Refining pedotransfer functions for estimating peat bulk density

S.J. Chapman[1], J. Farmer[1,2], A. Main[1] and J. Smith[2]

[1]The James Hutton Institute, Craigiebuckler, Aberdeen, AB15 8QH, UK
[2]Institute of Biological and Environmental Sciences, University of Aberdeen, UK

_____

SUMMARY

Several previous studies have demonstrated the close relationship between peat dry bulk density and gravimetric moisture content. However, the basis for including peat ash (mineral) content or variation in the specific gravity of peat solids has not been covered. Here we present a theoretical basis for estimating peat dry bulk density for saturated peats from values of moisture content and, where available, ash content. The theory is evaluated using datasets obtained from Scotland, Ireland and Indonesia where both dry bulk density and peat moisture content have been measured. Deviations from theory are discussed in terms of peat gas volume and possible errors in the determination of peat dry bulk density.

KEY WORDS: peat ash content, peat dry bulk density, peat moisture content, peat solids specific gravity

_____

INTRODUCTION

The bulk density of peat is recognised as one of the defining physical parameters and its characterisation is essential to any estimation of peatland carbon stocks. Values typically vary between 0.05 and 0.26 g cm^{-3}, with increases in bulk density as one goes from acrotelm to catotelm, from bog peat to fen peat, from fibrous peat to amorphous peat (and increasing with degree of humification), from deep peat to shallow peat, as one samples down the peat profile (but not always), and from near-natural sites to areas impacted by drainage and other management interventions (Lindsay 2010). Päivänen (1969) also showed subtle increases in bulk density going from _Sphagnum_ peats, through _Carex_ peats to woody peats.

Obtaining values of peat dry bulk density is not an easy task, particularly in profiles deeper than one to two metres. Hence, there tends to be a paucity of data on bulk density. Such data are needed, for example, when estimating total carbon stocks in peatlands. This is particularly the case for blanket peat, the form of peatland most common in Scotland (Chapman _et al_. 2009). While bulk density may not be measured, it is common during peat core sampling to measure other parameters such as loss-on-ignition (or ash content), carbon content, gravimetric moisture content or degree of humification by some suitable method. Here we investigate the possibility of using one or more of these other measures as a pedotransfer function in order to determine values for bulk density.

THEORY

Our concept of 'peat' coincides approximately with that of Joosten _et al_. (2017) "peat is sedentarily accumulated material consisting of at least 30 % (dry weight) of dead organic material". This is similar to the definitions of 'organic soil material', i.e. containing at least 12–18 % organic carbon or 20–30 % organic matter (depending upon the clay content of $0->50$ %; Avery 1980), 12–18 % organic carbon (depending upon the clay content of $0->60$ %; USDA 1999) or ≥ 20 % organic carbon (IUSS Working Group WRB 2015). However, for current purposes, these definitions amount to somewhat arbitrary divisions of the peat-to-mineral-soil continuum, as our approach embraces all possible combinations of organic matter (OM), mineral particles, water and air.

Päivänen (1969) showed how peat bulk density could be derived from what he called "laboratory volume weight" but what is actually a laboratory dry bulk density, or particle packing density of dried and milled peat. He obtained reasonable correlations between actual dry bulk density and laboratory volume weight (r^2 > 65 %, n = 316), and a good correlation (r^2 > 84 %) with the humification index on the von Post scale (von Post 1922). Later, Laine & Päivänen (1982) derived the theoretical relationship between bulk density and water content for saturated peats, which gave a much better correlation (r^2 > 99 %, n ~ 260). Rearranging their formulae we obtain:

$$D_b = 1 \Big/ \left(\left(M/(1-M) \right) + \left(1/D_s \right) \right) \qquad [1]$$

where D_b is dry bulk density (g cm^{-3}), M is gravimetric moisture content (g water g^{-1} fresh weight peat) and D_s is the specific gravity of peat solids (g cm^{-3}), which they fixed at 1.5 g cm^{-3}.

In studies where both dry bulk density and moisture content have been determined, a negative linear relationship between the two has been presented (e.g., Tolonen & Ijäs 1982, Klemetti & Keys 1983). However, Laine & Päivänen (1982) recognised that the relationship deviates slightly from the linear, as also shown by Equation 1. This deviation increases as D_s increases, though the effect is marginal.

The D_s of peat solids depends upon the component plant material and the ash (mineral) content. Clymo (1970) gives the D_s of undecomposed *Sphagnum* as 1.54–1.65 g cm^{-3}, possibly depending upon the species. Driessen & Rochimah (1976) give D_s values of Indonesian peats as 1.26–1.80 depending upon the ash content, while Huat *et al.* (2009) give 1.05–1.9 for Malaysian peats. Galvin (1976) gives a value of 1.36 for Irish *Sphagnum* peat. Tolonen & Ijäs (1982) cite a D_s range of 1.3–1.6 for Finnish peats. In an earlier study on Finnish peats, Karesniemi (1972) showed how D_s increased with ash content with a range of 1.4–1.9. However, the higher values were only obtained in peats with up to 50 % ash; for those with ash content less than 10 %, D_s was generally less than 1.5.

