

where:

AF = area factor, ground area occupied per plant (ft², m²)

L_s = sample row length

W_r = sample row width

N_i = number of plants in the sample row

One method for determining AF is by throwing a 10' length of PVC pipe in the row middle and counting the number of plants in the row and one adjacent. Some investigators employ the "random" throw which is okay if in-row plant spacing is relatively uniform across the sampling area. However, if there are skips in the row due to uneven emergence or post-emergence plant mortality then it's important to account for these gaps as AF will over estimate nutrient accumulation when scaling to acres or hectares. A sound practice is to throw the pipe in an area of the row that looks representative of the whole plot, as opposed to a completely random throw. A second method to determine AF, described in **Appendix A**, measures the specific sample area, not stand counts. In the following exercise we employ Equation [2] to calculate the AF and sample area. This method does not require harvesting adjacent plants in a row.

Example 1. Maize biomass was collected by cutting six plants just above the brace roots and separating in two fractions: stover (stem + sheath + leaves + tassel + husk+ cob), and grain. The stover was shredded and a homogenous sub-sample oven-dried for moisture determination. The following measurements were reported:

Table 1.

Total stover weight, moist	Stover sub-weight, moist	Stover sub-weight, oven-dry
360.0 g	125.7 g	85.4 g

After shelling, whole grain kernels were weighed "as is" in a moist state and oven-dried at 90° C until a constant weight was achieved. The following measurements were reported:

Table 2.

Moist grain weight, shelled	Oven-dry weight
424.0 g	382.4 g

A sample of the stover and grain were submitted to a laboratory for nutrient analysis. The following concentrations were reported:

Table 3.

Fraction	Nutrient			
	%N	%P	%K	ppm Zn
Stover	0.72	0.05	2.07	21.7
Grain	1.26	0.22	0.36	22.0

Stand count for the sampled row and one adjacent was: 114, 113 per row. Plot length was 60' and row spacing 30".

Armed with this information, let's calculate the following:

- (1) % moisture content (MC) of stover and grain
- (2) mass of dry stover and grain solids
- (3) mass of the "as is" moist grain sample adjusted to 15.5% moisture content



Measuring Biomass, Nutrient Utilization, and Yield in a Maize Crop Part II.

Preamble

In Part I of this Agronomy Note, we demonstrated the importance of maize to the global food supply, and how increasing production in an environmentally sound and profitable way depends on measuring quantities like crop biomass, nutrient utilization, and grain yield. In Part II we'll show how to take the six crop measures in Part I and turn them into insights about the maize cropping system. To that end, we'll need the nutrient concentration from two maize tissue fractions: stover and kernels. Nutrient concentration can be determined analytically by laboratory testing. Agencies like the North Carolina Department of Agriculture (NCDA), University, and private labs are equipped to test a variety plant, soil, water, and waste samples. Check with individual labs about test methods, sample submission, and processing requirements. Since the cost associated with tissue testing is not inconsiderable, attention should be given to compositing samples whenever possible, for example, as was done for stover and kernels in Part I.

Procedure

The general formula for nutrient accumulation is:

$$MA = \sum_{i=1}^n f_i \times C_i \quad [1]$$

where:

MA = mass accumulation

Σ = sum of the products $f_i \times C_i$

f_i = mass dry fraction of plant tissue (lbs., kg)

C_i = concentration of nutrient in f_i (mg kg⁻¹, %, ppm)

Laboratory plant tissue tests are usually highly precise. The main sources of error calculating mass accumulation, MA , are in the measurement of mass dry fraction of plant tissue; whether mass fraction is measured on individual plants or averaged; and, determination of the ground area factor when scaling to acres or hectares.

The ground area factor requires knowledge of the number of plants in the sample area and in-row spacing. The most accurate way to obtain in-row spacing is by counting the number of plants in the whole plot or portion sampled. This can be done manually with hand-held counting devices, or by analyzing digital unmanned aerial vehicle (UAV) imagery for which there are numerous well-vetted algorithms for precisely counting plant population. The general formula for calculating the ground area factor is:

$$AF = \frac{L_s \times W_s}{N_i} \quad [2]$$

- (4) total dry biomass in pounds per acre and kilograms per hectare
- (5) grain yield in bushels per acre at 15.5% moisture content
- (6) above-ground mass accumulation of N, P, K, and Zn in the stover and grain fractions individually and sum of the two fractions

Solution (1) % moisture content (MC) is given by:

$$\% MC = \frac{\text{mass of water}}{\text{mass of moist sample}} \times 100 \quad [3]$$

where the mass of water in the numerator is:

$$\text{Moist mass} - \text{dry mass} = \text{mass of water}$$

Note that in Equation [3] the denominator is the field moist "as is" mass of plant tissue, whose moisture content per unit mass is thereby determined. This is known as "wet basis" moisture content, which is always a fractional value ranging from 0 to 100%. Moisture content can also be calculated on a "dry basis" or ratio value that can exceed 100%. Although wet and dry basis moisture contents are interconvertible, it is important to know which basis has been used because the results are incomparable. In the commodities trade, the moisture content of agricultural materials and food products is usually expressed on a wet basis, which should not be confused with "fresh", "air-dry", "oven-dry" mass, or "dry matter". See **Appendix B** for details on moisture content, the relationship between wet and dry basis, and expressions of wet and dry mass of a substance. In this exercise, we'll convert mass fresh weight to oven-dry weight.

