Terra Rossa catenas in Wisconsin, USA

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1. Introduction

Terra Rossa is a term given to reddish, clay-rich soil occurring on hard carbonate bedrock (Durn, 2003) and the first reference to these characteristic soils dates back to 1848 (Joffe, 1936). The red color is due to the formation of hematite and these soils generally have mixed clay mineralogies (Boero and Schwertmann, 1989). They are often found in areas with Mediterranean climates (Spain, France, Italy, Portugal, Greece, Bulgaria, Romania, Croatia, Slovenia, Turkey, Israel, and Jordan), but have also been described in Australia, Bermuda, China, Indonesia, Ireland, Jamaica, Japan, Mexico, Russia and the Tibetan Plateau among others (Bautista et al., 2011; Peng and Zhu, 2009; Glazovskaya and Parfenova, 1974; Herwitz et al., 1996; Maejima et al., 2005; Mee et al., 2004; Mella and Mermut, 2010; Muhs and Budahn, 2009; Smith and McAlister, 1995).

The origin of Terra Rossa has been widely debated (Joffe, 1936) but the classic theory is that these soils are formed in situ from carbonate dissolution and the weathering of insoluble material. The carbonates are dissolve by chemical weathering until only insoluble components remain, which become the parent material for the soil (Foster et al., 2004; Cal, 1966; Mella and Mermut, 2010; Moresi and Mongelli, 1988). Large amounts of carbonate weathering may be needed and the input of aeolian particles has been found to comprise considerable parts of Terra Rossa soils in the Mediterranean regions (Yaalon, 1997), parts of Australia (Mee et al., 2004), Greece (Macleod, 1980) and in Croatia (Wroblewski et al., 2010).

In the USA, Terra Rossa soils have been described in several states: Texas (Cooke et al., 2007; Rabenhorst and Wilding, 1986), Illinois (Ballagh and Runge, 1970), Maryland (Bourgault and Rabenhorst, 2011), Indiana (Olson et al., 1980; Shunk et al., 2009) and Wisconsin (Frolking, 1978; Knox et al., 1990; Stiles and Stensvold, 2008). Studies of Terra Rossa in Wisconsin have reported a wide range of depths at which it occurs and a range of thicknesses of the red clay. In part such differences are due to large spatial heterogeneity caused by irregular weathering of the limestone followed by soil erosion and other landscape processes (Frolking et al., 1983). Detailed knowledge about the clay subsoil is of importance as the clay acts as a cap over the limestone and influences water and solute movement through the landscape.

This study focuses on Terra Rossa catenas in parts of the unglaciated regions or Driftless Area of Wisconsin, USA. The objectives of our research were to assess where such soils occur in the landscape, at what depth the clay is found, and its thickness. We hypothesized that the catena approach is a useful concept for studying the Terra Rossa as soils along a hillslope are related through physical processes, explicitly linking the landscape and the soil (Brown and Olson, 1950; Brown and Thorp, 1942; Dan and Yaalon, 1971; Swanson, 1985). Soil sampling along catenas has been done in several recent studies (e.g. Odgers et al., 2008), but to our knowledge the catena concept has not been applied to study the Terra Rossa in the Driftless Area of Wisconsin. In our study, a total of 144 pedons was sampled of 16 catenas.

2. Materials and methods

2.1. The study area

The Driftless Area of Wisconsin is a region of stream-dissected uplands in the southwest part with an area of about 41,000 km² (Hole, 1976). It has not been glaciated within the Quaternary period.
The unglaciated area extends into Minnesota, Iowa, and Illinois, but the greatest extent is found in Wisconsin. The study was conducted in a 70 km² area near Verona in Dane County, South central Wisconsin (Evans and Hartemink, 2014). The land use of the study area is primarily agriculture, with maize, soya and alfalfa as the most common field crops. The present climate of the Driftless Area is characterized by warm, moist summers and cold, drier winters. The mean annual precipitation is 857 mm, and for July, the wettest month, the precipitation averages 104 mm and the driest month, January, averages 20.8 mm. The mean annual temperature is 7.3 °C, while the warmest month, July, averages 21.7 °C, and January the coldest month averages −9.7 °C.

