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1   **Estimation of Soil Clay Content from Hygroscopic Water Content Measurements**

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25   **ABSTRACT**

26   Soil texture and the soil water characteristic (SWC) are key properties used to estimate

27   flow and transport parameters. Determination of clay content is therefore critical for

28   understanding of plot scale soil heterogeneity. With increasing interest in proximal soil sensing,

29   there is the need to relate obtained signals to soil properties of interest. Inference of soil texture,

30   especially clay mineral content, from instrument response from electromagnetic induction and

31   radiometric methods is of substantial interest. However, the cost of soil sampling and analysis

32   required to link proximal measurements and soil properties, e.g. clay mineral content, can

33   sometimes outweigh the benefits of using a fast proximal technique. In this paper, we propose

34   that determination of a soil's hygroscopic water content at 50% atmospheric relative humidity

35   (RH^{50}), which is time and cost efficient, and particularly suitable for developing countries, can

36   act as a useful surrogate for clay content in interpreting soil spatial patterns based on proximal

37   signals. We used standard clays such as kaolinite, illite and montmorillonite to determine the

38   water release characteristic as a function of hygroscopic water content. We also determined clay

39   content of soils from temperate (Arizona, USA) and tropical (Trinidad) regions using the

40   hydrometer method, and hygroscopic water content for soils equilibrated at RH^{50}. We found

41   linear dependence of clay percentage and RH^{50} for a range of soil mineralogies. Hygroscopic

42   water measurements offer an inexpensive and simple way to estimate site specific clay mineral

43   content that in turn can be used to interpret geophysical signal data in reconnaissance surveys.

44

45   **Keywords**: Hygroscopic water, clay, water release curve, soil texture, geophysics, radiometrics,

46   electromagnetic induction

2

47   **Abbreviations:** EMI, electromagnetic induction; RH, relative humidity; SWC, soil water

48   characteristic.

49

INTRODUCTION

Soil texture (percentage of sand, silt and clay) is a fundamental parameter in soil science (Gee and Bauder, 1986) and a major component of the soil natural capital (Robinson et al., 2009a). Texture is widely used in agriculture and engineering as well as in basic research to estimate for example water release curves in flow and transport modeling (Schaap et al., 2001). Soil texture, especially clay content, controls magnitude and rates of many physical, chemical and hydrological processes in soils. Important soil phenomena such as nutrient storage, nutrient availability, water retention, and stability of aggregates may vary across the field in response to the spatial variability of clay percentage. Soil moisture which is the major control for rainfall-runoff response in a watershed (Robinson et al., 2008a) has been directly linked to clay variability (Crave and Gascuel-Odoux, 1997). Net nitrification and CO_2 release has been shown to depend on water content and clay content (Schjonning et al., 2003). Knowledge of texture, especially the spatial distribution of clay content, is therefore important for a range of ecosystem services, including provisioning through agricultural production and regulating of the hydrological cycle through filtering and buffering. A growing challenge in soil science is to map soil natural capital, of which texture is a component, in a way that allows us to scale from the soil profile, to field, to regions.

Proximal sensing techniques, especially geophysical sensors that infer spatial textural information from instrument response to ions adsorbed on clay minerals (Robinson et al., 2008b), provide an invaluable means for filling the 'intermediate' scale data gap. Electromagnetic induction (Doolittle et al., 1994; Triantafilis et al., 2001; Triantafilis and Lesch, 2005), resistivity (Samouelian et al., 2005), induced polarization (Slater et al., 2006) and radiometrics (Rawlins et al., 2007) are techniques progressively used to determine soil properties

73   or spatial patterns related to texture, inferred from mineralogy and cation binding. In case of

74   electrical methods, cations adsorbed to 2:1 clay minerals can be used to interpret, or determine,

75   the spatial pattern of clay percentage in non-saline soils (Triantafilis et al., 2001; Triantafilis and

76   Lesch, 2005; Sudduth et al., 2005; Harvey and Morgan, 2008). This method is limited to clays

77   that adsorb cations to counter balance negative charge sites, and is less likely to work for clay

78   minerals with low surface areas, e.g. kaolinites. In case of radiometrics, many clay minerals e.g.

79   hydrous micas and illites can be detected through their potassium isotope signal (Taylor et al.,

80   2002). Knowledge of clay content is therefore critical for the signal interpretation of proximal

81   sensing instruments.

82   Direct, grid-like soil sampling for identifying spatial textural patterns has several

83   limitations among which the need for high-intensity sampling and associated costs for analyses

84   are the most constraining ones. In addition, minimizing soil disturbance, i.e. not filling the

85   landscape with holes is vital for many hydrological process studies. In many cases, an

86   understanding of soil spatial patterns, and delimiting of hydrological functional units, is more

87   important than the exact knowledge of soil properties (Grayson and Blöschl, 2000). The costs for

88   independently measuring soil properties for calibration of proximal signals have always been an

89   issue, such that Lesch et al. (1995 a, b) developed efficient sampling methods for interpreting

90   EMI signal response from directed soil sampling. Even with approaches like theirs, the particle

91   size analysis presents a substantial cost for calibration, especially if multiple fields are sampled.

92   In this paper we propose that under many circumstances, a site specific calibration

93   between clay percentage and hygroscopic water content could be used to greatly reduce the

94   number of particle size analyses that might be done for a proximal sensing site calibration.

95   Estimating clay percentage from hygroscopic water content presents a cost efficient, simple and

96   reliable surrogate for correlating proximal signal response to soil clay content; although the

97   paper does not specifically explore EMI calibration. Our major goal is to investigate if simple,

98   cost and time efficient hygroscopic water content measurements can be used to estimate clay

99   contents for soils with varying mineralogies.

