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Optimizing accuracy of protocols for measuring dry matter and nutrient yield of forage crops

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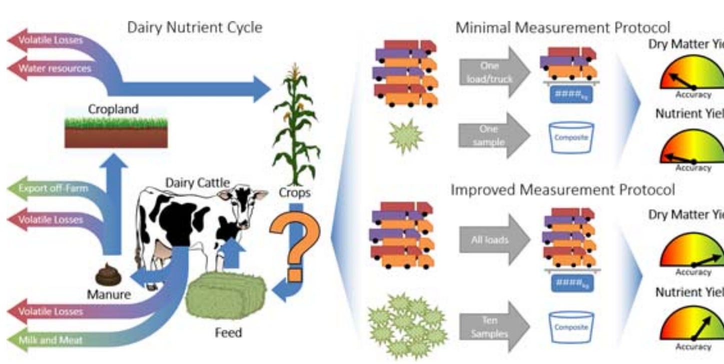
HIGHLIGHTS

- Dairy farmers need to accurately measure forage yield to avoid nutrient pollution.
- Achievable accuracy of dry matter and nutrient yield measurements was quantified.
- Simulations resampled full yield datasets to quantify then propagate uncertainty.
- Sufficient accuracy is achieved by weighing all loads and increasing load samples.
- Farmers and regulators should consider the accuracy of practicable measurements.

GRAPHICAL ABSTRACT



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ABSTRACT

Farmers around the world must precisely manage nutrients applied to and removed from crop fields to maintain production and without causing nutrient pollution. This study is the first to quantify the baseline accuracy of current industry measurement protocols and achievable accuracy from intensifying protocols for measuring dry matter (DM), nitrogen (N), potassium (K), and phosphorus (P) yields from forage crops harvested for silage. The 'true' DM and nutrient yields of three fields each of corn, sorghum, and small grain were intensively measured by weighing and sampling every truckload of harvested forage. Simulations quantified the accuracy of practical sampling protocols by repeatedly subsampling the complete dataset for each field to measure average truckload weight and average DM and nutrient concentrations. Then uncertainty was propagated to DM, N, P, and K yield calculations using standard error equations. Yields measured using current industry protocols diverged from the true yields of some fields by more than ±40%, emphasizing the need for improved protocols. This study shows that improving average DM and nutrient concentration measurements is unlikely to improve accuracy of yield measurements if average load weight is not precisely measured. Accuracy did not come within 27% of true yields without weighing all truckloads on some fields even when DM and nutrient concentration measurements were perfectly accurate. Once all truckloads were weighed, the timing of forage sample collection to measure average DM concentration had the greatest impact on accuracy; precision improved by an average of

Abbreviations: DM, dry matter; N, nitrogen; P, phosphorus; K, potassium; ADMC, average dry matter concentration; ALW, average load weight; ANC, average nitrogen concentration; APC, average phosphorus concentration; AKC, average potassium concentration; CI, confidence interval; CIR, confidence interval range; ANOVA, analysis of variance.

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6.2% when >3 samples were evenly spaced throughout the harvest compared to the same number of consecutive samples. All crop fields are affected by within field variation in growing conditions that results in heterogeneity in DM and nutrient yield. Globally, this study provides foundational methodology to quantitatively evaluate and improve yield measurement protocols that ultimately support sustainable crop production.

1. Introduction

Cropland has been targeted globally as a source of nutrient pollution (Harter et al., 2012; Oenema et al., 2007; Tamminga, 2003). About 30% of global arable land is used to grow feed for livestock and about 50% of the biomass consumed by livestock are forages, which are often preserved as silage (Herrero et al., 2013; Steinfeld et al., 2006). Farmers can maintain desired forage yields while minimizing nutrient pollution by utilizing nutrient management planning (Beegle, 2000). Accurately measuring nutrient and dry matter (DM) yield of forage crops is essential for the successful execution of nutrient management plans. In addition to environmental stewardship, accurate determination of DM and nutrient yields are important to managing feed inventories and forage purchases or sales.