In a further refinement, Landva *et al.* (1983) expressed D_s in terms of the specific gravity of the organic matter (D_{OM}) and of the ashed solids (D_{Ash}):

$$1/D_s = \left((1 - p_{Ash})/D_{OM} \right) + \left(p_{Ash}/D_{Ash} \right) \qquad [2]$$

where p_{Ash} is the proportion of ash (g ash g^{-1} dry weight peat), which may range, in theory, from zero (pure OM) to unity (100 % mineral soil). Predictably, the range of D_s values calculated using Equation 2 for their Canadian peats was similar to those given above. Combining Equations 1 and 2 gives:

$$D_b = 1 \Big/ \left(\left(M/(1-M) \right) + \left((1 - p_{Ash})/D_{OM} \right) + \left(p_{Ash}/D_{Ash} \right) \right) \qquad [3]$$

We should note that 'ash' in very low ash peats results from the minerals chemically associated with the organic matter, while in peats of higher ash content it will also include mineral material that has been added to the peat through wind or water action, atmospheric deposition or mixing with mineral soil layers. However, from a practical point of view, it is the residue following loss-on-ignition and is assumed to have a specific gravity similar to that of soil mineral material.

Equations 1 and 3 apply to saturated peats. However, it is possible to apply them to non-saturated peat, i.e. either peat above the water table or peat below the water table that contains gas pockets, by including the proportion of air or gas filled volume, p_g:

$$D_b = (1 - p_g) \Big/ \left(\left(M/(1-M) \right) + \left((1 - p_{Ash})/D_{OM} \right) + \left(p_{Ash}/D_{Ash} \right) \right) \qquad [4]$$

Usually p_g is not known but Equation 4 can be used to estimate it when both D_b and M have been measured. Ideally p_{Ash} should also be measured but otherwise a fixed value for D_s can be used. Equation 4 of course can be derived from first principles, considering peat to be a combination of solid, liquid and gaseous phases.

In this article we apply Equation 2 to the data of Karesniemi (1972), which then gives values for D_{OM} and D_{Ash}. We evaluate Equation 3 using data from some Scottish, Irish and Indonesian peats where bulk density, moisture content and ash content were measured. We also determine laboratory volume weight for a set of Scottish peats to assess its use in predicting bulk density.

METHODS

Peat samples were obtained from several locations across Scotland (Figure 1). Samples from two basin peatlands (Middlemuir and Red Moss, Netherley) were collected from below the water table using a Russian (also known as Macaulay) sampler to a maximum depth of 5 m. Samples were also obtained from a selection of NSIS sites (National Soil Inventory of Scotland, sampled in 2007, Chapman *et al.* 2013) which were predominantly blanket peat. These were taken from the sides of profile pits and were necessarily only from the surface to a maximum depth of 1 m. Two sets of data where both bulk density and moisture content values were known, from Shetland (blanket peat, 0–180 cm) and Allt a'Mharcaidh (semi-confined peat, 10–87 cm), were added. These were also from profile pits but the original samples were not available for further
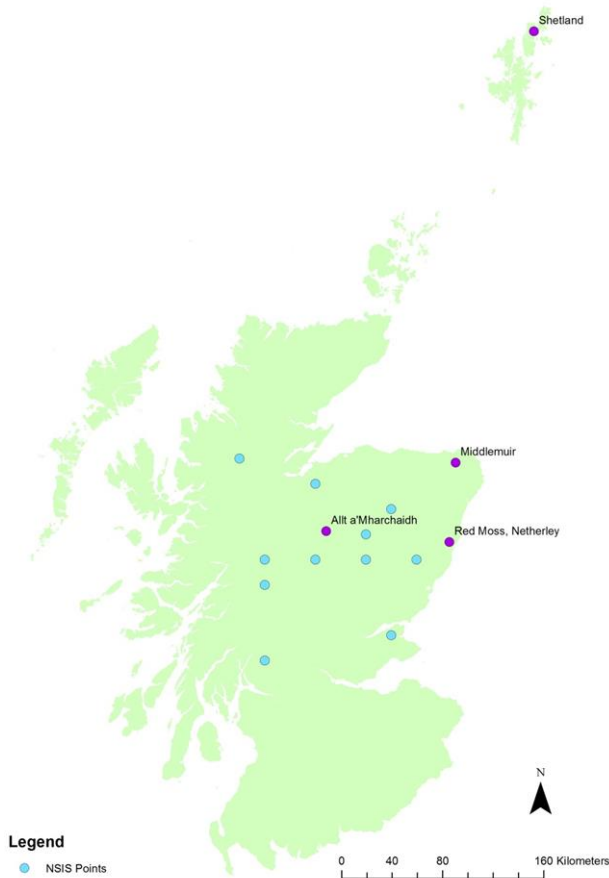
Figure 1. Locations of peat sampling sites within Scotland.

analysis. The p_{Ash} values were not available, so they were all assigned the value of 0.0395, which was the mean ash content of all the samples from Middlemuir, Red Moss and the NSIS set. In practice, Equations 3 and 4 are not very sensitive to changes in p_{Ash} (see below). A set of data on Irish fen, basin (raised bog) and blanket peats from County Clare where bulk density, ash and moisture contents had been published (Finch *et al.* 1971) was examined. These had been collected from the sides of profile pits dug to 1 m. A dataset on tropical peats, part of a PhD study by one of us (JF), was also available, which had been sampled with a Russian sampler (Eijelkamp, The Netherlands) at six sites (3–12 cores *per* site) to a maximum depth of 3.8–6 m. These were from three areas in Jambi province, Indonesia: two indigenous intact peat swamp forest sites located at 104° 21' 29.29 "E, 1° 27' 48.31" S and 104° 15' 29.92" E, 1° 30' 10.68" S, and an area of logged forest and three oil palm plantation sites located at 103° 49' 59.74" E, 1° 38' 31.78" S. Both peat moisture content (M) and dry bulk density (D_b)

had been determined. Ash content values (p_{Ash}) were missing from some cores and so these were taken as the mean from the other replicate cores at the same depth. No ash values were measured at the first intact peat swamp forest site and so these were taken from corresponding depths at the second intact peat swamp forest site.