The bedrock underlying the Driftless Area of Wisconsin consists of nearly horizontal beds of sedimentary rocks, primarily sandstone and dolostone of Ordovician age, with some shale. The dolostone generally forms the ridges with the less resistant sandstone and shale occurring on the slopes and underneath the valley fill (Slater and McSweeney, 1992). The insoluble content of the dolostone is about 8 to 10% (Frolking, 1978).

In the Driftless Area, loess covers much of the landscape. The loess is from large outwash plains of the glaciers and rivers that would dry up or shrink seasonally and deposit some of their load (Hole, 1976). The prevailing wind direction was from the west, as it is today, and so the depth of the loess is the thickest, up to several meters, and the coarsest near the Mississippi in the west of the state, and thins to only a few centimeters in the east. The Driftless Area was affected by a periglacial climate and erosional processes during the last ice age that ended about 12,000 years ago. The periglacial conditions caused mass wasting and hillslope erosion due to solifluction and sheet wash and these processes reduced the depth of loess on side slopes. Much of the colluvial material was removed by alluvial activity and transported downstream after the glaciers receded. The dissected nature of the Driftless Area is attributed to erosion activity during the Pleistocene epoch.

2.2. Soil sampling and analysis

We have made 144 pedon observations along 16 catenas in June–August 2012 (Fig. 1). Catenas were selected based on slope and aspect, and the sampling interval between pedons was determined by the length of the catena and the elevation difference between the top and bottom sampling points. At each sampling point, information was collected on landscape and soil properties, including the presence of red clay, the depth of the red clay, and the thickness of the loess and the solum. The observations were made using a 7 cm Edelman auger. The average depth of the solum was 46 cm (±25 cm); where the clay was found the thickness was on average 23 cm (±14 cm) (Evans and Hartemink, 2014). Samples were taken from each soil horizon and color was determined by standard Munsell color chart.

### Table 1

Characteristics of the 16 sampled catenas in a 70 km² area of the Driftless Area of Wisconsin, USA. Mean thickness of red clay layer in cm (± 1 standard deviation).

<table>
<thead>
<tr>
<th>Catena</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of pedons</td>
<td>8</td>
<td>13</td>
<td>10</td>
<td>17</td>
<td>13</td>
<td>9</td>
<td>8</td>
<td>5</td>
<td>7</td>
<td>10</td>
<td>11</td>
<td>9</td>
<td>6</td>
<td>6</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>Number of pedons with Terra Rossa</td>
<td>0</td>
<td>7</td>
<td>6</td>
<td>12</td>
<td>5</td>
<td>5</td>
<td>7</td>
<td>5</td>
<td>5</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>4</td>
<td>0</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Aspect</td>
<td>SE</td>
<td>W</td>
<td>E</td>
<td>S</td>
<td>S</td>
<td>NE</td>
<td>E</td>
<td>W</td>
<td>NW</td>
<td>W</td>
<td>SE</td>
<td>W/NW</td>
<td>N/NW</td>
<td>NW</td>
<td>E</td>
<td>W</td>
</tr>
<tr>
<td>Avg. slope (%)</td>
<td>7</td>
<td>11</td>
<td>11</td>
<td>8</td>
<td>6</td>
<td>9</td>
<td>12</td>
<td>11</td>
<td>8</td>
<td>13</td>
<td>8</td>
<td>10</td>
<td>9</td>
<td>17</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>Elevation difference (m)</td>
<td>22</td>
<td>20</td>
<td>29</td>
<td>18</td>
<td>23</td>
<td>30</td>
<td>36</td>
<td>18</td>
<td>28</td>
<td>24</td>
<td>22</td>
<td>14</td>
<td>11</td>
<td>28</td>
<td>22</td>
<td>11</td>
</tr>
<tr>
<td>Length (m)</td>
<td>320</td>
<td>185</td>
<td>185</td>
<td>250</td>
<td>270</td>
<td>370</td>
<td>320</td>
<td>210</td>
<td>330</td>
<td>240</td>
<td>290</td>
<td>200</td>
<td>150</td>
<td>170</td>
<td>280</td>
<td>130</td>
</tr>
<tr>
<td>Sampling pedon interval (m)</td>
<td>30</td>
<td>15</td>
<td>20</td>
<td>20</td>
<td>30</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>45</td>
<td>15 to 30</td>
<td>40</td>
<td>20</td>
<td>30</td>
<td>30</td>
<td>50</td>
<td>30</td>
</tr>
<tr>
<td>Thickness of red clay (cm ± SD)</td>
<td>0</td>
<td>21 ± 15</td>
<td>27 ± 14</td>
<td>21 ± 13</td>
<td>11 ± 6</td>
<td>27 ± 18</td>
<td>19 ± 4</td>
<td>40 ± 14</td>
<td>15 ± 5</td>
<td>17 ± 17</td>
<td>41 ± 19</td>
<td>29 ± 20</td>
<td>0</td>
<td>28 ± 16</td>
<td>35</td>
<td></td>
</tr>
</tbody>
</table>
All samples were analyzed for particle size with the hydrometer after air-drying and 2 mm sieving; the samples were dispersed with sodium hexametaphosphate, mechanically shaken followed by wet and dry sieving (Burt, 2004). Red clay material exhibits a range of textures and color and in some cases it was difficult to distinguish it from loess. The distinguishing factors mostly used were color and texture, and in the field red clay horizons were distinguished when it was (i) redder than other horizons or (ii) difficult to auger through, or (iii) sticky and firm or very firm when moist. Laboratory coloring and particle size analysis was used to validate the field assessments. Despite the variation in color and clay content (36–45%) we use the term “red clay” throughout this paper to indicate the material that has been derived from the weathering of the dolostone. Details of the 16 catenas are given in Table 1.