100   In soils, soil solution electrical conductivity EC_e, volumetric soil water θ_v and clay

101   contents are the major factors influencing bulk soil electrical conductivity EC_a (Friedman, 2005)

102   and EMI signal response. In the case of radiometrics, clay content, and to a lesser extent soil

103   moisture are the driving factors. The intimate relationship between soil clay content and

104   hygroscopic water content is well established (Briggs and Shantz, 1912, Banin and Amiel, 1970;

105   Petersen et al., 1996), but not widely exploited. It was proposed as a method for determining soil

106   surface area, but largely abandoned because water tends to cluster on charged clay mineral

107   surfaces, not forming a monolayer like EGME, which has a lower dielectric constant, or non-

108   polar nitrogen (Quirk and Murray, 1999). Therefore, we hypothesize that soil hygroscopic water

109   content, whose determination is fast and technically less involved than particle size analysis,

110   positively correlates with clay percentage in both temperate and tropical soils, and can provide a

111   useful surrogate for soil clay content. Other research groups have presented results that

112   emphasize the strong correlation between hygroscopic water and clay contents (Banin and

113   Ameil, 1970; Petersen et al., 1996, Tuller and Or, 2005; Resurreccion et al., 2011), however,

114   there is no specific water potential or relative humidity agreed upon at which these relationships

115   should be determined.

116   Clay content and type of clay minerals determine the magnitude of the soil specific

117   surface area (Petersen et al., 1996). Banin and Amiel (1970) presented data with specific surface

118   area showing a strong linear dependence (r^2=0.902) to clay contents. In the studies of Banin and

119   Amiel (1970) and Dirksen and Dasberg (1993), hygroscopic water content had a strong linear

120   correlation (r^2=0.936) with soil specific surface area. Recently, Logsdon et al. (2010) determined

121   hygroscopic water content of soils in a vapor-tight container over distilled water at ~99 %

122   relative humidity and concluded that higher hygroscopic water content is associated with high

123   soil specific surface area. To come to an agreement about a specific relative humidity level at

124   which hygroscopic water content ought to be determined, in-depth knowledge of the water

125   release characteristics of different clay minerals is required. Therefore, the objectives of the

126   present study were to: (1) determine the water release characteristics for standard source clays;

127   (2) define a suitable relative humidity level for estimating clay content for the source clays; and

128   (3) examine the relationship between hygroscopic water content and clay content using the

129   defined relative humidity for soils with varying mineralogies from temperate and tropical

130   regions.

131

132   **MATERIALS AND METHODS**

133   **Clay Minerals**

134   Standard 100 % source clay minerals were used to determine the hygroscopic water

135   content as a function of relative humidity. The selected samples were the same as used in Lebron

136   et al. (2009) and included: Silver Hill illite from Montana (IMt-1) and Ca-montmorillonite from

137   Cheto, AZ (SAz-1) obtained from the Clay Mineral Society's Source Clay Repository; Wyoming

138   bentonite (Aqua Technologies of Wyoming, Casper); and kaolinite from the Lamar pit (Bath,

139   SC). The SAz-1 montmorillonite was saturated with Na, Ca or Mg to produce clay samples

140   saturated with a single ion (Goldberg and Glaubig, 1987).

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7

Soil Samples

The first set of samples contained tropical soils from the University of the West Indies soil sample collection in Trinidad. Trinidad is the southernmost of the Islands of the Lesser Antilles in the Caribbean Sea and is situated $10^o3'$N $60^o55'$W and $10^o50'$N $61^o55'$W. The 23 soils used for this study were collected from different locations across the island, representing a range of soil types including kaolinitic, micaceous, and montmorillonitic soils (Table 1). In addition, 20 temperate soils from the University of Arizona Department of Soil, Water and Environmental Sciences' source soil collection, again representing a wide range of mineralogies and clay content were analyzed (Table 1).

Furthermore, a number of datasets originating from both Trinidad and the USA that were previously used for EMI calibration were investigated. Soils from Trinidad were collected from Guayaguayare, Moruga, Centeno and Woodland from locations identified via an EMI-directed soil sampling method (Lesch et al., 2000). Data from the USA were obtained from the T.W. Daniel Experimental Forest (TWDEF) in northern Utah and the Reynolds Mountain East catchment within the Reynolds Creek Experimental Watershed in southwestern Idaho (Abdu et al., 2008).

Clay and Soil Sample Analysis

The water release characteristics for the source clays were measured with a Dewpoint Potentiameter (WP4-T, Decagon Devices, Inc., Pullman, WA, USA). The clay samples were oven dried at 105^oC and then left equilibrating with the ambient laboratory atmosphere at controlled temperature (25^oC) for several months. Once the humidity level of interest had been reached and was stable for 2-3 days, samples were weighed with an analytical balance and the

165   soil water potential was determined with the WP4-T. Relative humidity was measured using a

166   humidity sensor (Thermo Hygro, Thermo-Fisher, Waltham, MA). In order to establish a range of

167   humidities this experiment lasted about 5 months. Soil water potential was converted to relative

168   humidity via the well-known Kelvin equation:

169
$$\Psi_w = \frac{RT\rho_w}{M_w} \ln\left(\frac{e}{e_0}\right) \tag{1}$$

170   where Ψ_w is soil water potential, R is the universal gas constant (8.31 J K^{-1} mol^{-1}), T is the

