

DEVELOPMENT AND EVALUATION OF A LOW-COST PROBE-TYPE INSTRUMENT TO MEASURE THE EQUILIBRIUM MOISTURE CONTENT OF GRAIN

P. R. Armstrong, S. G. McNeil, N. Manu, A. Bosomtwe, J. K. Danso, E. Osekre, G. Opit

ABSTRACT. Storage of grain in bags is common in Africa, Asia, and many other less developed countries making a bag probing method well-suited for moisture content (MC) measurement. A low-cost meter was developed under a USAID project to reduce post-harvest loss (PHL). The meter, referred to as the PHL meter, measures the MC of maize and other grains based on relative humidity (RH) and temperature (T) measurements obtained by a small digital sensor located in the tip of a tubular probe that can be inserted into bags of grain or other grain bulks. Measurements are used by equilibrium moisture content (EMC) equations programmed into the meter to predict MC. A handheld reader connected to the probe provides a user interface.

The PHL moisture meter was evaluated based on laboratory studies in the United States and field studies in Ghana. Meter readings from field studies were compared to two commercial meters, a John Deere Chek-Plus-SW08120 grain moisture tester and a DICKEY-john GAC[®]2100 Agri meter. The John Deere portable moisture meter is a low-cost meter by developed country standards (~US\$250, 2016 price); the GAC 2100 bench-top moisture meter is an approved moisture tester by the Grain Inspection, Packers and Stockyards Administration (GIPSA) and has been a highly regarded and used electronic meter. Laboratory studies indicated that the PHL meter may require up to 6 min to take a measurement because of the time required by the probe tip and sensor to equilibrate to grain conditions. Methods to reduce the measurement time by measuring temporal equilibration rates were developed. These can be programmed into the reader to shorten measurement time for many conditions. The accuracy of the PHL moisture meter was comparable to the GAC 2100 moisture meter for maize below 15% MC_{wb}. Average differences showed a positive offset of 0.45% for the PHL meter relative to the GAC 2100. The PHL meter provided an effective tool to probe bulk grain and bags.

Keywords. Equilibrium moisture content, Grain storage, Maize, Moisture content, Moisture meter, Post-harvest.

Maize (*Zea mays* L.) is an important food crop produced by many countries. It also serves as a raw material for starch and ethanol production, animal feed, and industrial products. The

vast majority of grain in Africa, 60% to 70%, is stored at the farm level to provide a food reserve, as well as seed for planting (FAO and INPhO, 1998). Post-harvest losses account for 20% to 30% of the annual crop losses amounting to \$4 billion USD (CIMMYT, 2013), with significant losses attributed to inadequate drying and because of high moisture content (MC) during storage.

The two main factors that affect cereal grains in storage are the moisture content and temperature (T) (Gonzales et al., 2009). Exposure of maize to humid conditions during storage will lead to the absorption of water by the grain from the immediate environment even if the maize was appropriately dried after harvest (Devereau et al., 2002). This leads to an increase in the maize MC, resulting in insect infestation and more deterioration (Suleiman et al., 2013). Grain MC and T can also affect the grain quality, quantity, and biochemical reactions, as well as its storability (Hellevang, 1995). Knowledge and control of the MC is a major critical component in post-harvest storage to ensure the quality of food products in industry (Amin et al., 2004).

A primary moisture measurement method involves determining the mass of an undried and dried sample to determine the amount of water in the sample. In secondary methods,

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The authors are **Paul R. Armstrong, ASABE Member**, Research Agricultural Engineer, USDA, Agricultural Research Service, Center for Grain and Animal Health Research, Stored Product Insect and Engineering Research Unit, Manhattan, Kansas; **Samuel G. McNeil, ASABE Member**, Associate Extension Professor, Food and Bioprocess Engineering, University of Kentucky, BAE, Princeton, Kentucky; **Naomi Manu**, MPhil Student in Entomology, **Augustine Bosomtwe**, Student, **James K. Danso**, MPhil Student in Entomology, **Enoch Osekre**, Senior Lecturer, Department of Crop and Soil Sciences, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana; **George Opit**, Associate Professor, Entomology and Plant Pathology Department, Oklahoma State University, Stillwater, Oklahoma. **Corresponding author:** Paul R. Armstrong, USDA, ARS, CGAHR, SPIERU, 1515 College Avenue, Manhattan, KS 66502; phone: 785-776-2728; e-mail: paul.armstrong@ars.usda.gov.

the MC is determined indirectly from the empirical relationship between physical and chemical features and the actual MC obtained from primary methods such as standard oven drying methods (Chen, 2003). Some common secondary methods rely on the electrical characteristics of the grain, such as capacitance and conductance. Near-infrared spectroscopy can also be used but is generally more expensive although it can also measure compositional parameters. The need for a low-cost moisture meter in developing countries has been advocated for several years to help mitigate post-harvest losses of grain (World Bank, 2011; Maier, 2015). There are many reports of significant grain losses due to molding, which can make the grain unacceptable from a consumer quality perspective; this can also lead to the development of unacceptable mycotoxins that render the grain unusable and detrimental to human and animal health (Wu and Khlangwiset, 2010; Zain, 2011). Both of these situations can have economic effects on small farmer holdings by reducing the grain that can be retained for the family and the grain available to sell for cash.