From Table 1, subtract the oven-dry stover sub-weight from moist sub-weight:

$$125.7 - 85.4 = 40.3 \text{ g H}_2\text{O in moist stover.}$$

$$\% \text{ MC stover} = 40.3 / 125.7 \times 100 = 32.1\% \quad \checkmark$$

From Table 2, subtract the oven-dry weight of shelled grain from its moist weight:

$$424.0 - 382.4 = 41.6 \text{ g in moist grain.}$$

$$\% \text{ MC grain} = 41.6 / 424 \times 100 = 9.8\% \quad \checkmark$$

Solution (2) Mass of solids at a specific degree of wetness is given by:

$$\text{Mass 'dry' solids} = \text{Moist mass} \times \frac{100 - \% MC}{100 - \% Dry} \quad [4]$$

where %MC is the moisture content per Equation [3], and %Dry is the moisture content at a specified degree of wetness. When %Dry = 0, the equation simplifies to:

$$\text{Mass 'dry' solids} = \text{Moist mass} \times (1 - \% MC_{dec})$$

where %MC_{dec} is the moisture content decimal percentage.

For the stover fraction, total mass dry (0% MC) solid weight is:

$$360 \text{ g} \times (1 - 0.321) = 244 \text{ g} \quad \checkmark$$

And for the grain fraction, mass dry solid weight is:

$$424 \text{ g} \times (1 - 0.098) = 382 \text{ g} \quad \checkmark$$

Solution (3) We can use Eq. [4] to adjust the weights to any % MC. For maize grain, 15.5% is the degree of wetness identifying a bushel of grain in the trade. The weight of a field moist grain sample at 15.5% moisture content is given by:

$$\begin{aligned} \text{Mass weight @ 15.5\% MC} &= 424 \text{ g} \times \frac{100 - 9.8}{100 - 15.5} \\ &= 452.6 \text{ g} \end{aligned}$$

Solution (4) Dry biomass per acre is given by:

$$\frac{\text{lbs.}}{\text{acre}} = \text{g dry mass} \times \frac{\text{lb}}{453.6 \text{ g}} \times \frac{43,560 \text{ ft}^2}{\text{acre}} \times \frac{1}{SA \text{ ft}^2}$$

Where SA is the sample area in square feet. The sample area is calculated from the area factor:

$$SA = AF \times \text{sample number}$$

$$AF = \frac{60 \text{ ft} \times 5 \text{ ft}}{114 + 113}$$

$$AF = \frac{300 \text{ ft}^2}{227}$$

$$AF = 1.322 \text{ ft}^2$$

$$SA = 1.322 \text{ ft}^2 \times 3$$

$$SA = 3.966 \text{ ft}^2$$

For stover, dry biomass production is:

$$\begin{aligned} \frac{\text{lbs.}}{\text{acre}} &= 244 \text{ g} \times \frac{\text{lb}}{453.6 \text{ g}} \times \frac{43,560 \text{ ft}^2}{\text{acre}} \times \frac{1}{3.966 \text{ ft}^2} \\ &= \frac{5,908 \text{ lbs.}}{\text{acre}} \end{aligned}$$

And for grain:

$$\begin{aligned} \frac{\text{lbs.}}{\text{acre}} &= 382.4 \text{ g} \times \frac{\text{lb}}{453.6 \text{ g}} \times \frac{43,560 \text{ ft}^2}{\text{acre}} \times \frac{1}{3.966 \text{ ft}^2} \\ &= \frac{9,259 \text{ lbs.}}{\text{acre}} \end{aligned}$$

Total biomass is the sum of the two fractions:

$$5,908 \text{ lbs./acre} + 9,259 \text{ lbs./acre} = 15,167 \text{ lbs./acre} \quad \checkmark$$

Kilograms per hectare (kg/ha) is given by:

$$\begin{aligned} \frac{\text{kg}}{\text{hectare}} &= \frac{\text{lbs.}}{\text{acre}} \times 1.12 \\ \frac{\text{kg}}{\text{hectare}} &= \frac{15,167 \text{ lbs.}}{\text{acre}} \times 1.12 \\ &= \frac{16,987 \text{ kg}}{\text{hectare}} \text{ or } \frac{17 \text{ Mg}}{\text{hectare}} \quad \checkmark \end{aligned}$$

where 1 Mg = 10⁶ grams or 1,000 kg. The conversion factor 1.12 can be derived via unit factor analysis (not shown).

