberellin. Farnum and Finley were developed by breeders at Washington State University and released in 2008 and 1997, respectively. Norwest 553, a product of a cooperative venture between Oregon State University and Nickerson UK, was released in 2007.

Farnum and Finley have been planted extensively in the Horse Heaven Hills area of south-central Washington. Norwest 553 was planted on many farms in eastern Oregon during the 5 yr since its release in 2007. It has been replaced, in more recent times, by a related cultivar less susceptible to winterkill.

Seed was removed from sampling bags used to store grain from the 2013 harvest. Shriveled, cracked, or broken seed, and seed with damaged embryos, was discarded. Ninety-six seeds of each cultivar were weighed individually. Seeds having a weight within one standard deviation of the mean were used for research described in this publication.

Collection and Preparation of Soil
The soil used in this experiment was a Ritzville silt loam (course-silty, mixed, superactive, mesic Calcic Haploxeroll). Collected soil was removed from the 0–100-mm depth of a tilled (summer-fallow) farm field (45.50° N, 119.87° W). This soil, representative of many dryland hectares in the Columbia Plateau region of the inland Pacific Northwest, is mostly single-grained and 31% sand, 59% silt, and 10% clay. It has an organic C content of 5.5 g kg⁻¹, a pH of 7.1, and a cation exchange capacity of 12 cmol kg⁻¹.

Water was added to half the soil to bring the gravimetric water content up to 15%. Moistened soil was mixed by hand and divided among 10 large, heavy-duty (3 mm thick) construction-grade plastic bags. Remaining soil was passed through a 2-mm sieve to remove clods, air dried at 20°C for 10 d, and then placed in 20-L buckets. Plastic bags containing moist soil were sealed tight. Air-dried soil in buckets was covered with loose fitting lids. Soil in bags and buckets was stored in a cool (10°C) room until planting.

Planting Containers, Seedzone Details, and Seed Placement
A generic, thin-walled, 4-cm × 30-cm plastic bag was compressed into the bottom of a 165-cm³ planting cone (SC10 Ray Leach Cone-tainers) to plug drainage holes. A 100-mm-thick layer of moist (15% gravimetric water content) soil was placed on top of the plastic and packed, using a wooden dowel, to an approximate

<table>
<thead>
<tr>
<th>Cultivar</th>
<th>Stature</th>
<th>Plant height†</th>
<th>Coleoptile length†</th>
</tr>
</thead>
<tbody>
<tr>
<td>Farnum</td>
<td>Standard-height</td>
<td>88</td>
<td>93</td>
</tr>
<tr>
<td>Finley</td>
<td>Standard-height</td>
<td>90</td>
<td>75</td>
</tr>
<tr>
<td>Norwest 553</td>
<td>Semidwarf</td>
<td>72</td>
<td>53</td>
</tr>
</tbody>
</table>

† Plant height and coleoptile length are traits influenced by genetic makeup and environmental factors.
bulk density of 1.3 g cm\(^{-3}\). A single wheat seed was carefully pressed, crease side down, into the moist soil. Twenty-five millimeters of moist soil was placed on top of the seed, followed by a 75-mm-thick layer of sieved and air-dried soil.

**Laboratory Setup and Collection of Emergence Force Data**

Each planting cone containing soil and seed was inserted into another (empty) cone held upright in the center of a bucket filled with sand (Fig. 1A). Each bucket was raised from the laboratory bench using a scissor jack until the soil surface, at the lip of the planting cone, was almost in contact with a circular pad glued to the bottom of a small open-ended plexiglass box (Fig. 1B). The pad material (Part no. 703142, True Value Company) provided a rough surface that prevented sideways growth of the emerging first leaf. The plexiglass box was used to connect the rough surface pad to a single point (LCAE-600G, OMEGA) load cell. The load cell was made stationary by attachment to a piece of aluminum tubing connected to a 25-cm-diam. steel rod welded to a heavy-duty wrought-iron base plate.

The weight of the plexiglass box and rough surface pad, attached to each load cell, ranged from 48 to 94 g and was the baseline gravitational force value of output. Variance in baseline gravitational force was due to differences in the mass of fabricated plexiglass boxes and the quantity of glue used to attach them to rough surface pads. The baseline reading was reduced by an amount equal to the upward force of the emerging first leaf. The upward force is reported using units of mass (g), instead of dynes, because we believe doing so is intuitively logical. It is also consistent with what has been done in the past (Williams, 1956, 1963; Arndt, 1965; Gerard, 1980; Bouaziz et al., 1990).

First leaf emergence force data were collected from a randomized complete block design with three treatments (cultivars) and nine replications. Each replication was a block. Each block was defined as a “run.” Each run was conducted for 10 d. Runs were used as the blocking term to remove the influence of ambient (air) temperature and/or soil moisture differences that occurred during the experiment. Emergence force was measured at 2-min intervals until 8 to 10 h after first leaves buckled (Fig. 2). Buckling is a collapse, deformation, and folding of the first leaf that occurred while it pushed against the load cell. The same below-surface phenomenon occurs in the field. It is a problem when the force exerted by the first leaf cannot overcome the density or strength of overlying soil. Before-buckling emergence force (BBEF) was measured after a rapid 9- to 14-g increase and just before a sudden 3- to 7-g decrease in force readings—parameters validated during work conducted prior to the start of this experiment. Data were collected using six load cells (two randomly selected load cells per cultivar) during each run. Emergence force data from the two load cells for each cultivar were averaged and recorded as one observation.