Low-cost grain moisture meters have been developed and show promise but do not seem to be universally accepted, as indicated by their low adoption rate (World Bank, 2011). The technology they use must be simple, inexpensive, and robust. The meter developed by the International Rice Research Institute (IRRI) has a very small sampling chamber because it was intended for rice (Gummert and Borlagdan, 2012). As such, it may not be accurate when used for larger kernel grains like maize or soybeans. Many meters use a resistive or capacitive technology that requires the meter to be calibrated to a particular type of grain (Rai et al., 2003). While this is not a significant barrier, it does require collecting a large number of samples and laboratory measurements to develop and test the calibration.

Armstrong and Weiting (2008) developed a practical equilibrium moisture content (EMC) meter, which was largely made possible by the development of a miniaturized and accurate commercial relative humidity (RH) and T sensor by Sensirion AG (Stäfa, Switzerland). The equilibrium grain moisture content is measured on the basis of the RH and T of the air surrounding the grain. The advantages of this type of meter are (a) that a bag can be easily probed, allowing the sensing point to be inserted into or permanently embedded in grain for moisture measurement, and (b) the ability to use well-established EMC prediction equations for a broad range of grains and legumes so less calibration is required. Suitability of EMC prediction equations should however be addressed in future work to assure they predict local varieties well. The digital sensor allows greater adaptability to other electronic digital platforms including tablets or phones and thus eliminating a specialized hardware user interface. The major disadvantage is that it requires the grain and environment to be in equilibrium. Equilibrium conditions in modern grain silos are established within three hours after aeration indicating this occurs fairly quickly (Chandra B Singh, 2017, Personal Communication, Stored Grain Facilities, University of South Australia). This gives some indication that bagged grain may establish equilibrium in similar times but warrants investigation. The moisture meter also requires time for the probe and sensor to adjust to the T

and RH conditions of the grain once it has been inserted into the bulk.

The USAID multi-country project, Feed the Future Innovation Lab for the Reduction of Post-Harvest Loss, administered by Kansas State University, includes the deployment of moisture meters to several countries. A low-cost moisture meter was developed as part of this project by using relatively simple technology that could potentially be produced in-country. The meter is adapted from ideas developed by Armstrong and Weiting (2008) but differs in that their work examined methods to make meter measurements more quickly while the present work focused on affordability and appropriate technology for local manufacture. Because of its association with the Post Harvest Loss Innovation Lab, it is referred to as the PHL moisture meter.

The objectives of this study were to characterize the measurement performance of the PHL meter and determine the time required for measurement and accuracy compared to a GIPSA-approved reference method (GAC 2100 Agri, DICKEY-john Corp., Auburn, Ill.) and a low-cost commercial meter, the John Deere Moisture Chek PLUS, model SW08120 (AgraTronix Streetsboro, Ohio). Field tests of these three moisture meters were performed to determine their performance and the practical aspects of using the PHL meter, as well as provide preliminary information on the moisture levels of maize in Ghana.

MATERIALS AND METHODS

PHL MOISTURE METER DESCRIPTION

The PHL moisture meter (fig. 1) was designed as a probe meter for measuring moisture content in bulk or bagged grain and uses the equilibrium moisture relationships of grain to determine the MC. This is achieved by using a small digital sensor to measure the relative humidity (RH) and temperature (T) of the interstitial air in the grain. The meter is most suitable for measuring the MC of bulk grain and it requires equilibrium conditions to exist in the grain to obtain an accurate measurement. The MC dry basis (MC_{db}) is calculated by using the Modified Henderson equation shown as equation 1 (*ASAE Standards*, 2005a) with coefficients (K, N, and C) that have been previously defined for various grain types. This particular equation was chosen as it provides good accuracy for maize. Other EMC equations can be implemented as necessary for better accuracy with other commodities.

$$MC_{db} = \left[\frac{\ln(1 - RH)}{-K(T + C)} \right]^{1/N} \quad (1)$$

where

- MC_{db} = moisture content, dry basis,
- K, N, and C = coefficients defined for various grain types,
- RH = relative humidity (decimal), and
- T = temperature ($^{\circ}C$).

The benefits of the PHL moisture meter compared to other types of meters include its relatively low cost. The component and material costs for the PHL meters used in this study are \$85 USD; construction and assembly costs are



Figure 1. The PHL moisture meter showing the meter parts and probe use.

additional. It uses an inexpensive \$28 USD sensor that is accurate and replaceable; a newer version of this sensor costs about \$3 USD. Simple electronics and components, described below, are used so it can be adapted to unsophisticated manufacturing environments.