3. Results

3.1. The Terra Rossa

The red clay subsoil was found in 72 of the 144 pedons. In total 82 red clay horizons were described and 12 pedons had more than one horizon of red clay. Most pedons that had a red clay subsoil had one horizon and in 11 pedons two horizons of red clay were described. In one pedon three horizons were described. The horizonation was based on color and the amount of coarse fragments and differences in the amount of clay. The layers with moist colors of 5YR 3/4 had the highest clay content (47%). The clay was very sticky when wet and it had a strong angular blocky structure. Moist values of 3 or darker were found in 45 of the 82 horizons, and moist chromas of 3 or darker were found in 24 horizons. More than half of the horizons had over 40% clay. In four horizons, the clay content was below 30%, and 29 horizons had clay contents between 30 and 40% (Fig. 2).

The depth of the loess above the red clay varied considerably. The mean was 50 cm of loess, but it ranged from 7 to 130 cm (Fig. 3). The thickness of the red clay ranged from 4 cm to 60 cm with a median thickness of 20 cm (Fig. 3). In every pedon where the red clay was found the soil depth was less than 2 m and the depth was limited by dolostone bedrock. The bedrock beneath the red clay was found to be soft and weathered in 26 pedons, and in other 13 pedons depth was limited by fractured, channery dolostone.

We had insufficient data to classify all the pedons sampled but most of the soils with the red clay subsoil would classify as Typic Hapludalfs, the shallow pedons would be classified as Lithic Hapludalfs whereas the pedons with thick topsoils would be classified as Argiudolls.

3.2. The catenas

The red clay was found in almost every part of the landscape but not in the soils of the valley bottoms; it was present in soils on summits, shoulders, backslopes, and footslopes. It has an irregular distribution across the landscape and the variation in its presence or absence is in the order of tens of meters. For example, at one location the red clay had a thickness of 20 cm whereas in a pedon 10 m further it was absent. Below is a brief description of some of the characteristics and variation of the 16 catenas that were sampled.

Catena 1 was on a dolostone ridge but no red clay was found in any of the 8 pedons. Catenas 2, 3 and 4 were close to each other (Fig. 1) and more than half of the pedons had red clay layers. The red clay was found to be thin in catenas 5 and 6 (Table 1). In every pedon where the red clay was found the soil depth was less than 2 m and the depth was limited by dolostone bedrock. The bedrock beneath the red clay was found to be soft and weathered in 26 pedons, and in other 13 pedons depth was limited by fractured, channery dolostone.

We had insufficient data to classify all the pedons sampled but most of the soils with the red clay subsoil would classify as Typic Hapludalfs, the shallow pedons would be classified as Lithic Hapludalfs whereas the pedons with thick topsoils would be classified as Argiudolls.
soils on slopes exceeding 15% and the red clay was also found in the lower part of landscape (catenas 2, 4 and 6).

Fig. 4 illustrates a typical catena with the *Terra Rossa* on the summit position and on mid-backslope. It also shows that soil depth is limited on the summit and upperslope positions, and that the depth increases downslope.