Solution (5) Grain yield in bushel per acre (bu/acre) can be calculated from mass dry weight of grain:

$$\begin{aligned}\frac{bu}{acre} &= \frac{\frac{9,259 \text{ lbs.}}{acre}}{0.845 \times \frac{56 \text{ lbs.}}{bu}} \\ &= 196 \frac{bu}{acre} \quad \checkmark\end{aligned}$$

Or alternatively, from the mass of grain @ 15.5% MC:

$$\begin{aligned}\frac{bu}{acre} &= \frac{43,560 \text{ ft}^2}{acre} \times \frac{1}{3.966 \text{ ft}^2} \times 452.6 \text{ g} \times \frac{lb}{453.6 \text{ g}} \times \frac{bu}{56 \text{ lbs.}} \\ &= 196 \frac{bu}{acre} \quad \checkmark\end{aligned}$$

Solution (6) The aboveground mass accumulation of nutrients N, P, K, and Zn is given, in turn, by Equation [1]:

Stover N: 5,908 lbs./acre \times 0.72/100 = 42.5 lbs. N/acre

Grain N: 9,259 lbs./acre \times 1.26/100 = 116.7 lbs. N/acre

Total aboveground mass of N accumulated:

$$42.5 + 116.7 = 159.2 \text{ lbs. N/acre} \quad \checkmark$$

Stover P: 5,908 lbs./acre \times 0.05/100 = 3 lbs. P/acre

Grain P: 9,259 lbs./acre \times 0.22/100 = 20.4 lbs. P/acre

Total aboveground mass of P accumulated:

$$3 + 20.4 = 23.4 \text{ lbs. P/acre} \quad \checkmark$$

Stover K: 5,908 lbs./acre \times 2.07/100 = 122.3 lbs. K/acre

Grain K: 9,259 lbs./acre \times 0.36/100 = 33.3 lbs. K/acre

Total aboveground mass of K accumulated:

$$122.3 + 33.3 = 155.6 \text{ lbs. K/acre} \quad \checkmark$$

Stover Zn: 5,908 lb/acre \times 21.7/10⁶ = 0.13 lb. Zn/acre

Grain Zn: 9,259 lb/acre \times 22/10⁶ = 0.20 lb. Zn/acre

Total aboveground mass of Zn accumulated:

$$0.13 + 0.20 = 0.33 \text{ lb. Zn/acre} \quad \checkmark$$

Mass Balance and Nutrient Indicators

If we applied 180 lbs. N/acre at the beginning of the season, what is the mass balance assuming 100% fertilizer N uptake?

Answer: 180 – 158.6 = +21.4 lbs. N/acre.

Where did the surplus 21.4 lbs. N/acre go?

Answers might include leaching below the root zone into groundwater (NO₃-N is mobile in the soil and potentially a pollutant); under saturated conditions, i.e., poor internal drainage combined with excess precipitation, NO₃-N volatilizes to gaseous N₂, producing nitrous oxide (N₂O), a process that contributes to global warming; and, a fraction may be captured in the microbial biomass, which is constantly cycling.

Bottom line: interpretation of nutrient mass balance depends on knowledge of the specific chemical interactions of nutrients in the soil. A positive balance may build reserves for some nutrients whereas for others, like nitrogen, plant-available reserves are more fleeting (one reason why routine soil fertility reports do not include nitrogen). A negative mass balance, if allowed to persist over cropping cycles, will exhaust the supply of nutrients in the soil.

We can use mass balance to calculate the Partial N Balance (PNB, Dobermann 2007):

$$\begin{aligned}\frac{\text{Crop N}}{\text{Fertilizer N}} \\ \frac{\frac{159.2 \text{ lbs. N}}{acre}}{\frac{180 \text{ lbs. N}}{acre}} = 0.88\end{aligned}$$

PNB indicates the share of N removed by the maize crop relative to applied N. Values >1 indicate soil mining, whereas values <1 as in our case, indicate N application in excess of crop demand. Balancing nutrient supply and demand in any cropping system is tricky as it often depends on factors outside the control of the operator. Thus achieving a PNB = 1 year after year is unrealistic. But comparatively, the values can inform us about the efficacy of agronomic inputs under different exposures.