Technical Description

The meter has a 750 mm long \times 12.5 mm diameter aluminum probe that can be inserted into the grain. The probe tip contains an RH/T digital sensor (SHT75, Sensirion AG, Staefa, CHE) that is connected to a handheld reader by a cable. The probe end surrounds the sensor and has multiple holes to allow the ambient air to reach the sensor. The primary electronics and hardware of the handheld reader include an Arduino Pro Mini 3.3V microcontroller (Adafruit Industries New York, N.Y.), an LCD display (NHD-C0216CZ-NSW-BBW-3V3, New Haven Display, Elgin, Ill.), three momentary-type input buttons (B3F-4155, Omron Electronics, Osaka, Japan), a 4N25 opto-isolator (Vishay Intertechnology Inc., Malvern, Pa.), a NTR4003N transistor (ON Semiconductor, Aurora, Colo.), a TM5RF1-44(50) telephone connector (Hirose Electric Group, Tokyo, Japan), a battery connector, and ten passive resistive and capacitance components. The software was written in the Arduino 1.6.1 Integrated Development Environment (<https://www.arduino.cc>) and contains functions that read the sensor, calculate the EMC, monitor the button inputs, and drive the LCD display. All electronics are hand mounted and thus older style, through-hole, components were chosen over surface-mount. The Arduino controller was chosen because it is well

documented, widely distributed, and the software development environment is free. Telephone connectors and wiring were used because of cost and availability. Printed circuit boards (PCB) for sensor mounting and the handheld reader were designed with ExpressPCB freeware (www.expresspcb.com) which also fabricates the boards. The ExpressPCB service is a cost-effective solution for small production runs. The PCB is adaptable to other enclosures and plastic tube substitutes could be used instead of the aluminum tube. The display shows the RH, T, and MC, and the user interface allows for the selection of different grain types via the center input button.

DETERMINING EQUILIBRATION TIMES FOR PHL MOISTURE METER

The PHL moisture meter requires time for the probe to equilibrate with the grain conditions after it is inserted into the grain bulk. The equilibration requires the aluminum tube and sensor in the probe to attain the ambient grain conditions. The sensor itself has a short response time of a few seconds, which is considered to be insignificant compared to the equilibration time between the grain air and probe due to its thermal capacity. The small amount of ambient air inside the probe prior to its insertion may also have a small effect on the equilibration time.

Tests using different maize MC and T conditions were used to determine the equilibration times by inserting the probe into the grain under the various grain conditions and recording T and RH measurements versus time. The maize conditions were about 8°C, 22°C and 30°C at 10%, 15% and 20% MC_{wb}. The maize was conditioned to these three MCs by drying or adding water to a commercial yellow dent hybrid. Each sample was approximately 16 kg and stored in a sealed plastic bucket for two weeks after conditioning. The final MCs of the conditioned samples were 10.1%, 15.3% and 20.6% MC_{wb}, determined by a GAC 2500 (DICKEY-john, Auburn, Ill.). The Modified Henderson coefficients used for MC prediction were $K = 0.000086541$, $N = 1.8634$ and $C = 49.810$. Two probe types were used for the tests: a standard probe and a probe with a plastic foam plug inserted into the tube just in front of the sensor. The foam plug was tested to determine whether it could minimize potential air flow in the tube caused by convection which could affect the equilibration time. In total, six PHL moisture meters were used; three had standard probes and three had foam inserts to obtain triplicate readings. Equilibration measurements were conducted by inserting the probes into the grain and recording measurements of T, RH and MC at one-minute intervals for 12 min. This was also done with the other meters, resulting in triplicate readings. The individual maize buckets were cooled or heated in a temperature-controlled chamber and monitored until maize had reached the desired T. Each bucket was then removed and measurements were made at a room temperature of 22°C. All tests were completed at the Center for Grain and Animal Health Research, USDA-ARS laboratory in Manhattan, Kansas.

COMPARISON OF MOISTURE METERS TESTED UNDER FIELD CONDITIONS

Field measurements of maize MC were collected in two separate studies to examine the practicality and accuracy of the PHL moisture meter compared to other moisture meters (i.e., the John Deere and GAC 2100 moisture meters). These field measurement studies were conducted at various locations in the Middle Belt and Northern Ghana (fig. 2). These studies included moisture measurements from: (1) an ongoing study of insect infestation of bagged maize in storage warehouses beginning in 2015 and (2) moisture assessments of commercial bagged maize in select Ghanaian markets conducted in 2016.