Laboratory volume weight is not normally measured in contemporary analysis; its value related more to peat extraction for fuel use and so was of relevance to peat survey in Finland (Laine & Päivänen 1982) and to the Scottish Peat Surveys, which were conducted in the 1950–1960s. One of our further objectives is, however, to use the extensive data from these surveys where laboratory volume weight, ash content and moisture content have been measured to obtain bulk density values, particularly for deeper peat profiles; this will be the subject of a separate publication. Laboratory volume weight was measured in samples from Middlemuir, Red Moss and the NSIS sites. The precise protocol for its measurement during the Scottish Peat Surveys is no longer available. Comparison with the literature (Päivänen 1969) revealed that there were several variants on the methodology and the following protocol was adopted. The peat was air-dried at 27 ℃ and subsequently at 105 ℃. The dried sample was hammer-milled using a 1 mm grid on the mill, 20–30 ml placed into an adapted 50 ml syringe body and tapped 30 times by hand on the bench from a height of 3 cm. From the volume and weight of the sample the laboratory volume weight could be calculated. The von Post humification index was measured in samples from Middlemuir and Red Moss.

A summary of the various datasets used in the analysis is given in Table 1. Linear regression, multiple linear regression, non-linear regression and Lin's concordance correlation coefficient testing were performed using Genstat 18 (VSN International Ltd, Hemel Hempstead, UK).

RESULTS

The data of Karesniemi (1972) are shown in Figure 2. The data points were transcribed from the group mean values given in the paper and the fitted line for Equation 2 was run with weights according to the number of samples in each mean ($r^2 = 0.984$, standard error of observations = 0.0642, P < 0.001). The values of D_{OM} and D_{Ash} (± standard error) were 1.438 ± 0.003 and 3.024 ± 0.073 g cm^{-3}, respectively. We repeated the evaluation of Equation 2 using the data of Hobbs (1986), which gave a similarly good fit

Table 1. Datasets and associated parameters; mean and range (min – max).

Dataset	No. sites	No. samples	Attributes measured				
			Bulk Density (g cm^{-3})	Moisture (g water g^{-1} fresh weight)	Ash (%)	Humification Index	Laboratory Volume Weight (g cm^{-3})
Middlemuir	1	20	0.105 (0.079 – 0.139)	0.896 (0.870 – 0.920)	4.28 (2.80 – 5.52)	8.71 (8 – 9)	0.687 (0.615 – 0.730)
Red Moss, Netherley	1	8	0.102 (0.061 – 0.207)	0.903 (0.818 – 0.942)	2.15 (0.38 – 3.99)	6.00 (3 – 9)	0.548 (0.273 – 0.667)
Shetland	3	13	0.141 (0.114 – 0.201)	0.848 (0.795 – 0.884)			
Allt a'Mharchaidh	1	6	0.111 (0.073 – 0.149)	0.902 (0.869 – 0.937)			
NSIS	11	20	0.129 (0.100 – 0.180)		5.62 (1.40 – 18.34)		0.643 (0.467 – 0.782)
Jambi, Indonesia	6	672	0.114 (0.015 – 0.349)	0.887 (0.539 – 0.983)	2.14 (0.31 – 38.86)*		
County Clare, Ireland	12	17	0.159 (0.039 – 0.530)	0.857 (0.630 – 0.916)	11.54 (2.00 – 54.45)		

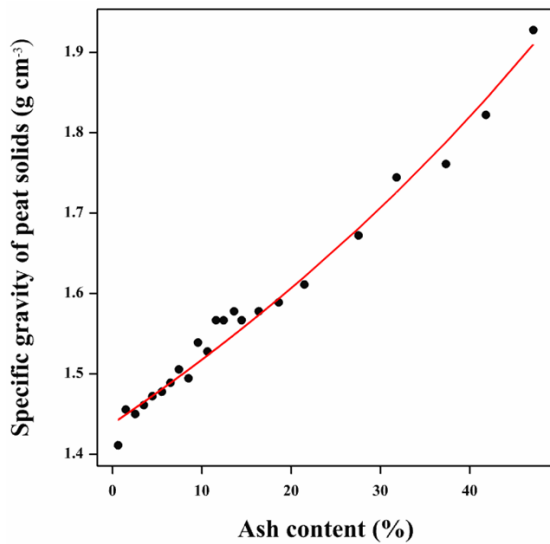*Values for 66 % of samples only

Figure 2. Increase in specific gravity of peat solids with ash content; data of Karesniemi (1972).
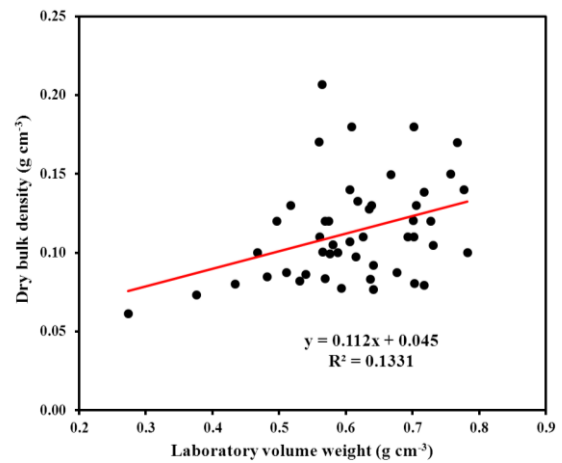