The share of fertilizer N allocated to yield is described by Crop Nitrogen Use Efficiency (NUE_{crop}, Martinez-Feria 2018):

$$\begin{aligned}\frac{\text{Yield N}}{\text{Fertilizer N}} \\ \frac{\frac{116.7 \text{ lbs. N}}{acre}}{\frac{180 \text{ lbs. N}}{acre}} = 0.65\end{aligned}$$

NUE_{crop} represents the fraction of fertilizer N removed from the system; the balance, 0.35, is returned as organic residue (stover) or inorganic fertilizer N:

$$180 \text{ lbs. N/acre} \times 0.35 = 63 \text{ lbs./acre N (rounded)}$$

Alternatively, we can adapt the Yield N/Fertilizer N ratio above to define Partial Factor Productivity (PFP, Dobermann 2007):

$$\begin{aligned}\frac{\text{Yield}}{\text{Fertilizer N}} \\ \frac{\frac{196 \text{ bu}}{acre}}{\frac{180 \text{ lbs. N}}{acre}} = \frac{1.09 \text{ bu}}{\text{lb N}}\end{aligned}$$

PFP measures input use efficiency expressed as yield per unit input, i.e. bushels produced per pound of fertilizer N applied. PFP and its reciprocal, lb N/bu, are commonly used to assess yield goals in determining nitrogen rates. In practice, PFP is strongly influenced by soil type, climate, and cropping rotation, often blurring the relationship between PFP and economic yield (Wortman et al. 2019). Nonetheless, PFPs are widely utilized in the trade, e.g. "one bushel of expected yield requires *x* pounds of N". At one time, PFP for maize was approximately 1.25 bu/lb

N, but nowadays with improved genetics and other factors PFPs around 0.80 can maximize profitability. Another benefit of PFP is that it doesn't involve determining tissue nutrient concentration. So it can be used to compare cropping efficiency over space and time at no cost apart from monitoring yield and fertilizer N inputs.

Another indicator is Nitrogen Utilization Efficiency (NUE, Moll et al. 1982):

$$\frac{\text{Yield}}{\text{Crop N}} = \frac{\frac{196 \text{ bu}}{\text{acre}}}{\frac{158.6 \text{ lbs. N}}{\text{acre}} \times \frac{1}{0.845}} = \frac{1.04 \text{ bu}}{\text{lb N}}$$

NUE indicates the ability of the crop to produce yield relative to crop N.¹ Note that Crop N is expressed on the same moisture basis as Yield. Yield and Crop N could also be expressed on a dry basis, but we'd have to convert bushels (volume) to pounds (mass). However, the result would be the same. NUE values are useful for comparing genotypes to identify superior physiological efficiency in converting crop N to economic yield. NUEs for nutrients other than N are possible (see Figure 1).

Lastly, we consider nutrient removal rates and yield:

$$\frac{\text{Yield N}}{\text{Yield}} = \frac{\frac{116.7 \text{ lbs. N}}{\text{acre}} \times \frac{1}{0.845}}{\frac{196 \text{ bu}}{\text{acre}}} = \frac{0.70 \text{ lb N}}{\text{bu}}$$

This shows 0.70 lb N removed from the field with every bushel of grain. Table 4 compares nutrient removal rates determined in this exercise with averages ($n=2,338$) obtained across 39 different counties in Ohio.

Table 4.

Source	lb nutrient/bushel grain			
	N	P ₂ O ₅ *	K ₂ O*	Zn
Culman et al. 2019 (Ohio)	0.74	0.35	0.20	0.0010
CPF Agronomics 2021 (NC)	0.70	0.28	0.24	0.0012

*oxide basis. Conversion factors: P × 2.291 = P₂O₅; K × 1.205 = K₂O

Admittedly, single-value indicators like NUE don't reveal a lot unless the aggregate data are plotted in a way that makes underlying trends visible. This has been done for nitrogen and phosphorus in Figure 1. Four important points can be taken from these data:

- Most NUEs fall between 0.8 and 1.2 bu/lb N and 2.0 - 3.0 bu/lb P₂O₅.
- NUEs on the tail end represent less-adaptive genotypes mostly yielding under 100 bu/acre grain.
- Low NUE (N<0.80; P₂O₅ <2.0) observations are mostly under Rainfed-Free Drain and Wet-No Drain exposures, though some exceptions can be noticed.
- On average, NUE was relatively invariant above 100 bu/acre regardless of land drainage.

Figure 2 provides further insight about maize NUE spread averaged over genotype. These data suggest that genotypes are unequally adaptive for fertilizer N and P utilization.

We can quantify the impact of drainage on maize yield and nutrient utilization. For example, if we applied 180 lb N/acre, the following yield outcomes are predicted:

Optimal: 180 lb N/acre × 1.01 bu/lb N = 182 bu/acre.

Wet-No Drain: 180 lb N/acre × 0.84 bu/lb N = 152 bu/acre.

Average net gain = 180 – 152 = 28 bu/acre. If maize grain is trading at \$6.50/bu the marginal return on investment in improved drainage is 28 bu/acre × \$6.50/bu = **\$182/acre**.