171   absolute temperature (^{o}K), ρ_w is the density of water (kg m^{-3}) and M_w is the molecular weight of

172   water (0.018 kg/mol). The ratio of e, the water vapor pressure, to e_0, the saturation vapor

173   pressure, is the temperature-dependent relative humidity, which can be rewritten as:

174
$$RH = \frac{e}{e_0} = \exp^{\frac{M_w \Psi_w}{\rho_w R T}} \tag{2}$$

175   The soil samples originating from Trinidad were first oven-dried at 105 ^{o}C and then equilibrated

176   with the ambient atmosphere of a temperature-controlled room (25 ^{o}C) with a monitored relative

177   humidity (Thermo Hygro, Thermo-Fisher, Waltham, MA) of ~50 %. The steps developed to

178   measure hygroscopic water content (θ_{hw}) at RH^{50} are described below:

179

180   1. Weigh the sample containers using a four-decimal analytical balance (W_c).

181   2. Weigh approximately 10 g of air-dried sample into the sample containers and place them in

182   the oven to dry at 105 ^{o}C for 24 hours, weigh again directly from the oven before cooling, using

183   a thermal isolator to protect the balance ($W_{ovendry}$).

184   3. Allow the oven-dried samples to equilibrate to RH^{50} at ambient conditions in the laboratory.

185   Equilibration of our samples was achieved within 48 to 72 hours when RH was monitored using

186   a thermohygrometer sensor.

187   4. Measure the humidity, monitor over a 2 hours period, if 50 % is maintained reweigh the

188   equilibrated samples to determine the moisture gain (W_{RH50}).

189   5. The θ_{hw} at RH^{50} in the sample is calculated gravimetrically as:

190

191   $$\theta_{hw} = \frac{(W_{RH50} - W_c) - (W_{ovendry} - W_c)}{(W_{ovendry} - W_c)} \quad\quad\quad (3)$$

192

193   The samples from Arizona were equilibrated at 50 % humidity and 25 ^{o}C using a temperature

194   and humidity controlled environmental chamber (1007H Temperature/Humidity Chamber,

195   TestEquity, LLC, Moorpark, CA, USA). An additional experiment was conducted to determine

196   how fast soils re-adsorb water following oven-drying. To achieve this, oven-dried soil samples

197   were weighed and kept in the environmental chamber at 50 % relative humidity and 25 ^{o}C. The

198   soil samples were then weighed in 3 hour intervals to capture the initially highly dynamic change

199   in water content. The time interval was then stepwise increased to 6, 12, and 24 hours for a total

200   time period of 15 days. The clay content was determined with the hydrometer method (Gee and

201   Bauder, 1986). Organic matter was removed using hydrogen peroxide (35 % H_2O_2) and

202   dispersed using 5 %-sodium hexametaphosphate.

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207 **RESULTS**

208 **Source Clay Samples**

209   Results for hygroscopic water content (θ_{hw}) as a function of relative humidity are

210 presented in Fig. 1. The data for 2:1 clay minerals show a substantial increase in θ_{hw} at low

211 humidities, a levelling off at RH values between about 50-60 % and then increasing water

212 content again at RH values above 80 %. Both the 2:1 clays montmorillonite and illite adsorbed

213 more than 0.05 m^3 of water per gram of oven dry soil at RH values of ~50 %. However, kaolinite

214 didn't adsorb water until ~80 % humidity or higher.

215

216 **Determination of Hygroscopic Water Content at RH^{50}**

217   Based on results from the water release curves (Fig. 1) we adopted the RH^{50} for

218 equilibrating our soils as a compromise value considering the range of mineralogies. This also

219 represents a relatively stable point at which the change of θ_{hw} with humidity is at a minimum;

220 RH^{50} is also commonly attained in the laboratory meaning no special equipment is required to

221 equilibrate the soils at this humidity.

222

223 **Water Uptake and Equilibration of Samples at RH^{50}**

224   After adopting the RH^{50} for equilibrating our soils, we determined the time for samples to

225 readsorb water in the lab following oven drying. The results of the rate at which water uptake

226 occur using the Arizona soils data set after oven drying is presented in Fig. 2. The facilities at the

227 laboratory in Arizona allowed samples to be analyzed in greater detail under more tightly

228 controlled conditions. In our experimental method soils are oven dried and then allowed to re-

229 equilibrate at RH^{50} to determine the fraction of hygroscopic water. The samples tend to

230   equilibrate within ~2 days (Fig. 2). We suggest leaving the samples for a minimum of 54 hours,

231   which seems appropriate for re-equilibration. This is convenient for laboratory scheduling, as

232   soils may be removed from a drying oven, after drying overnight, and then be weighed with the

233   start of equilibration at ~9 am. Samples can be left to equilibrate for two days and then measured

234   around 3 pm or later to determine the water uptake.

235

236   **Effect of Organic Matter Removal on Water Adsorption at RH[50]**

237   Hygroscopic water content as a function of the clay percentage of untreated and treated

238   Arizona soils that have had organic matter removed are presented in Fig. 3. The purpose of this

239   was to determine if the presence of organic matter strongly affected the relationship between the

240   hygroscopic water content and clay percentage. The removal of organic matter results in slightly

241   lower water adsorption, confirming that the clay percentage is the major factor in determining

242   the amount of water adsorbed. Based on the regression lines shown, and assuming that the

243   organic matter is largely responsible for any additional water adsorption, ~5 % difference in

244   organic matter for a soil with ~50 % clay may result in an 8 % difference in the estimated clay

245   percentage, which is acceptable for using field soil for a reconnaissance survey. This indicates

246   that for these soils, organic matter was not a major issue, but in future work we might want to

247   examine how different types of organic matter adsorb water and whether the relationship is

248   linear.