Figure 3. Regression of dry bulk density on laboratory volume weight for a set of Scottish peat samples (Middlemuir, Red Moss and NSIS).
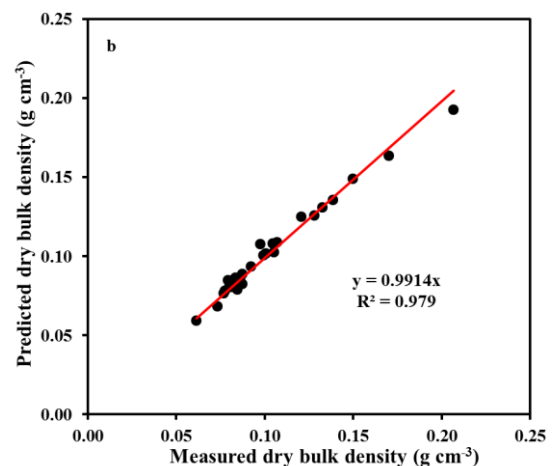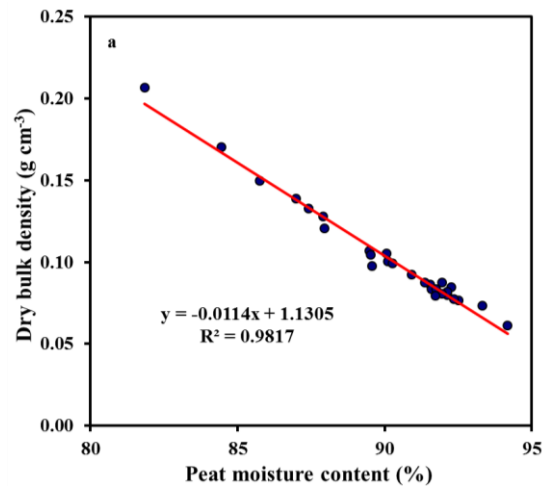

Figure 4. Regression of measured dry bulk density on gravimetric moisture content (a) and of predicted dry bulk density on measured dry bulk density (b) for a set of Scottish basin peats (Middlemuir and Red Moss).

($r^2 = 0.984$, standard error of observations = 0.0517, $P < 0.001$, data not shown). The values of D_{OM} and D_{Ash} were 1.422 ± 0.012 and 2.742 ± 0.018 g cm^{-3}, respectively. However, in the following we use the values given by Karesniemi as his study was mainly of *Carex* and *Sphagnum* peatlands in Finland whereas that of Hobbs was mainly of fen peats in England.

Using samples from Middlemuir, Red Moss and the NSIS, regression analysis revealed a significant but weak relationship between dry bulk density and laboratory volume weight (Figure 3). The relationship could be improved by removing one or two data points which had come from near-surface samples and which had particularly high dry bulk density values, e.g. the value over 0.2 came from a sample that represented an old cut-over surface which had previously been dried and consolidated. However, the regression was still not very good (data not shown).

Where values for moisture content were available (the basin peats, Middlemuir and Red Moss), it was found that that the relationship between dry bulk density and moisture content was much closer ($r^2 = 0.982$, standard error of observations = 0.0045, $P < 0.001$; Figure 4a). Including data from blanket and semi-confined peat (Shetland and Allt a'Mharcaidh) gave a similar regression line but with greater scatter ($r^2 = 0.839$, standard error of observations = 0.0140, $P < 0.001$; see Figure A1a in Appendix). Further regression analysis was performed to ascertain whether the relationships could be improved further by adding the humification index or laboratory volume weight

(in a multiple linear regression analysis). The results indicated that the addition of laboratory volume weight gave some minor improvement but the addition of humification index did not. However, the number of samples where these additional attributes are known is limited and including them would be of limited practical value. Hence, it was decided to use just moisture and ash content (where available) as the basis for predicting dry bulk density as described by Equation 3, with the advantage that this has a theoretical basis. The data for the basin peats gave an almost 1:1 relationship for predicted dry bulk density against measured dry bulk density ($r^2 = 0.979$, standard error of observations = 0.0044, $P < 0.001$; Figure 4b). Including data from blanket and semi-confined peat still gave an almost 1:1 relationship but again with greater scatter ($r^2 = 0.833$, standard error of observations = 0.0167, $P < 0.001$; Figure A1b).

Equation 3 was also applied to the Irish peat data. There was a slight under-prediction of dry bulk density but the equation broadly held, even though several samples were high in ash (Figure A2, Table 1).

Applying Equation 3 to the tropical peat samples again gave a 1:1 relationship but with a much greater degree of scatter ($r^2 = 0.359$, standard error of observations = 0.0476, $P < 0.001$; Figure 5). Inspection of the data suggested that many of the surface samples had a significant air (or gas) component, i.e. they were not saturated. Calculation of p_g using rearranged Equation 4 suggested that this was significant for most samples taken from above 100 cm (i.e. 0–15, 15–30, 30–50 and 50–100 cm). Recalculating the relationship omitting all samples above 100 cm reduced the scatter ($r^2 = 0.571$, standard error of observations = 0.0245, $P < 0.001$; Figure A3) though this resulted in some under-prediction of the dry bulk density. Separating the tropical data by land use (intact peat swamp forest, logged forest and oil palm plantation) revealed some variation in the degree of fit (Figures A4, A5 and A6, respectively).