1. Moisture Measurements from the 2015 Insect Infestation Study. Moisture measurements were taken on a monthly basis at the following four sites: (1) Animal Husbandry facility, Ejura, (2) Crop Research Institute, Ejura, (3) a warehouse in Techiman, and (4) a warehouse in Wenchi as described in detail by Paudyal et al. (2017). Nine bags were measured at each site. Each site consisted of three bag treatments: (1) Betallic-treated polypropylene bags (PP), (2) untreated PP bags, and (3) Deltamethrin (DM)-incorporated PP bags. All bags were 50 kg size and filled with maize from a common source for each site. The DM-incorporated bags were a commercial product of Vestergaard Frandsen (Lausanne, Switzerland) and were being evaluated for their effectiveness in controlling insect infestation. The MCs of the maize in the bags were measured three times at upper, center, and lower locations within the bag by probing with the PHL moisture meter. Samples were then taken from the center and two opposite sides near the inner surface of each bag and measured with the John Deere meter. A 1.2 m open-ended trier (grain probe) (Seedburo Equipment, Chicago,

Ill.) was used to sample maize from the bags. Samples from each bag were mixed thoroughly in a basin to ensure homogeneity. A 250 g sample was then weighed out with a dial spring scale (CAMRY, Yongkang, China). The 250 g maize sample was placed in a labeled plastic bag and placed in a 17 L Koolatron® 12 V portable electric cooler (P75, Koolatron, Brantford, Canada) for transport to the laboratory. Samples were stored in a laboratory cooler at approximately 2°C until moisture tested.

Monthly measurements were collected for six consecutive months (March to August 2015). During this study, attempts were made to use oven-dried reference measurements by using standard methods (ASAE Standards, 2005b) but were abandoned due to an erratic electrical supply that interrupted completion of a drying cycle. Because of the inability to obtain good oven reference moisture data, a GAC 2100 moisture meter was used for reference measurements in the subsequent commercial market survey of MC described below.

2. Commercial Market Survey of Maize Moisture Content - 2016. Moisture measurements were taken at commercial markets in the Middle Belt of Ghana in Ejura, Sekyedumase, Techiman, Amantin, Ofinso, Ayinasu, Abofour, Nkoranza, Wenchi, and Atebubu. Measurements were taken on 10 different bags of maize at each market. The bag size varied between 50 and 100 kg. Triplicate measurements were done for each bag with both the PHL and the John Deere moisture meters in the same manner as in the 2015 Insect Infestation Study. In addition to on-site moisture meter data, 1 kg samples were obtained and returned to the laboratory for moisture measurement with the GAC 2100 moisture meter. Measurements were obtained in December, June, and July 2016. For the June and July data, two PHL and two John Deere moisture meters were used for measurements to compare results between duplicate meters.



Figure 2. Sites included in the two field measurement studies in Ghana that were conducted in 2015 and 2016.

RESULTS AND DISCUSSION

DETERMINATION OF EQUILIBRATION TIMES FOR THE PHL MOISTURE METER

Figures 3 and 4 show the changes in T, RH, and MC for 10% MC_{wb} maize at 22°C and for 20% MC_{wb} maize at 10°C, respectively, that were obtained with the PHL moisture meter. The plots, the average for three meters, indicated that T, RH and MC initially approached equilibrium rapidly but slowed significantly after the first 2 min. All other storage conditions showed similar trends. A preliminary comparison of probes with or without the plug showed no discernible difference; thus, foam plugs were no longer used in the PHL moisture meter design.

The derivative of the MC-Time curve was calculated using a finite difference approximation (eq. 2) between 1 and 11 min at 1-min intervals. The derivative provides a mathematical method for the comparison of different environmental measurements. This could also be incorporated into the Arduino program used as the stability criteria for the PHL moisture meter to indicate when a reading can be taken.

$$\frac{\partial MC}{\partial t}(t_i) = \frac{MC(t_i + \Delta t) - MC(t_i - \Delta t)}{2\Delta t} \quad (2)$$

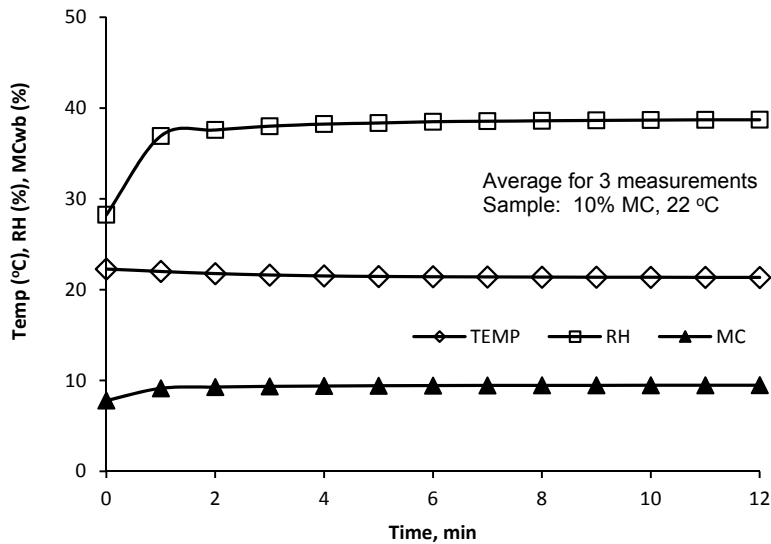


Figure 3. Average PHL moisture meter readings for T, RH, and 10% MC_{wb} maize samples at 22°C.