249   Fig. 4 compares the measurement error associated with determining the hygroscopic

250   water content of soil samples based on mass gained, with the measurement error associated with

251   determining clay content from sedimentation analysis using the hydrometer method. As

252   expected, the measurement errors are generally smaller at higher clay contents, with the % error

253   increasing rapidly at low clay contents. The error for the hygroscopic water content is generally

254   lower at low clay contents because our ability to weigh accurately is greater than our ability to

255   detect clay via sedimentation at low clay contents; from clay contents of 10-50 % the errors

256   involved are similar. This indicates that the greatest errors in estimating clay percentage from

257   hygroscopic water will be dependent on the spatial variability of organic matter, if not removed

258   from samples.

259

260 Hygroscopic Water Content as a Function of Clay Content for Soils Equilibrated at RH^{50}

261   Hygroscopic water content as a function of clay percentage for both the Arizona and

262   Trinidad soil data sets equilibrated at RH^{50} is presented in Fig. 5. The Trinidad soils are divided

263   according to major mineralogy, kaolinitic, micaceous and mixed clays, sesquioxides and

264   montmorillonitic; the Arizona soils were dominated by mica and illite clay minerals. These soils

265   represent the range of 2:1 and 1:1 clay mineralogies (Table 1) and indicate strong consistency in

266   response compared to the trendlines indicated for the different pure clay minerals. The soils

267   dominated by sesquioxides and montmorillonite have distinctively higher hygroscopic water

268   content values than the other soils. The montmorillonite follows the bentonite trendline, whilst

269   the micaceous and mixed mineralogy follows the illite trendline. Noticeably the oxide dominated

270   soil follows the bentonite trendline indicating this soil can adsorb a lot of water; highly

271   weathered tropical soils with amorphous oxides can have large surface areas on which water can

272   adsorb (Sanchez, 1976; Goldberg et al., 2001; Robinson et al., 2009b). In addition, some of the

273   kaolinitic soils (clay content 50-70 %) have higher water content than might be expected. This

274   may occur due to the presence of oxides in these soils, biasing values upwards and requires

275   further research. The r^2 values for the regression equations of hygroscopic water content as a

276   function of clay content were 0.78 and 0.68 for Arizona soils and all Trinidad soils, respectively.

277   This indicates a positive linear relationship between hygroscopic water content and clay content

278   for soils of varying mineralogies, from temperate and tropical regions. The relationship was only

279   superior in the Arizona soils compared to the Trinidad soils due to less mineralogical variation.

280   The r^2 for the Trinidad soils increased to 0.84 after removing the oxide and montmorillonite

281   soils.

282   A compilation of available data sets that contain both clay percentage information and

283   hygroscopic water content (RH^{50}) for samples taken from landscapes mapped with the EMI

284   sensor in the USA and Trinidad, are presented in Fig. 6. The results fall broadly in the same

285   location as in Fig. 5. The r^2 values with intercept set to zero, RMSE and corresponding

286   mineralogy are presented in Table 2. The r^2 values improve as the range of the clay percentage

287   broadens. All RMSE values for clay percentage as a function of RH^{50} fall below 10 % with the

288   median value being 5 %. This indicates that for these soils, RH^{50} was a reasonable predictor of

289   clay percentage. Placing a regression line through all data (clay % = 1037.5* RH^{50}) gave an r^2 of

290   0.70 and resulted in a RMSE of 6.5 % which may be acceptable for reconnaissance survey.

291   However, we do not advocate the use of a single relationship as it is mineralogy dependent. In

292   this regard a site specific calibration should be established between RH^{50} and clay percentage

293   that could then be used to estimate clay percentage from subsequent samples measured only for

294   RH^{50}. RH^{50} values would be useful for providing secondary data, in for example co-kriging

295   geostatistical methods (Lesch et al., 1995a). The results indicate reasonable correlations,

296   demonstrating that hygroscopic water content at RH^{50} has good potential to act as a pedotransfer

297   function to estimate clay percentage at least for reconnaissance surveys and as a secondary

298   variable for geostatistical interpolation.

299   **DISCUSSION**

300   Developing a standard approach to estimating clay percentage from the hygroscopic

301   water content relies on agreeing on an accepted relative humidity value at which to measure the

302   hygroscopic water content. Different authors have used different values, Banin and Amiel (1970)

303   used air dry samples, whilst Petersen et al. (1996) used a pressure of 1.5 MPa. Logsdon et al.

304   (2010) determined hygroscopic water content of air dry soils in a vapor-tight container over

305   distilled water at ~99 % relative humidity. In an effort to standardize a method, Lebron et al.

306   (2009), used a hygroscopic water content of 41 % to determine gypsum content in soils. They

307   used 41 % because this is the relative humidity achieved by equilibrating samples over a

308   saturated solution of K_2CO_3 in a dessicator, which makes standardization easier, especially given

309   the temperature stability of the RH of K_2CO_3. However, finding a salt that offers a temperature

310   stable RH at ~50-60% is not straightforward. Any chosen value of RH is a trade-off between

311   having a zone of minimal relative change of slope of the water release curve of the soil (Fig. 1),

312   and having enough water to obtain a meaningful measurement of hygroscopic water content.

313   RH^{50} was chosen as a compromise, bearing in mind this trade-off, which seems to work

314   reasonably well even in kaolinitic soils. The use of K_2CO_3 is appealing and good for 2:1 clay

315   mineral soils, but is not so good for kaolinitic soils which have essentially desorbed all their

316   water at RH 41%.