DISCUSSION

Contrary to the findings of Päivänen (1969), we did not find a good correlation between dry bulk density and laboratory volume weight. This may be due to the relatively small number of samples tested or to the protocol used for its determination being unsatisfactory. Determination of dry bulk density from laboratory volume weight has the advantage that dry bulk density can be determined on samples
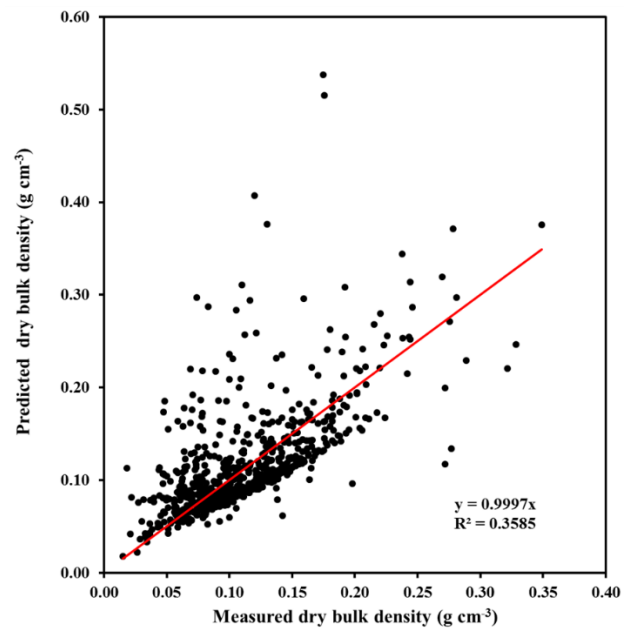

Figure 5. Regression of predicted dry bulk density on measured dry bulk density for a set of Indonesian peats (intact peat swamp forest, logged forest and oil palm plantation).

that have been dried or archived. However, we have previously shown that FTIR (Fourier Transform InfraRed) spectroscopy can also be used satisfactorily for this purpose (Chapman *et al.* 2013).

In agreement with Laine & Päivänen (1982), we found a good correlation between dry bulk density and moisture content for both basin and blanket temperate peats and also for tropical peats. Clymo *et al.* (1998) make mention of using this relationship for estimating dry bulk density but do not give the formula they used. Equation 3 implies that the relationship between dry bulk density and moisture content is not strictly linear. This was something Laine and Päivänen (1982) referred to but did not account for. The prediction of dry bulk density from moisture content, including ash content values where available, was satisfactory ($R^2 > 0.5$) for peat samples within the saturated zone, except for the Indonesian logged forest peats. However, for surface samples which contain an appreciable volume of air, the prediction over-estimates the dry bulk density values. If the proportion of air is known, then this can be included in the calculation; although in practice, where the proportion of air (or gas) has been determined, it is most likely that dry bulk density has also been measured. The predicted dry bulk density of the tropical peats appeared to be under-estimated. We cannot fully explain this. It

cannot be due to the peat samples being incompletely dried as this would affect both the bulk density and the moisture content values to a similar extent. The only explanation is that the volume of sample was under-estimated, resulting in over-estimation of the measured dry bulk density. Firstly, the volume of individual Russian samplers is quite variable and the manufacturer's stated volume cannot be relied upon (R. Lindsay, pers. comm.). Secondly, there are practical difficulties in precisely sampling these wood-based peats, particularly if the wood is relatively undecomposed. This second point may also explain the greater scatter for the Indonesian logged forest peats. Closer inspection of the data for individual cores from the logged forest showed that four of the twelve cores gave R^2 values >0.73, while the remaining eight gave poor regressions, suggesting that they may have been sampled from difficult profiles. Similarly, some cores from two of the oil palm sites gave poor results. Unfortunately, we do not have data on the degree of decomposition in these cores.

Calculation of the gas volume (g) clearly indicated whether the samples had been taken from above the saturated zone. Laine & Päivänen (1982) note that the gas volume below the saturated zone is generally less than 10 % but does introduce some scatter into the relationship between dry bulk density and moisture content. They suggest that part of this may be due to the loss of water during sampling; unless great care is taken it is difficult to tell whether a hole was gas or originally water-filled. Calculating p_g for the tropical peats, particularly those from the intact forest, resulted in negative values, presumably where the measured dry bulk density values were over-estimated. However, one oil palm plantation site showed some increase in p_g up to 18 % at depth (425 cm) which might suggest the presence of significant gas (possibly methane).

In our calculations we have used ash content values where they were available. However, including a precise ash content value is not absolutely necessary as p_{Ash} in the equations has a very minor effect on the calculated dry bulk density. Of course, a peat with a higher ash content will have a lower moisture content and it is the change in M that will largely determine the calculated bulk density. Similarly, the calculations are quite insensitive to values of D_{Ash} and only marginally sensitive to values of D_{OM} (within realistic limits). Hence, in the absence of specific values, it is sufficiently robust to use the Karesniemi values, or in the additional absence of any ash values, to use a

D_s value of 1.47 (assumes the Karesniemi values and a mean ash content of 0.0395 g g^{-1}).