**Coleoptile Diameter**

Coleoptile diameter was determined using a 0- to 25-mm ratchet stop 102 to 301 micrometer (Mitutoyo America Corporation). Diameter measurements were made 5 mm above the base, in the middle, and 5 mm below the tip of the coleoptile.

Diameter measurements in the middle of the coleoptile were made at a point equidistant from 5 mm above the base and 5 mm below the tip. Data were obtained from 10-d-old seedlings propagated in the dark, in folded and moistened 25-cm × 38-cm, heavy-grade germination paper (Anchor Paper Company), and at constant temperature (22°C) (Mohan et al., 2013). Data were collected during five runs. Measurements from
a random selection of 10 of the 15 coleoptiles of each cultivar (per run) were averaged and recorded as one observation.

**Statistical Analysis**
The Statistix 10 program (Analytical Software, 2013) was used to interpret independent and normally distributed data. The assumption of homogeneity of variance was verified using Bartlett’s test (Bartlett, 1937; Li et al., 2015). Sources of variation in BBEF and coleoptile diameter were determined with a single-factor ANOVA model for a balanced randomized complete block design. Treatment means were compared using Tukey’s honestly significant difference (α = 0.05) test (Carmer and Walker, 1985).

**RESULTS AND DISCUSSION**
The first leaf of seedlings of each cultivar began to push against the load cell 7 to 8 d after planting. This approximate time of contact occurred consistently during all nine runs. First leaf force increased in a nearly linear fashion and at a rate of 3.8 to 4.2 g h\(^{-1}\) until buckling. The average overall maximum (before buckling) force exerted by first leaves of seedlings used in this experiment was 15 to 20 g less than that exerted by the coleoptile of a bread cultivar (‘Nesma 149’) previously grown in Morocco and surrounding countries of North Africa (Bouaziz et al., 1990). It is also less than maximum force values reported for corn (Zea mays L.; Prihar and Aggarwal, 1975) and several broadleaf crop species (Williams, 1956, 1963; Gerard, 1980).

There was a significant cultivar effect on BBEF (Table 2). The average BBEF of semidwarf Norwest 553 was 12.2 g. Before-buckling emergence force of Norwest 553 was either equal to or greater than that of standard-height cultivars used in this experiment (Table 3). This outcome is intriguing because Norwest 553 has a shortened coleoptile. Its length (Table 1) is significantly less than that of Farnum and Finley (Lutcher et al., 2018). The consequence of a shortened coleoptile is the need for an increased distance of elongation of the first leaf. It seems reasonable to assume Norwest 553 could emerge with less force because its longer, below-surface first leaf might be more susceptible to buckling (Niklas, 1989, 1992; Vetter et al., 2014). Our data contradict this assumption.

The average (overall) coleoptile diameter of seedlings used in this experiment was 1.5 mm. This is 0.2 to 0.3 mm less than similar, average diameter measurements reported in 2004 for older lines from Australia or elsewhere in the world (Rebetzke et al., 2004). It is also less than an average “width” measurement obtained more...
recently from a large multiparent mapping population developed from cultivars having a spring growth habit (Rebetzke et al., 2014). There was significant among-cultivar variation in the diameter of coleoptiles (Table 2). Maximum diameter was observed near the base and in the middle of the Norwest 553 coleoptile (Table 3). The greater coleoptile diameter of this semidwarf line may have provided added stability to the emerging first leaf and could be responsible, at least in part, for enhanced BBF values. This hypothesis was not tested, but we believe it is worthy of future investigation. This potential cultivar effect is somewhat analogous to observed outcomes from research on roots of corn and soybean [Glycine max (L.) Merr.] (Bushamuka and Zobel, 1998), pea (Pisum sativum L.; Clark et al., 1999), rice (Oryza sativa L.; Clark et al., 2000), and wheat (Colombi and Walter, 2017).

CONCLUSIONS
The first leaf emergence force of Norwest 553, a semidwarf wheat with a short coleoptile, was either equal to or greater than that of standard-height (long-coleoptile) cultivars Farnum and Finley. Visual, in-the-field emergence ratings in 2013 and 2014 certified seed buying guides from Washington State University and the Washington State Crop Improvement Association are “high” for Finley and “moderate” for Farnum and Norwest 553. Discrepancy between our maximum force data and the emergence rating for Norwest 553 may be attributed to differences in the speed of emergence. This possible explanation is consistent with anecdotal observations of “slower” but “reasonable” emergence by farmers who have experimented with deep planting of this cultivar.

Greatest coleoptile diameters were measured on seedlings of Norwest 553. This was especially true for measurements near the base and in the middle of the coleoptile. The increased diameter of the Norwest 553 coleoptile may have provided added stability to its emerging first leaf and could be responsible for greater-than-average emergence force values.

Results from analysis of collected data support the idea that emergence from deep planting is a complex trait not solely controlled by genes that regulate coleoptile length. Subsequent work should focus on the correlation between coleoptile diameter and emergence from deep planting depths. Coleoptile length data should be collected from the same experiment. Coleoptile diameter and coleoptile length data could then be used in a multiple regression analysis to provide quantitative information about the combined effect of both attributes. It would be useful to know if the combined effect would allow for significantly better prediction of emergence from deep planting depths.

Conflict of Interest
The authors declare there is no conflict of interest.

Acknowledgments
We graciously acknowledge internal reviews provided by Ryan Graebner, Patrick Hayes, Russ Karow, and Robert Zemetra of Oregon State University and Arron Carter and William Schilling of Washington State University. Efforts described in this publication were made possible by funding from the Morrow County (Oregon) Board of Commissioners. We appreciate cooperation of, and feedback from, regional wheat producers.

References
doi:10.2134/agronj1962.00021962005400000045