317   The benefits of proximal sensing techniques in reconnaissance surveys have, to some

318   extent, been undermined by the cost and tedious requirements for soil sampling and analysis of

319   properties such as clay percentage required for their calibration. The removal of organic matter

320   from the samples in the current study resulted in only minimal reduction in adsorbed water (Fig.

321   4). This signifies that in soils low organic matter, clay percentage is the major factor in

322   determining the amount of water adsorbed. Clay percentage has been shown by previous workers

323   to be strongly correlated with specific surface area and hygroscopic water content (e.g., Banin

324   and Amiel, 1970; Petersen et al., 1996; Robinson et al., 2002). However, hygroscopic water

325   content which is a quicker and cheaper soil property to measure is often not routinely collected

326   by soil surveys (Robinson et al., 2002). Since the amount of water adsorbed by a sample varies

327   depending on the ambient humidity, finding a suitable relative humidity for the equilibration of

328   soils is important for the determination of hygroscopic water content to speed up the

329   interpretation of geophysical signals. In our study, RH^{50} was chosen as a compromise value from

330   the determination of hygroscopic water content for standard clays which generally yielded

331   hygroscopic water content values that were strongly correlated with clay percentage for both

332   tropical and temperate soils of varying mineralogies.

333

334

335   **SUMMARY AND CONCLUSIONS**

336

337   The work presented describes a simple, cost and time efficient method of estimating clay

338   content using hygroscopic water content measurements. To successfully determine the

339   relationship between hygroscopic water content and clay content it is important to identify a

340   suitable value of relative humidity for equilibration of soils. Based on our results on water

341   release curves of standard clay minerals, this value was identified to be ~50 %, a relatively stable

342   point at which the change in hygroscopic water content with humidity is at a minimum. This

343   value was then used to equilibrate soil samples from tropical (Trinidad) and temperate (Arizona)

344   regions exhibiting a wide range of soil mineralogy.

345   The work presented indicates positive correlations between soil hygroscopic water

346   content measured at RH^{50} and the clay percentage in the soil. Hygroscopic water content

347   measured at RH^{50} has good potential to act as a pedotransfer function to estimate clay percentage

348   for surveys. One of three approaches, with increasing accuracy, could be adopted:

349   1) estimate clay percentage from the linear hygroscopic water content calibration

350   presented for all soils.

351   2) perform a site specific calibration on a soil subsample between clay and relative

352   humidity.

353   3) perform a full calibration using particle size analysis.

354

355   With the growth of proximal sensing the first approach offers a cheap and rapid way to

356   estimate the dependence of soil geophysical signal response surfaces to hygroscopic water

357   content as a surrogate for soil clay percentage for reconnaissance survey. This may guide a

358   surveyor as to the major soil parameter contributing to the geophysical signal response.

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Table 1. USDA textural class, clay percentage and mineralogy of 23 tropical soils from the soil collection of the University of the West Indies, Trinidad and 20 temperate soils from the soil collection of the University of Arizona, USA.

| University of the West Indies soil collection			University of Arizona soil collection		
USDA textural class	Clay content (%)	Clay minerals	USDA textural class	Clay content (%)	Clay minerals
Sandy Loam	15	Kaolinitic	Coarse Sand	1	-
Sandy Loam	17	Micaceous	Fine Sand	2	-
Sandy Loam	18	Kaolinitic	Loamy Coarse Sand	6	Micaceous
Sandy Loam	19	Micaceous	Loamy Sand	10	Micaceous
Sandy clay Loam	27	Micaceous	Loamy Fine Sand	5	Micaceous
Sandy clay Loam	27	Mixed	Fine Sandy Loam	7	Illitic
Sandy clay Loam	29	Kaolinitic	Sandy Loam	15	Micaceous
Sandy clay Loam	29	Kaolinitic	Fine Sandy Loam	12	Micaceous
Sandy clay Loam	29	Kaolinitic	Loam	19	Illitic
Sandy clay Loam	29	Kaolinitic	Silt Loam	20	Micaceous
Sandy clay Loam	33	Kaolinitic	Silt Loam	20	Micaceous
Sandy clay Loam	35	Mixed	Loam	24	Micaceous
Clay Loam	35	Mixed	Sandy Clay Loam	25	Micaceous
Sandy clay	43	Oxidic	Sandy Clay Loam	31	Micaceous
Clay	45	Mixed	Clay Loam	36	Micaceous
Clay	51	Mixed	Silty Clay Loam	35	Micaceous
Clay	55	Kaolinitic	Silty Clay Loam	34	Micaceous
Clay	57	Mixed	Silty Clay	52	Illitic
Clay	63	Kaolinitic	Clay	54	Illitic
Clay	66	Kaolinitic	Sandy Clay	39	Micaceous
Clay	67	Mixed			
Clay	71	Montmorillonitic			
Clay	82	Mixed			

461 **Table 2. RMSE for the prediction of clay percentage from the RH^{50} values for a selection of**

462 **soils and the dominant mineralogy.**

Soil sampling location	r^2 (No. of samples)	Clay % RMSE	Dominant mineralogy
Moruga, Trinidad	0.40 (40)	6.6	Mixed
Guayaguayare, Trinidad	0.62 (46)	4.0	Kaolinitic
Woodland, Trinidad	0.40 (67)	9.0	Montmorillonitic
Centeno, Trinidad	0.87 (123)	6.2	Mixed
TW Daniels, Utah	0.63 (15)	3.5	Montmorillonitic
Reynolds Creek, Idaho	0.48 (17)	4.2	Montmorillonitic