Alternatively, a good approximation may be to rely purely on the correlation between dry bulk density and moisture content. We tested two equations, $D_b = 1/M - 1$, essentially a simplified Equation 3, and $D_b = 1 - M$, suggested from the plots of dry bulk density on moisture content. The former will always give a predicted bulk density value greater than that given by Equation 3 while the latter will always give a smaller value. The predicted bulk densities from the three equations were compared against the measured bulk densities using Lin's concordance correlation coefficient (Table A1, Appendix). Equation 3 gave the best fit for the Scottish basin and Irish peats. It was slightly inferior to $D_b = (1 - M)$ where the Scottish blanket and semi-confined peats were included but the difference was not significant. $D_b = (1/M - 1)$ gave the better fit for the Indonesian peats, though this was only significant for the intact peat swamp forest peat. This better fit might result from over-estimation of the measured bulk density for the Indonesian peats rather than being a consequence of not accounting for ash content and the specific gravity of peat solids.

CONCLUSIONS

The pedotransfer function derived by extending the theory of Laine & Päivänen (1982) enables dry bulk density to be estimated from peat moisture and ash contents. A restriction is that the peat samples should be from the saturated zone unless the gas-filled volume is known. The function will be useful either where bulk density has not been measured or where there are difficulties in obtaining a sufficiently intact sample for bulk density determination, for example in very sloppy peats or in very fibrous or woody peats. Where both dry bulk density and moisture content values are available, the latter can provide an independent check on the bulk density or they can be used to estimate the gas volume if present.

ACKNOWLEDGEMENTS

REFERENCES

Avery, B.W. (1980) *Soil Classification for England and Wales*. Soil Survey Technical Monograph No. 14, Rothamsted Experimental Station, Harpenden, 67 pp.

Chapman, S.J., Bell, J., Donnelly, D. & Lilly, A. (2009) Carbon stocks in Scottish peatlands. *Soil Use and Management*, 25, 105–112.

Chapman, S.J., Bell, J.S., Campbell, C.D., Hudson, G., Lilly, A., Nolan, A.J., Robertson, A.H.J., Potts, J.M. & Towers, W. (2013) Comparison of soil carbon stocks in Scottish soils between 1978 and 2009. *European Journal of Soil Science*, 64, 455–465.

Clymo, R.S. (1970) Growth of *Sphagnum* - methods of measurement. *Journal of Ecology*, 58, 13–40.

Clymo, R.S., Turunen, J. & Tolonen, K. (1998) Carbon accumulation in peatland. *Oikos*, 81, 368–388.

Driessen, P.M. & Rochimah, L. (1976) The physical properties of lowland peats from Kalimantan and their significance for land suitability appraisal. In: *Research on Peat and Podzolic Soils in Indonesia and their Potential for Agriculture*, Soil Research Institute, Bogor, Indonesia, 56–73.

Finch, T.F., Culleton, E. & Diamond, S. (1971) *Soils of Country Clare*. Soil Survey Bulletin No. 23, An Forais Talúntais, Dublin, 246 pp.

Galvin, L.F. (1976) Physical properties of Irish peats. *Irish Journal of Agricultural Research*, 15, 207–221.

Hobbs, N.B. (1986) Mire morphology and the properties and behaviour of some British and foreign peats. *Quarterly Journal of Engineering Geology*, 19, 7–80.

Huat, B.B.K., Asadi, A. & Kazemian, S. (2009) Experimental investigation on geomechanical properties of tropical organic soils and peat. *American Journal of Engineering and Applied Sciences*, 2, 184–188.

IUSS Working Group WRB (2015) *World Reference Base for Soil Resources 2014, Update 2015, International Soil Classification System for Naming Soils and Creating Legends for Soil Maps*. World Soil Resources Reports No. 106, FAO, Rome, 203 pp.

Joosten, H., Tanneberger, F. & Moen, A. (eds.) (2017) *Mires and Peatlands of Europe: Status, Distribution and Conservation*. Schweizerbart Science Publishers, Stuttgart, 780 pp.

Karesniemi, K. (1972) Dependence of humification degree on certain properties of peat. In: *The Proceedings of the 4th International Peat Congress,* Volume 2, International Peat Society, Otaniemi, Finland, 273–282.

Klemetti, V. & Keys, D. (1983) Relationship between dry density, moisture content and decomposition of some New Brunswick peats. In: Jarrett, P.M. (ed.) *Testing of Peats and Organic Soils, ASTM STP 820*, American Society for Testing and Materials, Philadelphia, 72–82.

Laine, J. & Päivänen, J. (1982) Water content and bulk density of peat. In: *The Proceedings of the International Symposium of the IPS Commissions IV and II "Peat, its Properties and Perspectives of Utilization"*, International Peat Society, Minsk, USSR, 422–430.

Landva, A.O., Korpijaakko, E.O. & Pheeney, P.E. (1983) Geotechnical classification of peats and organic soils. In: Jarrett, P.M. (ed.) *Testing of Peats and Organic Soils, ASTM STP 820*, American Society for Testing and Materials, Philadelphia, 37–51.

Lindsay, R. (2010) *Peatbogs and Carbon: a Critical Synthesis to Inform Policy Development in Oceanic Peat Bog Conservation and Restoration in the Context of Climate Change*. Report to RSPB Scotland, University of East London, UK, 344 pp.

Päivänen, J. (1969) The bulk density of peat and its determination. *Silva Fennica*, 3, 1–19.

Tolonen, K. & Ijäs, L. (1982) Comparison of two peat samplers used in estimating the dry peat yield in field inventories. *Suo (Helsinki)*, 33, 33–42.