In turn, N utilization efficiency improved by:

182 bu/acre × 1.01 bu/lb N – 152 bu/acre × 0.84 bu/lb N
= **+54 lb N/acre**.

With fertilizer N prices edging up, this represents a cost savings. It also fosters environmental stewardship since organically bound crop N is effectively immobilized.

The same assessment can be made for P/P₂O₅ or any nutrient of interest.

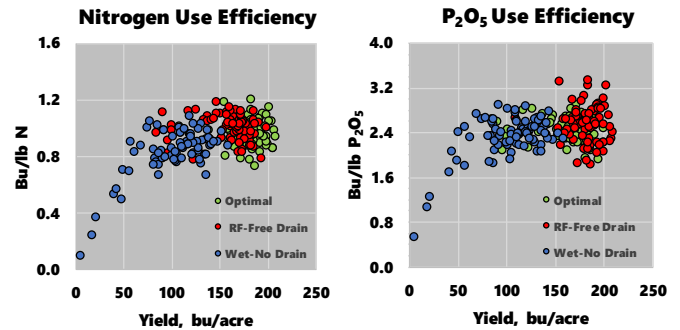


Figure 1. Nitrogen and phosphorus (P₂O₅) use efficiency for elite maize genotypes ($n=18$) under three land drainage regimes. Data source: Walters CPF Agronomics and Poole BAE NCSU.

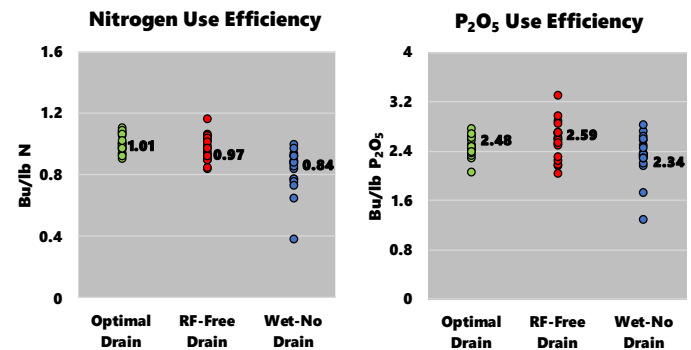


Figure 2. Dot plots showing the spread of N and P₂O₅ use efficiency for elite maize genotypes under three land drainage regimes. Each dot represents a single genotype NUE averaged over field plot replicates. Numbers in bold adjacent to the dots are the average NUE for that drainage regime. Data source: Walters CPF Agronomics and Poole BAE NCSU.

¹ NUE has been defined other ways in the literature for example, as the ratio Crop N/Fertilizer N and Yield N/Fertilizer N, which are herein defined as Partial N Balance after Dobermann 2007 and NUE_{crop} after Martinez-Feria 2018.

Summary

Crop biomass can be expressed on wet or dry basis. Typically, grain moisture content is expressed as percentage based on wet weight (wet basis). Whereas dry basis is used mainly in research for example, when calculating mass balance of essential nutrients in cropping systems. Therefore, it is important to know which has been used, or is needed. Chemical interactions between nutrients and soil are important factors when interpreting nutrient mass balance.

We have also shown that mass balance can be used to calculate indicators like Partial Nutrient Balance (PNB), Partial Factor Productivity (PFP), Nitrogen Utilization Efficiency (NUE), and nutrient removal rate. Other indicators have been defined, but these are the most widely referenced in the agronomic literature.

Appendix A. Calculating Area Factor (AF) Method 2

This method measures the specific sample ground area. As such, it doesn't depend on stand counts. Sample area is given by:

$$SA = L_s \times W_r$$

where:

SA = ground area occupied by sample plants (ft^2 , m^2)

L_s = length of sample area

W_r = width of sample area

The procedure involves sampling adjacent plants in a row and measuring the distance between plants in the row plus the distance between the center of the two plants flanking each sample plant. Figure A1 illustrates the procedure.



Here, three plants D1, D2, D3 were sampled in a row. Plants D0 and D4 are the two plants flanking. The cumulative distance between plants in centimeters is shown. The length of the sample area is given by:

$$L_s = 0.5 \times (D_4 - D_3 - D_1) + D_3$$

$$L_s = 0.5 \times (65 - 50 - 17) + 50$$

$$L_s = 49 \text{ cm}$$

where D1 is the distance between the center of the two plants D1, and D0 flanking the sample plants, D3 is the distance between the center of D0 and sample plant D3, and D4 is the distance between the center of the two plants flanking.

Sample area in square feet:

$$SA = 49 \text{ cm} \times \frac{1 \text{ inch}}{2.54 \text{ cm}} \times \frac{\text{ft}}{12 \text{ inches}} \times 2.5 \text{ ft}$$

$$SA = 4.019 \text{ ft}^2$$

It can be noticed that the sample area using method 2 is larger than in Solution (4) above, 4.019 ft^2 vs. 3.966 ft^2 even though the plants were harvested from the same plot. The difference is due to how area per plant is calculated. Aboveground biomass calculated using method 2 will be lower than method 1 if plants are evenly spaced in the row as shown in Figure A1.