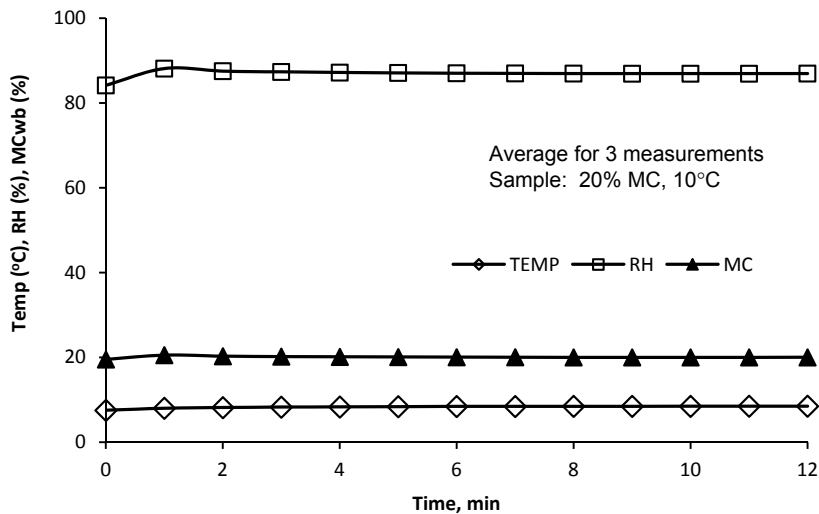


Figure 4. Average PHL moisture meter readings for T, RH, and 20% MC_{wb} maize samples at 10°C.

where $\frac{\partial MC}{\partial t}$ is the MC derivative with respect to time, t_i is the time of interest, and Δt is the time interval.

Figure 5 shows that MC readings at the 6-min point provide reasonably stable readings for which the average rate change is less than 0.05% MC_{wb}/min. Thus, 6 min is the suggested minimum time after the probe is inserted in the bulk maize sample before a MC reading can be taken. The standard deviation of the three meter readings at the 6 min time ranged from 0.05% to 0.26% MC_{wb} across all conditions of MC and temperature.

The PHL moisture meter and the GAC 2500 measurements are compared in table 1. The results show a greater error for the PHL moisture meter at higher moisture levels and higher temperatures. This is most pronounced at the nominal temperatures of 21°C and 32°C at the high 20%

moisture level. The increase in the error is caused in part by the higher sensor error at high RH levels as suggested by Uddin et al. (2006). The EMC prediction equations are also increasingly sensitive to small changes in RH above 90% RH (Armstrong et al., 2012).

FIELD MOISTURE MEASUREMENTS

Moisture Measurements in the Insect Infestation Study.

Figures 6 to 9 show that PHL moisture meter measurements were consistently lower than JD moisture meter readings. The monthly readings done on replicate bags show how the moisture changed over time. Climate data (i.e., the prevailing mean T and RH level) were used to help explain the observed changes. EMC values calculated from the mean T and RH climate data by using the Modified Henderson equation are shown in figure 9 for Kumasi, Accra, and Tamale. All

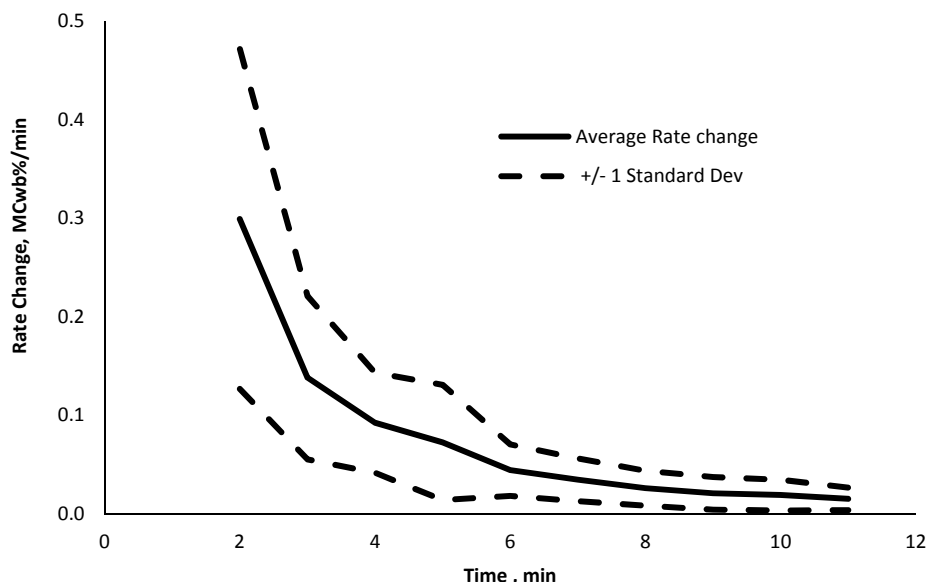


Figure 5. Change in the MC rate with respect to time. Averages for all test conditions show a limit of one standard deviation of the rate change.