USDA (1999) *Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys*. Agriculture Handbook Number 436, United States Department of Agriculture Natural Resources Conservation Service, Washington, 886 pp.

von Post, L. (1922) Sveriges Geologiska Undersökningens torvinventering och några av dess hittills vunna resultat (SGU peat inventory and some preliminary results). *Sveriges Mosskulturföreningens Tidskrift*, 36, 1–27 (in Swedish).

_____

Author for correspondence: Dr Steve Chapman, Ecological Sciences Group, The James Hutton Institute, Craigiebuckler, Aberdeen AB15 8QH, Scotland, UK.
Tel: +44 (0) 1224 395325; E-mail: steve.chapman@hutton.ac.uk; Web: www.hutton.ac.uk/staff/steve-chapman
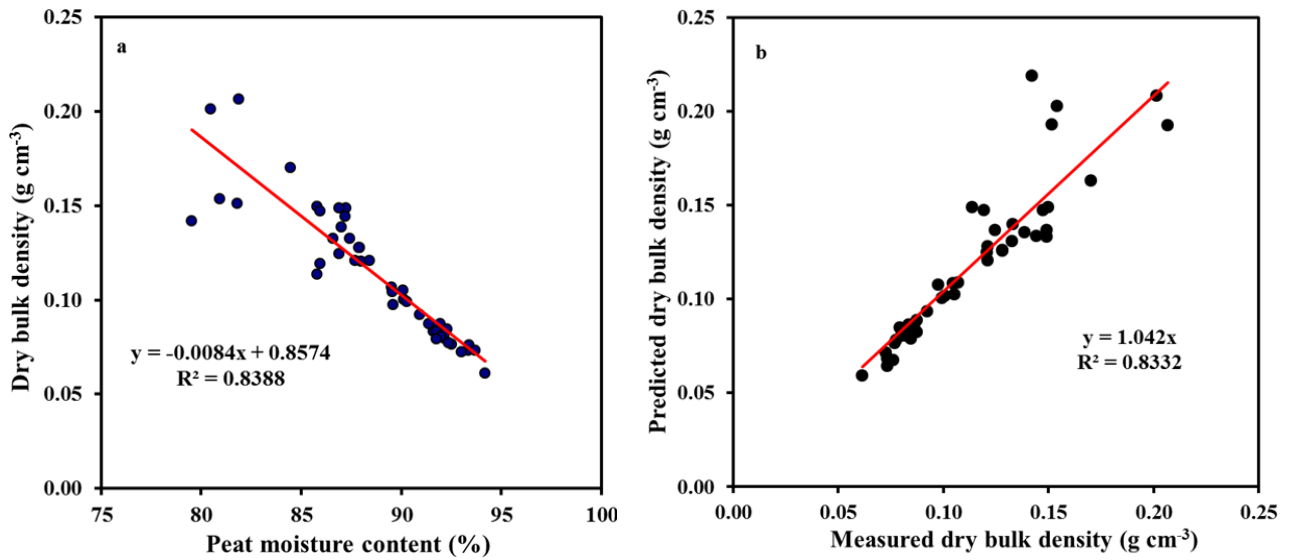
Appendix

Figure A1. Regression of measured dry bulk density on gravimetric moisture content (a) and of predicted dry bulk density on measured dry bulk density (b) for a set of Scottish basin, blanket and semi-confined peats (Middlemuir, Red Moss, Shetland and Allt a'Mharcaidh).
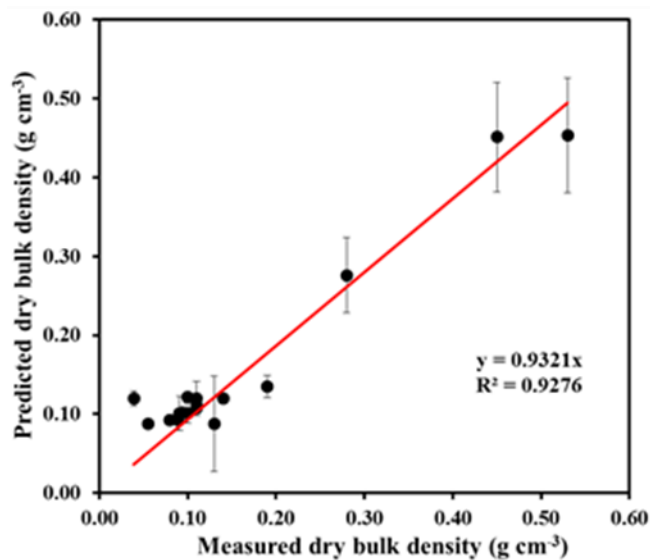