Which method to use?

That will depend on factors like the degree of precision planting and whether the stand achieved is close to the target planting density. In general, when in-row plant spacing is relatively uniform and full stand (or close) has been achieved, method 2 is preferred as it guards against over-estimating biomass and, in turn, nutrient accumulation. Both methods are, however, scientifically valid.

Appendix B. Wet vs Dry Basis Moisture Content

Moisture is a major constituent of many agricultural materials and food products. Moisture content is a critical factor in food quality, marketing, preservation, and exposure to deterioration. Determination of moisture content is necessary to quantify the amount of other constituents, commonly referred to as "dry solids", on a standard basis. Dry solids include things like crop stover (a combination of mostly structural carbohydrates, and mineral matter), and grain (mostly starch, lipids, some protein and minerals), two constituents commonly referenced in commodity marketing channels.

Moisture content can be defined as the quantity of water present in a moist material. The terms "moisture" and "water" are generally used interchangeably. Here, we reserve the term "water" for the substance H_2O , and "moisture" as H_2O that is absorbed by, or diffused in, a moist substance. That substance could be anything: food, soil, wood, fertilizer, etc.

Moisture content can be expressed two ways:

- Wet basis (wb)
- Dry basis (db)

Wet basis moisture content is the amount of water per unit mass of a moist substance, defined as:

$$MC_{wb} = \frac{\text{mass of water}}{\text{mass of moist substance}} \quad [\text{B1}]$$

where MC stands for moisture content, and the subscript wb designates "wet basis".

Dry basis moisture content is the amount of water per unit mass of dry solids:

$$MC_{db} = \frac{\text{mass of water}}{\text{mass of dry solids}} \quad [\text{B2}]$$

where subscript db designates "dry basis". Mass of dry solids means moisture-free, as in oven dry or "bone dry". Note that in Equations [B1] and [B2], the numerators are the same, but the denominators are different. In practice, terms MC_{db} and MC_{wb} may be unspecified, appearing simply as "% MC " or equivalent. Right side of Equations [B1] and [B2] tell the difference.

In the case of moisture content dry basis (MC_{db}), the denominator *mass of dry solids* represents a single, undifferentiated, variate, "dry solids". Whereas, the denominator in moisture content wet basis (MC_{wb}) has two variates, *mass of water* (H_2O), plus *mass of dry solids*.

$$MC_{wb} = \frac{\text{mass of water}}{\text{mass of water} + \text{mass of dry solids}} \quad [B3]$$

Mathematically, this can be denoted as:

$$MC_{wb} = \frac{m_w}{m_w + m_d} \quad [B4]$$

Where m_w and m_d symbolize the mass of water and mass of dry solids, respectively.

Wet and dry basis moisture content are different, but related, quantities. The relationship can be deduced mathematically by dividing the numerator and denominator in Equation [B4] by m_d , the *mass of dry solids*:

$$MC_{wb} = \frac{\frac{m_w}{m_d} \{MC_{db}\}}{MC_{db} \frac{m_w}{m_d} + \frac{m_d}{m_d}} \quad [B5]$$

This creates a new expression with MC_{db} present in both numerator and denominator, because $MC_{db} = m_w/m_d$ by Equation [2]. The term m_d/m_d in the denominator cancels out, which is unity, symbolized by 1:

$$MC_{wb} = \frac{MC_{db}}{MC_{db} + 1}$$

This can be re-written as:

$$MC_{wb} = \frac{MC_{db}}{1 + MC_{db}} \quad [B6]$$

Equation [B6] expresses wet basis moisture content in terms of dry basis.

Similarly, we can express dry basis moisture content in terms of wet basis:

$$MC_{db} = \frac{MC_{wb}}{1 - MC_{wb}} \quad [B7]$$

This inversion can be obtained by dividing the numerator and denominator as in Equation [B5] using m_{ms} :

$$MC_{db} = \frac{m_w}{m_d} = \frac{m_w}{m_{ms} - m_w} = \frac{m_w}{m_w + m_d - m_w}$$

$$MC_{db} = \frac{\frac{m_w}{m_w + m_d}}{\frac{m_w + m_d}{m_w + m_d} - \frac{m_w}{m_w + m_d}} = \frac{MC_{wb}}{1 - MC_{wb}}$$

where m_{ms} represents the mass of two variates $m_w + m_d$ from Equation [B4].