Table 1. PHL and GAC 2500 moisture content measurements.^[a]

Nominal Moisture Content(%wb)	Moisture Content (%wb)			
	PHL at 8°C	PHL at 21°C	PHL at 32°C	GAC 2500
10	10.5 (-0.2)	9.4 (0.7)	9.7 (0.7)	10.1
15	15.8 (-1.1)	14.3 (0.8)	13.7 (1.2)	15.3
20	19.6 (0.5)	16.5 (3.6)	16.1 (3.8)	20.6

^[a] The PHL measurements were recorded at 6-min intervals. The difference between the meters is in parentheses.

three curves show an increase in EMC corresponding to the respective rainy seasons. Accra and Kumasi, which are climatologically similar, have similar characteristics, while Tamale has significantly lower EMC values and greater variation throughout the year.

Ejura, Techiman, and Wenchi, which are geographically close, show similar EMC variation (fig. 6). A slight increase

in EMC from May through August was observed to also be similar to that suggested by the climate data for Kumasi (fig. 9). MC measurements in the northern markets in or near Tamale (Kukuo, Lameshegu, Yendi, and Katinda) showed that the EMC decreased from November to December (fig. 8). These measurements again mirror the climate data predictions for the EMC. It appears that bagged grain responds readily to a monthly variation in climatic conditions.

B. Moisture Measurements for Commercial Markets.

Measurements with the two similar PHL and JD moisture meters (tables 2 and 3) show small differences that were typically <0.1% MC_{wb}. Compiling measurements from all of the field studies showed that the JD moisture meter had an average positive offset relative to the GAC 2100 of 2.37% MC_{wb}; the PHL moisture meter had a positive offset.

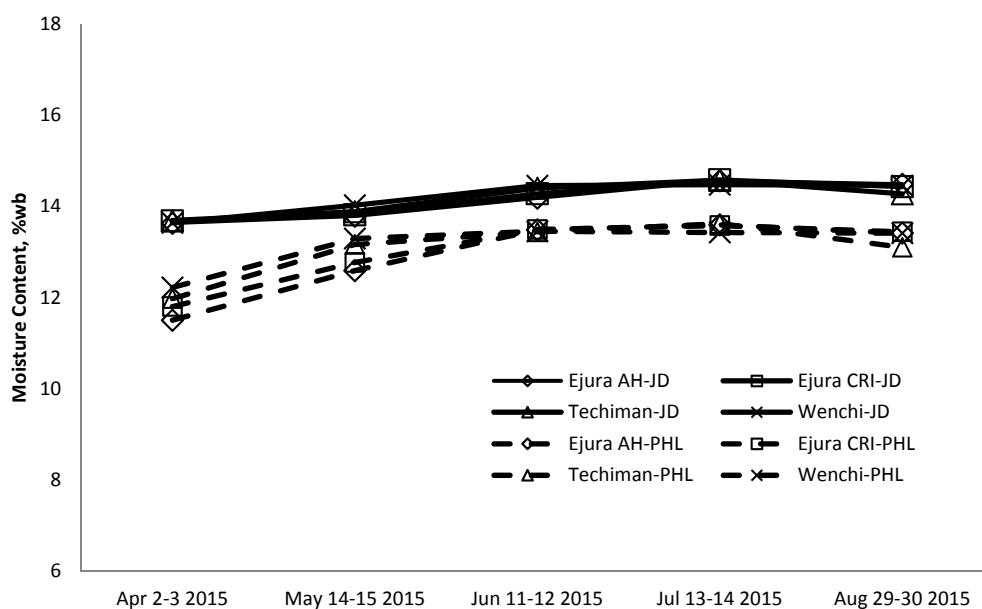


Figure 6. Monthly moisture measurements from April to August, 2015 at Ejura, Wenchi, and Techiman.

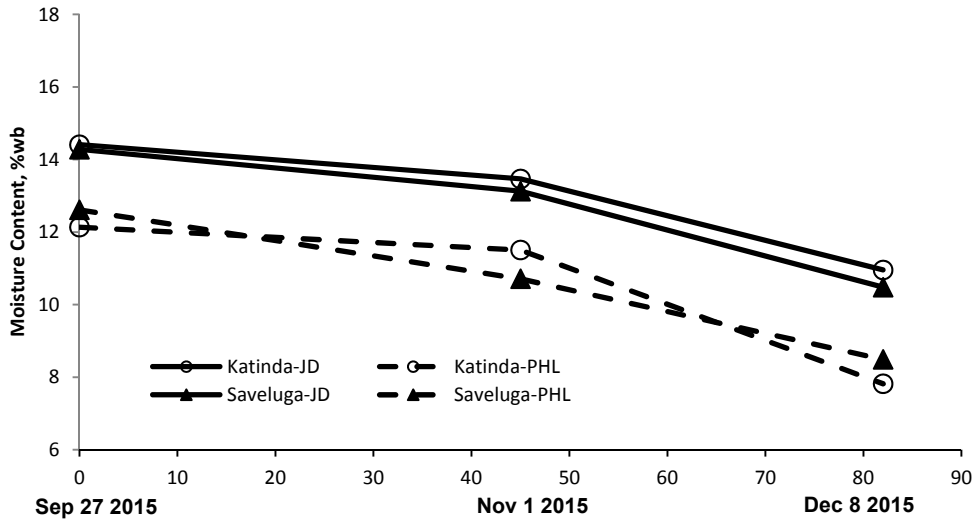


Figure 7. Monthly moisture measurements from September to December, 2015, in Northern Ghana near Tamale.