A correlation matrix was constructed to investigate the relationship between red clay characteristics and the landscape attributes elevation, slope, and aspect (Fig. 5). The clay percentage of a horizon is not correlated with elevation, aspect or slope, but the thickness of the red clay and depth of the profile were correlated — the scatterplot shows that this relationship is influenced by a few deep pedons and thick red clay layers. The correlation between the depth to the red clay and the depth of the profile was high ($r = 0.80$): deeper soils have thicker loess covers. The thickness of clay and the percentage of the profile composed of red clay were modestly correlated ($r = 0.60$). The scatterplot shows a high variability for soils with thick clay and the portion of the solum. The depth to the red clay and the percent of the profile composed of red clay were negatively correlated. Percent clay, thickness, and depth to the red clay are not strongly correlated.

4. Discussion and conclusions

We have presented our findings on the properties of the red clay and where such layers occur in the soils of 16 catenas. Considerable variation was found and here we discuss some of the trends and possible explanations for the observed differences and similarities.

The red clay of Wisconsin was first discussed by Chamberlain and Salisbury (1886) who considered the clays to be the weathered insoluble residuum of the dolostone. They calculated the average thickness of clay from over 1500 non-georeferenced observations to be 215 cm but observed that the thickness varied by topographic position. Whitson (1927) also wrote that the red clay of southwest Wisconsin has been derived from the insoluble material remaining after the carbonate bedrock has dissolved. He notes that loess has been mixed with the residual products and it is difficult to determine the exact contributions of both parent materials. He estimated the clay thickness between 60 cm and 300 cm. Table 2 summarizes the available studies on the red clay in the Driftless Area of Wisconsin. It shows the wide range in depths and thicknesses in all studies.

From the literature it was found that the red clay is formed from carbonate bedrock and present on uplands underlain by dolostone and absent on sandstone ridges and in valleys (Frolking, 1978; Knox, 1989; Whitson, 1927). Knox et al. (1990) reported the subsoil clay as a nearly continuous layer of yellowish-red clay a few meters thick occurring under loess and on the dolostone uplands. Areas more likely to be impacted by erosion will have thinner layers of red clay and at shallower depths, and the red clay is more likely to occur, and occur at greater depths and thicker, on level areas. Areas where flowing water converges are less likely to have red clay and if clay is present, it will be thinner and occur at shallower depths. Deep deposits are favored by attributes that protect the clay from erosion, these include coarse chert fragments and unevenly weathered dolostone with many depressions and tubes.

Fig. 4. Typical catena and soil profile diagrams (A, Bt, 2Bt and 2C horizons) in the study area, the 2Bt horizon is the red clay (*Terra Rossa*).

Fig. 5. Relationship between red clay (*Terra Rossa*) properties and landscape attributes (units as in Table 1). Bottom figures show scatterplots between the variable above and lateral to it, while the numbers are the correlation coefficient ($r$).
In our study, the red clay was not found on all dolostone ridges and absent on sandstone ridges and in valleys. On summit positions the red clay layer is thin (≤10 cm) if present. It was found in areas on slopes greater than 5%. The red clay is not present on all dolostone ridges. The variation of the soil depth and the red clay could be attributed to the variable nature of the bedrock. On ridges dominated by dolostone, pockets of sandstone were observed and outcrops of sandstone were observed jutting from the slope near catenas 5 and 10. The dolostone was observed to be variable, sometimes sandy, and other times high in silt, and the red clay inherits these variations. The variations in the bedrock possibly confound attempts to relate the terrain characteristics, such as slope or curvature, to the red clay.

From this study the following is concluded:

- In half of the sampled pedons of the study area red clay subsoils were found.
- The mean depth to the red clay was 50 cm but it ranged from 7 to 130 cm.
- The thickness of the red clay ranged from 4 cm to 60 cm with an average thickness of 25 cm.
- In every pedon where the red clay was found the soil depth was less than 2 m and the depth was limited by dolostone bedrock.
- The red clay subsoil is found in all positions of the landscape except in the valley bottoms.
- When it occurs on summit positions the thickness of the red clay is less than 10 cm.
- The variations in the bedrock revealed through the closely spaced sampling of the catenas affected attempts to relate the terrain characteristics, such as slope or curvature, to the red clay.

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