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Photogrammetry for the estimation of wheat biomass and harvest index

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ABSTRACT

Field-based next generation phenotyping has become of great interest to plant breeders and agricultural researchers in recent years, particularly for circumventing destructive or impractical phenotyping methods commonly used for certain traits. The non-destructive estimation of one such trait, above ground biomass (AGB), has been investigated repeatedly using 2D imagery, though little research has been conducted on 3D methods. The aims of the current study were to (i) investigate the use of readily-available consumer level digital cameras and software to estimate AGB, canopy height (CH) and harvest index (HI) of wheat plots, (ii) investigate the suitability of this data as a replacement for destructive sampling methods within a wheat breeding programme, and (iii) identify the point cloud density required for accurate estimation of AGB. To achieve this, a small plot trial of a single wheat cultivar was conducted in an irrigated nursery, at Roseworthy, South Australia. At physiological maturity plots were measured for CH and whole plots were harvested to attain AGB and threshed to measure grain yield and calculate HI. Prior to harvesting each plot was imaged using a digital camera, with these images being processed into 3D point clouds, which were subsequently used to estimate plot volume and CH. Strong correlations were observed between actual measurements of AGB, CH and HI to those estimated from point clouds. Images were processed in subset batches to determine an optimal number of images for processing. Stronger correlations between AGB and plot volume were observed when more images were processed, though as few as 48 images provided sufficiently accurate estimates of AGB. These methods were shown to be effective at estimating AGB, CH and HI and could be adopted by small scale research programmes. This study shows that a higher-throughput adaptation of this photogrammetry method could be used in phenotype intensive research such as plant breeding programmes.

1. Introduction

Above ground biomass (AGB) is a particularly troublesome trait to measure within breeding programmes due to the laborious and destructive methods needed to assess it. Despite this, AGB has been suggested as a potential trait of interest, for the improvement of grain yield, within cereal breeding programmes (Donald and Hamblin 1976; Damisch and Wiberg 1991; Sharma 1993; Richards 2000; Richards et al., 2002; Reynolds et al., 2012), particularly in relation to harvest index (HI) and radiation use efficiency.

With the rise in popularity of field-based next generation phenotyping, a number of studies have investigated commonly-available sensors, such as RGB cameras, multispectral cameras and LiDAR, to measure AGB non-destructively in field trials (Ehlert et al., 2009; Hosoi and Omasa 2009; Montes et al., 2011; Winterhalter et al., 2011; Bendig et al., 2014; Eitel et al., 2014; Amaral et al., 2015; Bendig et al., 2015; Li et al., 2015; Pittman et al., 2015; Schirrmann et al., 2016a; Schirrmann et al., 2016b).These studies have used a number of methods to estimate AGB, most commonly through canopy height or visual indices (VIs). While these studies have often shown strong relationships between AGB estimators and AGB, AGB is a complex trait and is three-dimensional (3D) in nature. Without taking account of this 3D information, estimating AGB from canopy height or VIs may be limited. It is also commonly agreed that the use of VIs can be limited due to saturation of the index (Tucker, 1977), and is therefore impractical to use at later crop growth stages or in very vigorously growing crops.

While many studies have focused on estimating AGB from two-dimensional spatial data, it is also possible to estimate AGB from 3D data. Airborne laser scanning (ALS) is a common method used in forestry research, where a LiDAR sensor is flown over the area of interest and laser returns are collected in a 3D point cloud. The point cloud can then be used for modelling and measuring, which has been successfully used as a tool to estimate forest AGB (Zolkos et al., 2013). With the success of LiDAR as a tool for measuring forest AGB, there is now keen interest in

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using LiDAR for phenotyping in agricultural research; however, the implementation of LiDAR and other similar sensors is hampered by the lack of simple data collection methods and the complexity of creating data processing pipelines. The interest in LiDAR as a research tool is the point cloud data it generates, however, this data can be collected through multiple methods and is not exclusive to LiDAR. A limited number of studies have investigated the use of point cloud data within agricultural research. However, they have not focussed on the direct estimation of AGB, instead investigating the potential to identify ears (Saeys et al., 2009), or individual plant organ area (Hosoi and Omasa, 2009).

With the increased use of Unmanned Aerial Vehicles (UAVs) as a data collection tool in many industries, including agriculture, there are now a number of readily available software packages (*e.g.* Pix4Dmapper Pro, DroneDeploy, Agisoft PhotoScan) that are capable of using red, green and blue (RGB) images to create point clouds. This is an example of photogrammetry, a method of obtaining measurements through photographs. Photogrammetrically-derived point clouds have been demonstrated to be an effective alternative to LiDAR to create a digital surface model (DSM) for forestry research (Herrero-Huerta et al., 2016) and to create DSMs for agricultural field trials (Bendig et al., 2014, 2015). While these models have been successful in estimating canopy height and have been used as a predictor for AGB, images obtained from UAVs typically have a low spatial resolution (in the context of agricultural field plots) and may not sufficiently capture the fine details of cereal crop canopies.