Around the world, ensiling is one of the most common ways to preserve forage. To produce silage, farmers ideally harvest small grains (wheat *(Triticum aestivum)*, oats, triticale, etc.), corn (*Zea mayz*), sorghum (*Sorghum bicolor*) and other forages when the crop is wet (55–75% moisture) and grains are immature. At harvest, the entire plant is chopped (to <1.25 cm) and then packed tightly into piles, bunkers, bags, or silos to anaerobically ferment. To quantify DM and nutrient yield from each field, farmers typically weigh truckloads of freshly chopped forage and collect grab samples, which are sent to a commercial lab for DM and nutrient analysis (Heguy et al., 2016). Recommended protocols based on expert judgement recognize that collecting more grab samples and weighing more trucks will lead to more accurate quantification of yield (Glunk et al., 2016; Kersbergen and Bosworth, n.d.; Ketterings et al., 2013; Lodsdon et al., 2008). Besides these qualitative recommendations, there are no available data to support how many forage samples or trucks must be collected or weighed, respectively, to accurately measure DM and nutrient yields. Neither the baseline accuracy of typical industry practices nor the quantitative gains from more rigorous sampling protocols are known.

The accuracy of DM and nutrient yield measurements has important consequences when data are used to judge regulatory compliance and efficacy (Oenema et al., 2003). Globally, farmers are required to measure nutrient application and removal to comply with regulations to control nutrient pollution (No. 2349, 2008; Schröder and Neeteson, 2008). Under these regulations, required measurements of nutrient and DM yields must be supported by data that show their accuracy is sufficient to evaluate regulatory compliance and efficacy.

Accurate quantification of DM and nutrient yields allow farmers to effectively manage feed inventories and forage sales and purchases. Many farmers either purchase or grow forage to meet the needs of their cattle. DM concentration of forage is integral in setting a fair price and ensuring sufficient quantities of feed are available. Additionally, nutrient and DM concentrations of silages are important aspects of feed quality and influence diet formulation for cattle. Uncertainty in forage yield measurements may negatively affect a farmer's ability to procure sufficient forage and feed their cattle cost effectively.

The objectives of this study were threefold. First, to establish the baseline accuracy of current industry practices for measuring the average truck weight, DM concentration, and nutrient concentration of forage harvested for silage. Second, to propagate the uncertainty of harvest measurements to calculations of DM and nutrient yield. Third, to quantify and compare the reduction in uncertainty from intensifying measurement protocols. Establishing both baseline and achievable accuracy of silage yield measurements will allow farmers and regulators to design measurement protocols that inform production and nutrient management goals.

2. Methods

2.1. Study environment

2.1.1. Local regulations

In California's Central Valley regulators have issued a series of regulations to reduce nitrate load to groundwater from agricultural land, starting with that managed by dairy producers. Dairy producers are required to monitor and report all nitrogen (N), phosphorus (P), and potassium (K) applied to and removed from each field where manure is applied. Compliance is judged based on the ratio of N applied to N removed (N Ratio) from each eligible field, which must not exceed 1.4 (R5-2007-0035, 2007; R5-2013-0122, 2013).

2.1.2. Study fields

Silage is a staple in the diet of the 1.8 million dairy cattle in California, most of which live in the Central Valley (California Department of Food and Agriculture, 2017). Study fields were selected to represent typical forage cropping systems and harvest practices in the Central Valley of California. Nine forage harvests across California's Central Valley were monitored; three fields each of corn, small grain (predominately wheat), and sorghum. Fields were distributed across counties and were managed by different dairy producers (Table 1).

2.1.3. Measuring true yields

The DM, N, P, and K yields from each field were intensively measured. Each truckload was weighed as it entered the facility and sampled when the freshly chopped forage was deposited near the pile. Four to six grab samples were collected from each load and composited to form the load sample. Each load sample was placed in a zip-lock bag, air evacuated, and stored on ice during transportation to labs at the University of California, Davis. Load samples were stored at 4 °C until further analyses.

Dry matter concentration was determined for each individual load sample by drying 25–40 g subsamples in triplicate, in a 55 °C oven for 24 h, weighing the dry residual, and dividing by wet weight. Ten load samples were selected randomly from each field and a representative subsample of each was sent to a commercial laboratory to determine N, P and K concentration according to the University of California Davis Analytical Lab or the Manure Analysis Proficiency Program protocols (Holstege et al., 2010; Peters et al., 2003). Only truckloads with confirmed load weights and corresponding DM analysis were included in the final dataset.