The denominator for moisture content wet basis, $1+MC_{db}$ returns a value *greater than* the numerator. Whereas, the denominator for moisture content dry basis, $1-MC_{wb}$ returns a value *less than* the numerator. This means that moisture content wet basis always has fractional values from 0-1 (0-100%)

whereas dry basis moisture content can have values >1 ($>100\%$). For the same set of values, moisture content dry basis is always greater than moisture content wet basis. Let's illustrate the interconversion of wet and dry basis moisture content by example.

Example 1. The moisture content of a sample was determined to be 80% wet basis. What is the dry basis moisture content?

Solution. Dry basis moisture content is given by:

$$MC_{db} = \frac{MC_{wb}}{1 - MC_{wb}}$$

First, convert mass percentage to a decimal fraction before substituting in the equation.

$$MC_{db} = \frac{0.8}{1 - 0.8}$$

$$MC_{db} = \frac{0.8}{0.2}$$

$$MC_{db} = 4 \times 100 = 400\%$$

This means the mass of water present in the sample is 4x the mass of dry solids., i.e. MC_{db} is a percentage equivalent of a ratio.

Example 2. Convert 60% dry basis moisture content to wet basis.

Solution. Wet basis moisture content is given by:

$$MC_{wb} = \frac{MC_{db}}{1 + MC_{db}}$$

Again, convert mass percentage to a decimal fraction before substituting in the equation.

$$MC_{wb} = \frac{0.6}{1 + 0.6}$$

$$MC_{wb} = \frac{0.6}{1.6}$$

$$MC_{wb} = 0.375 \times 100 = 37.5\%$$

This shows that 60% dry basis moisture content equals 37.5% wet basis, which is the fractional water content of the moist sample.

How does the interconversion of wet and dry basis moisture content relate to agricultural materials?

Earlier we defined a bushel of maize grain as weighing 56 lbs., with a wet basis moisture content of 15.5%. What is the mass weight of dry grain?

Solution. If 56 lbs. equals 100% of the mass weight of a bushel, the percentage of dry solids is $100 - 15.5 = 84.5\%$. The amount of dry grain in a bushel is therefore:

$$56 \text{ lbs grain} \times .845 = 47.32 \text{ lbs dry grain}$$

Thus, each bushel of maize grain contains exactly 47.32 lbs. "bone dry" solids, and $56 - 47.32 = 8.68$ lbs. water (H_2O).

What is the % moisture content of a bushel of maize grain expressed on a dry basis?

Solution. We know that, by definition, a bushel of maize grain has a wet basis moisture content of 15.5%. The conversion to dry basis is given by:

$$MC_{db} = \frac{MC_{wb}}{1 - MC_{wb}}$$

$$MC_{db} = \frac{0.155}{1 - 0.155}$$

$$MC_{db} = \frac{0.155}{0.845}$$

$$MC_{db} = 0.183 \times 100 = 18.3\%$$

Note that moisture content dry basis is greater than moisture content wet basis, so it's a reasonable solution in accordance with Equations [B6] and [B7]. This means that each pound of dry grain contains 0.183 lb. water. If a bushel of grain contains 47.32 lbs. dry grain, how much water would have to be added back to obtain 15.5% wet basis moisture content?

Solution.

$$47.32 \times .183 = 8.68 \text{ lbs of water}$$

$$47.32 + 8.68 = \frac{56 \text{ lbs grain}}{\text{bushel}}$$

This aligns perfectly with Equation [B3]:

$$MC_{wb} = \frac{\text{mass of water}}{\text{mass of dry solids} + \text{mass of water}}$$

$$MC_{wb} = \frac{8.68 \text{ lbs water}}{47.32 \text{ lbs dry solids} + 8.68 \text{ lbs water}}$$

$$MC_{wb} = \frac{8.68 \text{ lbs water}}{56 \text{ lbs moist solids}}$$

$$MC_{wb} = 0.155 \times 100 = 15.5\%$$

In conclusion, the following points are emphasized:

- Moisture content can be expressed two ways, wet basis and dry basis.
- Wet and dry basis moisture content are interconvertible, but are not the same thing.
- Moisture content dry basis can be greater than 100%.
- If wet or dry basis moisture content is not specified, ask. Every discipline has its preferred usage.
- Generally, wet basis moisture is used to describe the water content of agricultural materials and food products.

We hope the foregoing account will enable the reader to distinguish wet and dry basis moisture content and better understand their relationship. The symbology of variates in Equations [B1] and [B2] may differ, depending on usage, but this shouldn't alienate their unique properties.

Hmm...What Did You Say?

The agronomic literature abounds with technical jargon, sometimes redundant, often arcane. Take heart. Here's a list of common terms for agricultural mass- and moisture-determining processes including their definition and principle usage.

Air-dry: The mass of a substance in equilibrium with a well ventilated, indoor atmosphere. Most agricultural materials are *hygroscopic*, tending to exchange moisture with the atmosphere depending on factors like chemistry, water vapor pressure, seed coatings, among others. Air drying is utilized to deactivate microorganisms to prevent decomposition of fresh material. Not to be confused with sun drying, which occurs outdoors.