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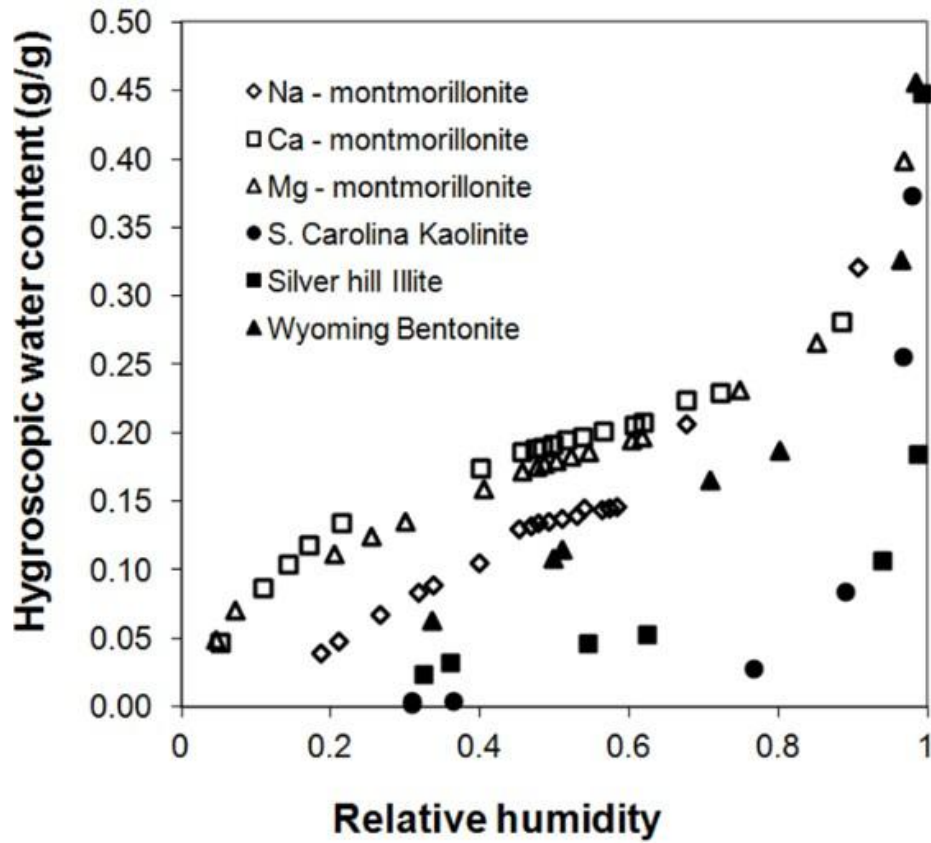
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466   Fig. 1. Water release curves for standard clays.