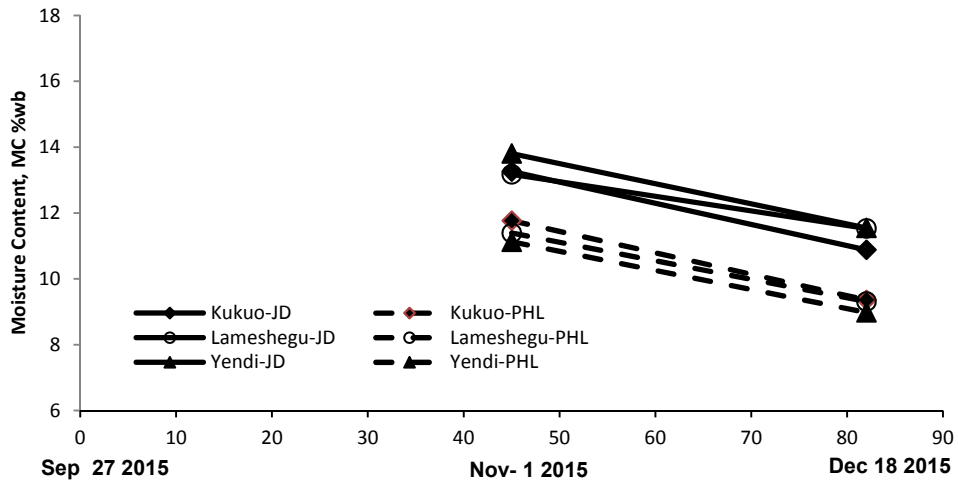


Figure 8. Monthly moisture measurements from September to December, 2015, in Northern Ghana near Tamale.

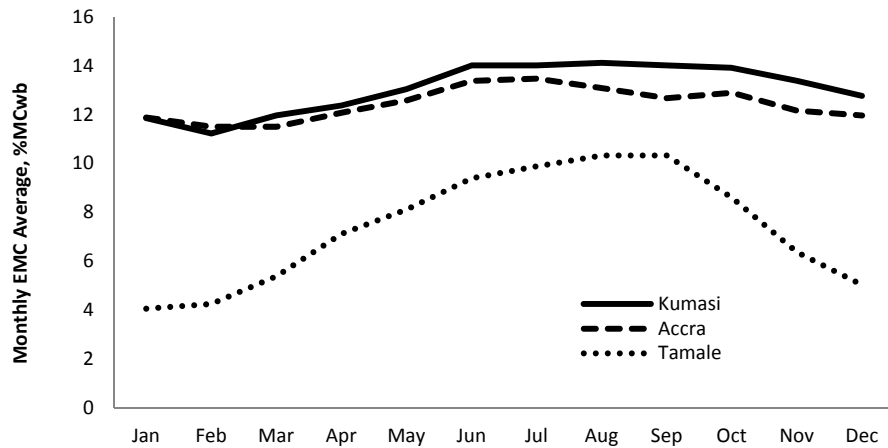


Figure 9. EMC for maize based on monthly climate averages of T and RH.

Table 2. Average moisture content readings obtained on 15 December 2016 with different moisture meters.^[a]

Location	Moisture Content, %wb		
	JD SW08120	PHL	GAC 2100
Ejura	13.1	10.3	10.1
Sekyedumase	14.4	12.6	12.5
Amantin	14.5	12.7	12.6

^[a] Readings were obtained from 10 bags (three replicates per bag for each meter) located at different market locations.

Table 3. Average moisture content readings obtained on 15-17 June and 15 July 2016 with different moisture meters.^[a]

Data Collection Date	Location	Moisture Content (%wb)				
		JD SW08120		PHL		GAC 2100
		Unit 1	Unit 2	Unit 1	Unit 2	2100
15-17 June 2016	Ofinso	15.0	15.1	14.4	14.3	13.2
	Ayinasu	14.9	15.1	13.2	13.2	12.9
	Abofour	14.4	14.3	13.3	13.3	12.6
	Techiman	14.2	14.4	11.7	11.8	11.5
15 July 2016	Nkoranza	14.6	14.6	12.4	12.4	11.8
	Wenchi	14.5	14.5	12.9	12.8	11.8
	Atebubu	14.2	14.0	11.1	11.0	11.1

^[a] Readings for each of the two units of JD and PHL moisture meters were obtained from 10 bags (three replicates per bag for each meter) located at different market locations.

of 0.45% MC_{wb}. The standard error of prediction for the PHL meter compared to the GAC 2100 was 0.57% MC_{wb} or 0.38% MC_{wb} when adjusted for the offset. The two JD moisture meters had similar offsets, and this is likely inherent for all of these models. The measurements shown in figure 10 shows there is better agreement between meters when the offset for the JD moisture meter is applied to its original measurements.