Biomass: The organic materials built up by plants through photosynthesis, and by livestock through feeding activity. Plant biomass can be separated into different fractions, e.g. leaves, stems, roots, fruit, or simply referenced in aggregate.

Bushel: In the US, agronomic yields of grain crops are measured in bushels (bu), which are units of volume that vary among crops (Table B1). Originally, the bushel was a unit of dry measure equal to 2150.42 cubic inches created by the Celtic peoples to ensure fair trade. Today, the bushel is identified on a standard weight and moisture basis to facilitate trading of grains. Globally, units of tons and metric tons are referenced and traded. These units do not vary among crops, nor are they tied to any standard moisture content. The bushel is not a scientific unit of volume. As such, it must be converted to other units (lbs., kg., tons) before using in scientific calculations. The conversion factors are called *test weights* (Table B1).

Table B1. Bushel weight and moisture specifications for different crops.

Crop	Bushel weight, lbs.	Specified moisture, %	Lbs. at 0% moisture
Corn	56	15.5	47.32
Soybean	60	13	52.2
Wheat	60	13.5	51.9
Barley	48	14.5	41.04
Oat	32	14	27.52
Rye	56	14	48.16

Source: Reese and Carlson, 2017.

Dry matter: The solid mass of a substance when completely dried, abbreviated DM or D.M. It is calculated as:

$$100\% - \% \text{ Moisture} = \% \text{ Dry Matter}$$

Dry matter basis: The proportion of total dry matter in a substance. Dry matter basis of 100% means 0% water is present (impossible to achieve in most cases). There are different usages for dry matter basis. Typically, it is used to compare the nutritional value of animal foods, particularly those tending to have high moisture content like forages. Alternatively, it is used to specify relative dry matter content assuming some water is present. For example, if a document states that mass weight is expressed on a 84.5% dry matter basis, it means the moisture content is 15.5%.

Dry weight: The mass of a substance with all water removed. Sometimes used interchangeably with dry matter (DM), dry solids (DS), total solids (TS).

Grain: The harvested seed of grasses such as maize, wheat, oats, barley. Globally, these are known as cereals. The seed, or fruiting body, of grasses is referred to botanically as a *caryopsis*, a single-seeded fruit in which the ovary wall (pericarp) is attached to seed coat (integument). Grain seeds are capable of storing carbohydrates (mainly starch), lipids, protein, and minerals.

Mass: A fundamental measurement of how much matter a body contains. All three states of matter: solid, liquid, and gas, have mass that is independent of location. Mass is reported in units of grams or kilograms in the metric system.

Moisture content: Used to describe the quantity of water in a moist material. Wet basis describes the water content per unit moist or “fresh” material. Dry basis describes the water content per unit dry solids. Water is a major constituent of many agricultural materials and food products. As such, moisture content is determined at each point in the marketing channel, especially where ownership changes. Grain buyers are unwilling to pay extra \$\$ for water, sellers don’t want to pay for pre-sale grain drying beyond what’s needed to preserve food quality, and shippers are limited by weight restrictions.

Oven-dry: The mass of a substance after drying at standard temperature for a prescribed period of time or until a constant weight is achieved. The residual moisture content of ‘oven-dry’ material is solely dependent on the procedure specified for that material. Normally it is not possible to achieve 0% moisture without some degree of thermal mass decomposition (See ASABE 1988).

Solid: State of matter having definite shape and volume. Solids capable of dissolving in liquid water to form a solution (solute) are called soluble or dissolved solids (sugar, salt). Those solids incapable of mixing with liquid water are called insoluble solids. Dry solids are solids with 0% moisture. Solids content may comprise a mixture of soluble and insoluble solids.

Stover: Stalks, leaves, cobs, husks left in the field after maize grain harvest (applies similarly to other crops). It is composed of structural carbohydrates like cellulose, hemicellulose, and lignin, and a small quantity of mineral matter. The percentage of stover left in the field may be large or small, depending on whether it is harvested for use as feed or bedding for livestock or feedstock for biofuels.

Water content: The proportion of the substance H₂O present in a material. Can be expressed on a gravimetric (mass per unit mass: m/m or w/w), or volumetric (mass per unit volume : m/v) basis.

Weight: Measurement of the gravitational force on a body. Weight depends on mass and location. For example, your body mass is the same no matter where you travel in the universe. Your weight, in contrast, changes from place to place depending on the force of gravitational acceleration. Sometimes we talk, imprecisely, about weight in grams or kilograms. Strictly speaking, weight should be measured in Newtons, the units of force.

Wet weight: The mass of a moist substance in its natural state without reference to moisture content. Also called fresh, moist, field moist, or ‘as-is’ weight.

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