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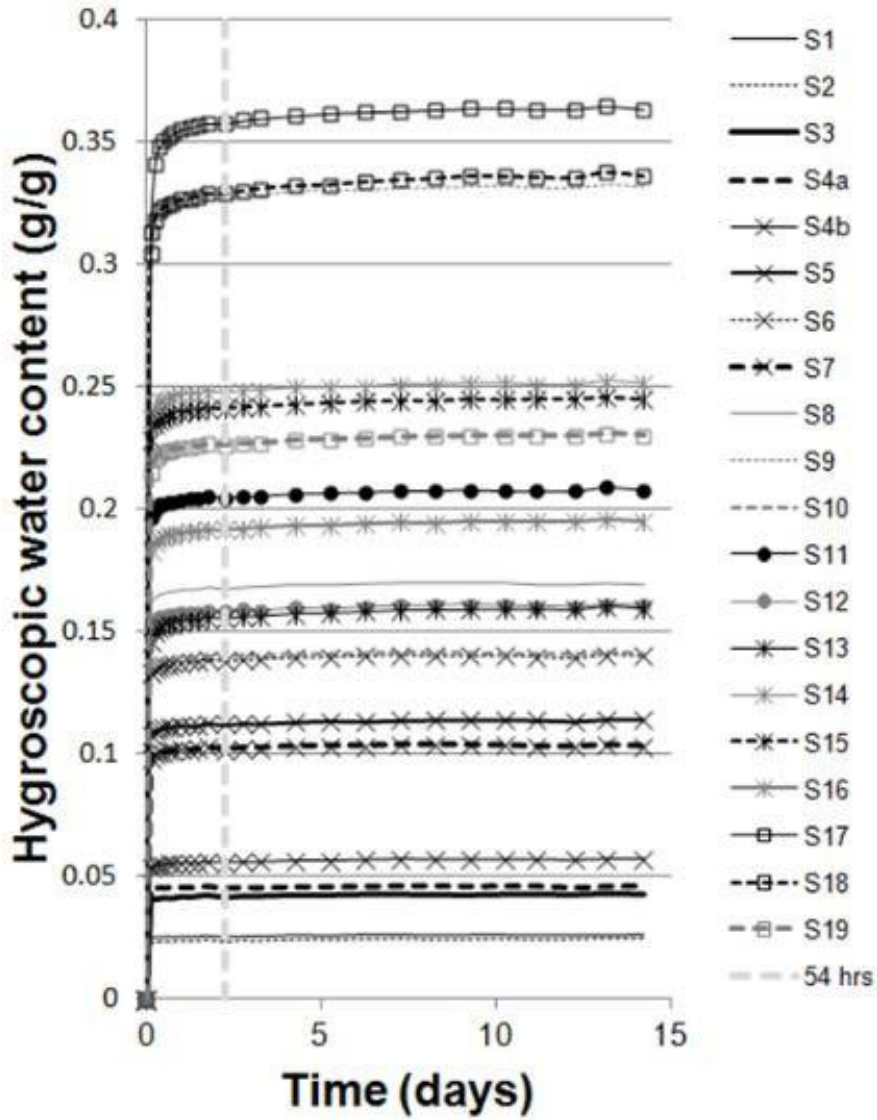
Fig. 2. Water uptake on treated temperate Arizona soils at 25°C indicating water is rapidly
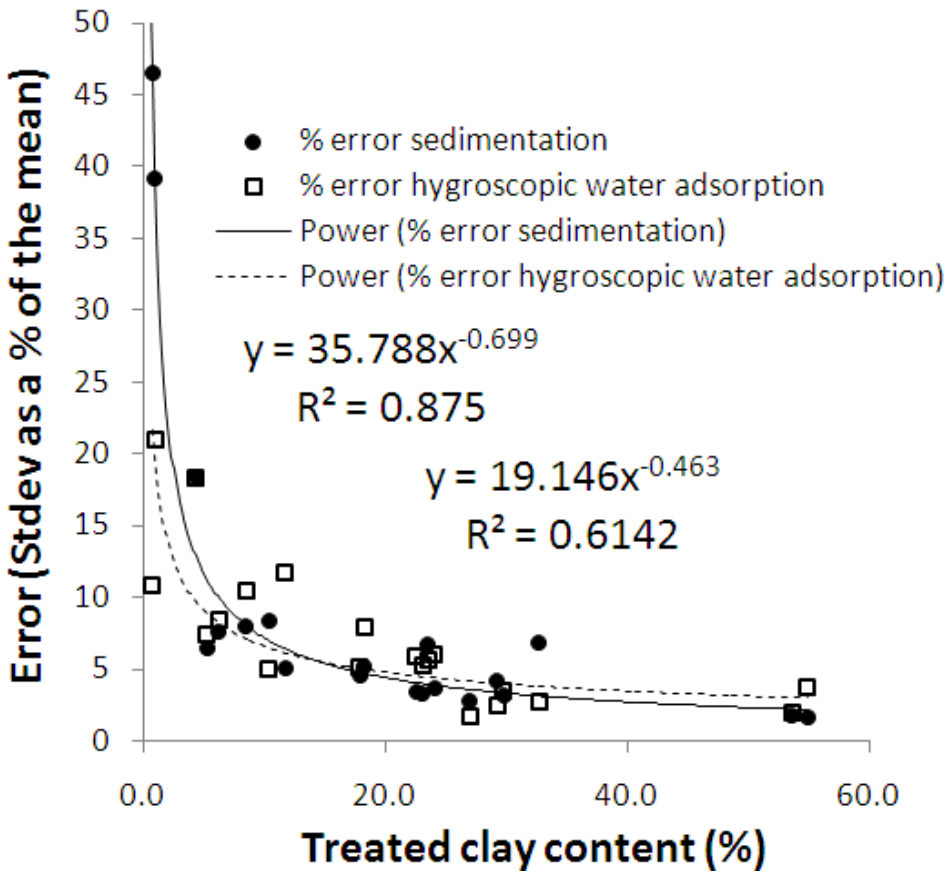
adsorbed in 48hrs.
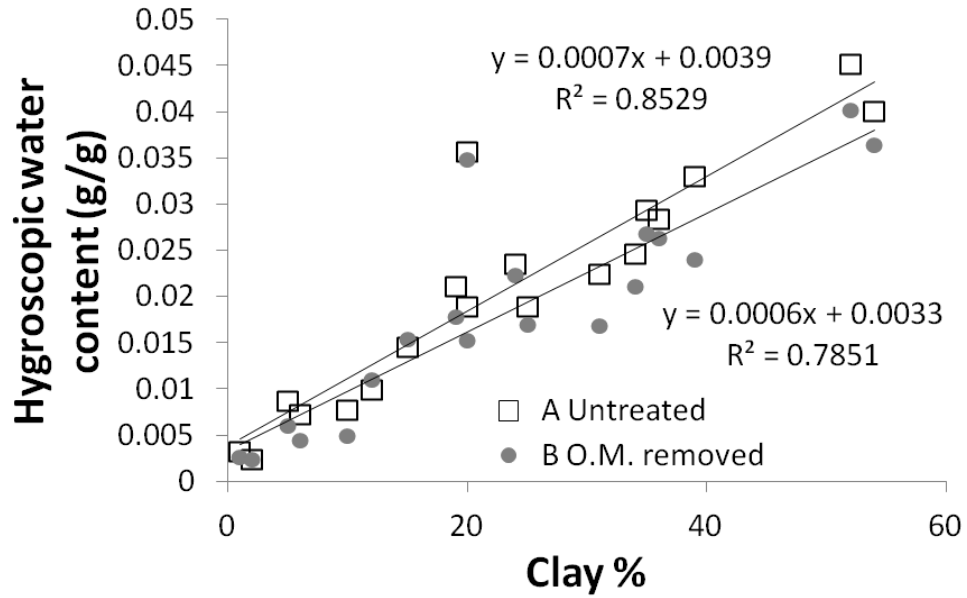
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477   Fig. 3. Hygroscopic water content as a function of the clay percentage comparing untreated and