In general, the moisture levels for the bagged maize were at good levels for storage. The highest moisture recorded for any one bag by the GAC 2100 was 14.3%, which was observed at the Ayinasu market. The average MC for all bags was 12.0% MC_{wb} with a standard deviation of 1.02%.

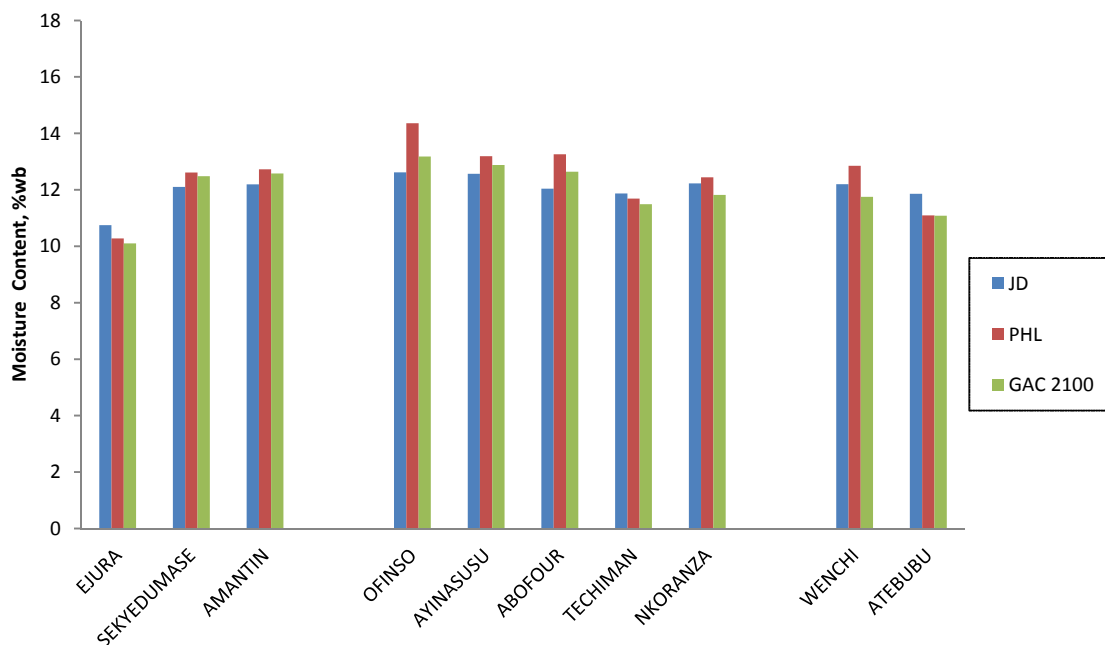


Figure 10. MC measurements from various commercial market locations showing differences between moisture meters. Values are the averages for 10 bags at each location, three replicates per bag. The JD moisture meter was corrected by subtracting a 2.33% MC_{wb} offset.

FUTURE DEVELOPMENT

The current version of the PHL moisture meter design utilizes common and relatively simple electronic and mechanical components that a small local manufacturer could assemble. Based on the findings of this study and feedback from field users, improvements to the meter should consider the following: (a) reducing the power requirements by the use of a better electronic design to improve battery life, (b) programming that would anticipate equilibrium conditions and (c) decreasing the measurement time by reducing the thermal capacity of the probe. Current efforts to incorporate Bluetooth communications to allow a smart device to act as the user interface are ongoing. This could eliminate some components and possibly lower cost as well as allow easier upgrades to the meter, such as new EMC coefficients and firmware. Newer sensor models from the manufacturer, Sensirion, are greatly reduced to about \$3 USD compared to the \$28 sensor used in this study and thus meter cost can be reduced by just incorporating this new sensor.

CONCLUSIONS

The PHL moisture meter provides a convenient and relatively low-cost method to measure the MC of maize and a number of other crops and is well suited for measuring bulk grains such as that in bags or silos. Because it utilizes equilibrium moisture relationships by measuring the T and RH to predict the MC; measurements may take up to 6 min to allow the aluminum tube and sensor in the probe to reach the ambient grain conditions. A method for determining the rate of change of the readings with respect to time could be incorporated into the programming of the PHL moisture meter to reduce the measurement time.

Field tests showed that the measurement accuracy of the PHL moisture meter was good compared to the GAC 2100 with a standard error of prediction of 0.57% MC_{wb}. It should be noted that based on laboratory tests that included high moisture maize (samples not encountered in the field tests), the PHL moisture meter underestimated the maize MC. The John Deere moisture meter measurements had a considerable positive offset (2.37% MC_{wb}) compared to the GAC 2100 measurements. These were adjusted to make its performance comparable to the PHL and GAC 2100 moisture meters by applying a simple bias adjustment. Slope and bias adjustment can likewise be programmed into this meter.

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