Figure A2. Regression of predicted dry bulk density on measured dry bulk density for a set of Irish peats. Standard error of observations = 0.0320, $P < 0.001$. Vertical bars show the range in predicted bulk density based on the range in measured moisture content.
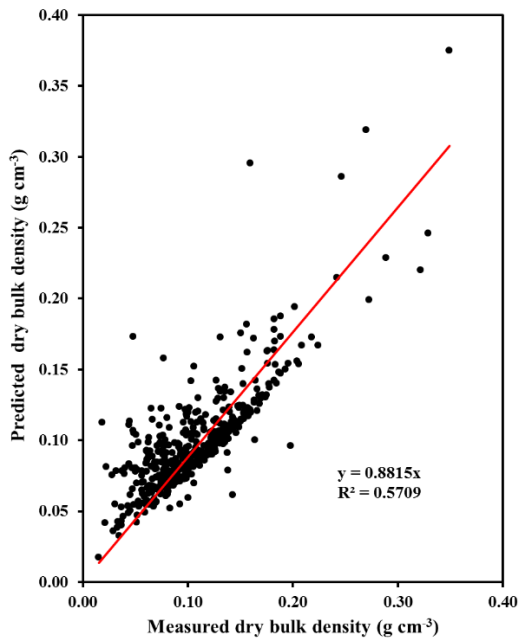
Figure A3. Regression of predicted dry bulk density on measured dry bulk density for a set of Indonesian peats (intact peat swamp forest, logged forest and oil palm plantation), omitting samples taken at depths less than 100 cm.
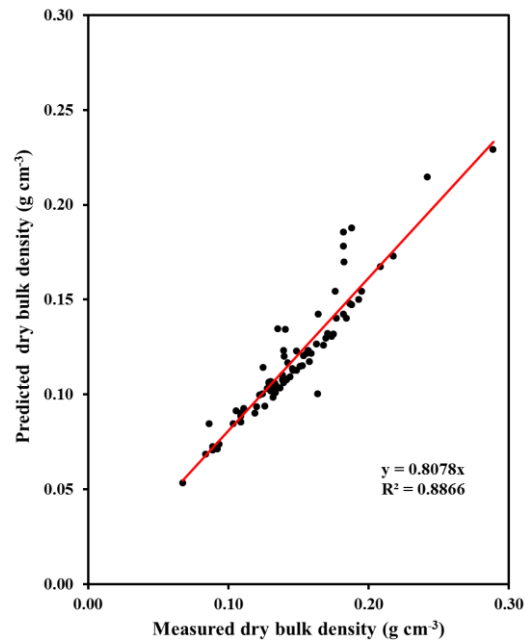

Figure A4. Regression of predicted dry bulk density on measured dry bulk density for a set of Indonesian intact peat swamp forest peats, omitting samples taken at depths less than 100 cm. Standard error of observations = 0.0108, P < 0.001.
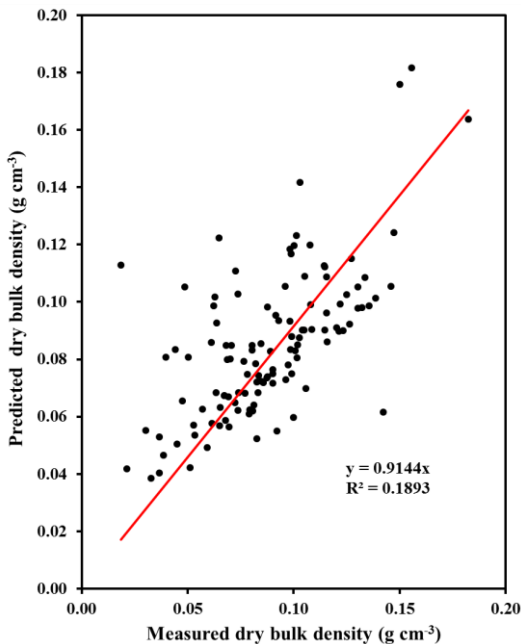

Figure A5. Regression of predicted dry bulk density on measured dry bulk density for a set of Indonesian logged forest peats, omitting samples taken at depths less than 100 cm. Standard error of observations = 0.0231, P < 0.001.
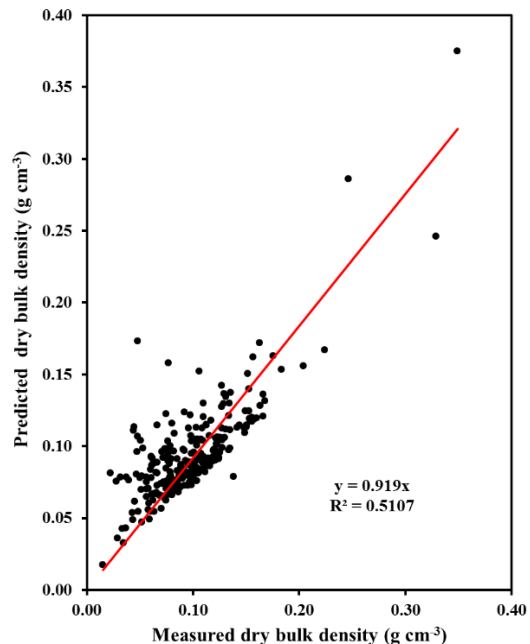

Figure A6. Regression of predicted dry bulk density on measured dry bulk density for a set of Indonesian oil palm plantation peats, omitting samples taken at depths less than 100 cm. Standard error of observations = 0.0238, P < 0.001.

Table A1. Lin's concordance correlation coefficients comparing three equations for predicting dry bulk density. Values followed by a different letter are significantly different ($P > 0.05$).

Peat source	Equation 3	$D_b = 1/M - 1$	$D_b = 1 - M$
Scottish basin	0.9897a	0.9611b	0.9736ab
Scottish basin, blanket and semi-confined	0.8946a	0.7947a	0.9123a
Indonesian intact peat swamp forest	0.6968b	0.8507a	0.6158b
Indonesian logged forest	0.6270a	0.6370a	0.6115a
Indonesian oil palm plantation	0.7765a	0.7799a	0.7499a
Irish fen, basin and blanket	0.9614a	0.9460a	0.8923a