478   treated temperate Arizona soils that have had organic matter (O.M.) removed.
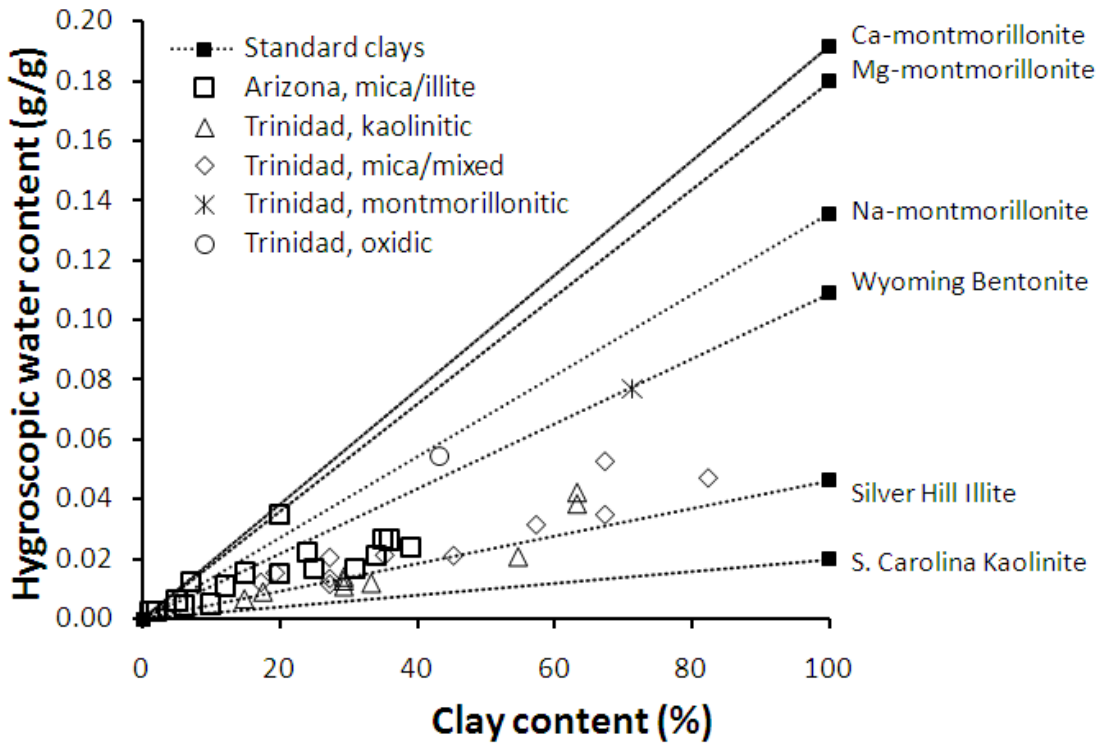
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482   Fig. 4. Trinidad and Arizona soils error as a function of the treated (organic matter removed) clay

483   percentage; the error is represented as the standard deviation (stdev) as a percentage of the mean

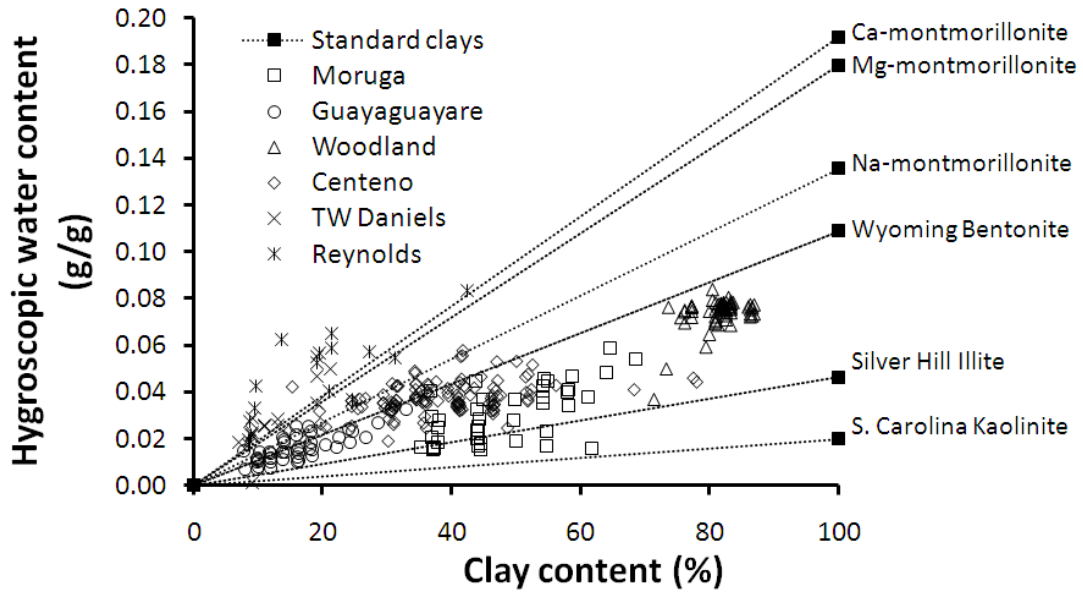484   of 4 independent replicates.

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489   Fig. 5. Hygroscopic water content (RH^{50}) as a function of clay percentage for 23 tropical

490   Trinidad soils divided by major mineralogy, 20 temperate Arizona soils, and 100 % clay

491   samples. The dashed linear trend lines join the 100% clay samples to the origin as a guide for

492   comparison with figure 6.

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498   Fig. 6. Five data sets showing field scale variability; one data set from a soil dominated by Ca

499   montmorillonite from Utah and four from Trinidad. The dashed linear trend lines join the 100%

500   clay samples to the origin as a guide for comparison with figure 5. For r^2 and RMSE see Table 2.