Photogrammetry can be utilised for the creation of point clouds, not only from UAV obtained imagery, but also from ground based images. Due to the small area of coverage, these point clouds are high fidelity and could potentially be used to estimate AGB in research plots, based on the volume of the canopy.

The objectives of this study were (i) to investigate the use of readily-available consumer level digital cameras and photogrammetry software to estimate wheat plot AGB, canopy height (CH) and HI, (ii) to investigate the suitability of this high fidelity point cloud data for replacing destructive manual measurements, within a wheat breeding programme, (iii) and, as a prelude to scaling up this method, to identify the point cloud density required for accurate estimation of AGB.

2. Methods

2.1. Site/Plant material

The study took place at the University of Adelaide, Roseworthy Campus, Australia (34°31′52.8″S 138°41′9.8″E). Plots were grown in an irrigated nursery, between November 2015 and May 2016. Plots (12) of the Australian bread wheat (*Triticum aestivum* L.) cultivar Halberd were sown in a factorial completely randomised block design, with a single factor of four target plant densities (100, 200, 300 and 400 plants/m^2). Halberd was selected based on its phenotype, as it is a slow maturing, strongly photoperiod sensitive and vernalisation insensitive, tall variety with many tillers and large biomass.

Plots were sown as 5 rows with a 17 cm row spacing, at a length of 3m. To enhance the uniformity within each plot, plots were shortened to 1.5 m in length and the northern most row was removed (due to poor germination), which reduced the total plot area to 1.02m^2.

2.2. Image capture

Plots were imaged 7 days prior to harvest, using a Canon EOS 100D digital camera. Ninety-six RGB images were taken per plot, using a three-ringed pattern of 32 images per ring, as shown in Fig. 1, with the shutter being manually triggered while navigating the perimeter of the plot. Images were taken at a focal length of 18 mm with an aperture of F8.0, shutter speed was adjusted *ad-hoc* to counteract unavoidable changes in lighting caused by variable cloud cover. Images were captured in JPEG format at a resolution of 5184 × 3456 pixels. A generic clay brick, measuring 230 × 110 × 75 mm, was included in each set of plot images to provide a known scale. In circumstances where the clay brick did not render properly point clouds were scaled on the space between plant rows.

2.3. Image processing

Three-dimensional point clouds were created for each plot from the set of 96 RGB images, using Pix4Dmapper Pro (Pix4D, 2016) photogrammetric software, running on a Windows 10 P, with 32 GB of RAM and a quad-core 4.0GHZ processer. Images were imported to Pix4D and then optimised and matched to create 3D point clouds, using ½ scale images, optimal point density and a minimum of three required matches. Appropriate scales were applied to each cloud and results were re-optimised and processed. Finally, a digital surface model (DSM) was created for each point cloud, using Pix4D's DSM processing tool, using methods of inverse distance weighting with noise filtering and a 'sharp' surface smoothing filter.

In addition to the point clouds produced from the 96-image set, a further five sets of point clouds were created for each plot, using subsets of 80, 64, 48, 32 and 16 images from the full set. Image subsets of 32 and 64 comprised of a single, or two 32-image rings respectively, with the subsets of 16, 48 and 80 comprised of half, one and a half, and two and a half, 32-image rings respectively. To create the 16-image half rings, images were removed from one side of the plot, leaving 16 images along one side. This method was selected as systematic removal of every second image, resulted in poor processing results due to insufficient image overlap (data not shown).

As a substitute for AGB the volume of plant material within individual plots was calculated with Pix4D's inbuilt volume tool, hereafter referred to as point cloud volume (PCV). For this process, individual polygons were drawn approximately 5 cm above the base of each plot (Fig. 2), with volume between this and the previously computed DSM of the plot being calculated automatically. Polygons were drawn at a height of 5 cm to ensure they were located above the furrow ridges in each plot to eliminate potentially confounding objects, such as rocks and clods of soil, during volume estimation.

Canopy height (CH) was measured from point clouds created with the full 96-image set, using Pix4D's inbuilt measurement tool. Height was measured at four randomly selected points within the top layer of canopy, with the average of these points representing overall canopy height and being referred to as point cloud canopy height (PCH) for the remainder of the study.

2.4. Manual measurements and sampling

Canopy height was measured with a ruler one day prior to image capture. Four randomly selected representative plants were measured within each plot. Measurements were taken from the base of each plant to the uppermost spikelet, and averaged to best represent canopy height.

Entire plots were harvested and AGB measured after physiological maturity (Zadoks growth stage 92–93) (Zadoks et al., 1974), with plants being removed at ground level. Plant material from each plot was individually weighed to attain a dry AGB weight. Plots were harvested on a dry summer day, inducing low crop moisture levels and negating the need for oven drying of material.

Above ground biomass samples from each plot were individually threshed, with the grain being retained and weighed to determine grain yield and calculate HI for each plot. Harvest index was calculated as grain yield per plot (kg)/AGB per plot (kg). Predictions of HI were also calculated from PCV measurements, by converting these to an AGB estimate, using the equation of linear regression between the two, *i.e.*

$$HI = \text{grain yield per plot (kg)}/(M^{*}\text{AGB per plot (kg)} + C) \quad (1)$$