Article Type:	Invited Methods Article - JoVE Produced Video
Manuscript Number:	JoVE57987R3
Full Title:	estimating sheet erosion rates from dendrogeomorphology
Keywords:	soil erosion; dendrogeomorphology; exposed roots; tree ring; ground microtopography; wood anatomy
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Additional Information:	
Question	Response
Please indicate whether this article will be Standard Access or Open Access.	Standard Access (US$2,400)
Please indicate the **city, state/province, and country** where this article will be **filmed**. Please do not use abbreviations.	Dendrolab.ch, Department of Earth Sciences, University of Geneva, Rue des Maraichers 13, CH-1205 Geneva, Switzerland

1 **TITLE:**
2 Estimating Sheet Erosion Rates from Dendrogeomorphology
3
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26 **KEYWORDS:**
27 Soil erosion; dendrogeomorphology; exposed roots; tree ring; ground microtopography; wood
28 anatomy
29

30 **SHORT ABSTRACT:**
31 Characterizing erosion from dendrogeomorphology has usually focused on accurately finding
32 the starting time of root exposure, by examining macroscopic or cell level changes caused by
33 exposure. Here, we offer a detailed description of different novel techniques to obtain more
34 precise erosion rates from highly accurate microtopographic data.
35

36 **LONG ABSTRACT:**
37 Sheet erosion is among the crucial drivers of soil degradation. Erosion is controlled by
38 environmental factors and human activities, which often lead to severe environmental impacts.
39 The understanding of sheet erosion is, consequently, a worldwide issue with implications for
40 both environment and economies. However, the knowledge on how erosion evolves in space
41 and time is still limited, as well as its effects on the environment. Below, we explain a new
42 dendrogeomorphological protocol for deriving eroded soil thickness (E_x) by acquiring accurate
43 microtopographic data using both terrestrial laser scanning (TLS) and microtopographic profile
44 gauges. Additionally, standard dendrogeomorphic procedures, dependent on anatomical

45 variations in root rings, are utilized to establish the timing of exposure. Both TLS and
46 microtopographic profile gauges are used to obtain ground surface profiles, from which E_x is
47 estimated after the threshold distance (*TD*) is determined, *i.e.,* the distance between the root
48 and the sediment knickpoint, which allows defining the lowering of the ground surface caused
49 by sheet erosion. For each profile, we measured the height between the topside of the root and
50 a virtual plane tangential to the ground surface. In this way, we intended to avoid small-scale
51 impacts of soil deformation, which may be due to pressures exerted by the root system, or by
52 the arrangement of exposed roots. This may provoke small amounts of soil sedimentation or
53 erosion depending on how they physically affect the surface runoff. We demonstrate that an
54 adequate microtopographic characterization of exposed roots and their associated ground
55 surface is very valuable to obtain accurate erosion rates. This finding could be utilized to
56 develop the best management practices designed to eventually halt or perhaps, at least, lessen
57 soil erosion, so that more sustainable management policies can be put into practice.
58
59 **INTRODUCTION:**
60 Both economic and environmental impacts produced by sheet erosion makes this topic in a
61 worldwide concern[1]. Several methods, from direct techniques to physical-based and empirical
62 approaches, are used to calculate soil erosion rates on a variety of temporal and spatial scales.
63 Direct techniques use field measurements under natural conditions and are mainly based on
64 the use of Gerlach troughs[2], water collectors[3], erosion pins[4] and profilometers[5]. Furthermore,
65 models of soil erosion have been increasingly focused on representing in detail the real physical
66 processes responsible for erosion[6].
67
68 Dendrogeomorphology[7] is a subdivision of dendrochronology[8] that it is successful in
69 characterizing frequency and magnitude of geomorphic processes[9–17]. Regarding sheet erosion,
70 dendrogeomorphology is usually employed to enhance or replace the methodologies
71 mentioned above, particularly in areas where erosion rates derived from direct techniques are
72 either scarce or unavailable. Dendrogeomorphology is a very flexible method for assessing soil
73 erosion and can be utilized to calibrate physical-based and empirical models, or perhaps as a
74 data   source   to   enhance   the   reliability   of   direct   estimation   techniques[18,19].
75 Dendrogeomorphology enables soil erosion to be established over large areas where exposed
76 roots are available. These exposed roots should show clear tree rings limits and respond to
77 annual growth patterns to be considered as optimum to apply dendrogeomorphological
78 techniques[20]. Further, exposed roots to be sampled should be preferably located in
79 homogenous units based on their reaction to soil erosion[21].
80
81 The conventional dendrogeomorphical way of estimating sheet erosion is grounded on
82 measuring *in situ* the eroded soil thickness (E_x) from the time of the very first exposure to the
83 present[22–24]. The ratio between these two variables is utilized to calculate an erosion value in
84 mm·yr[1]. Much of the research conducted to date has focused entirely on efficiently identifying
85 the initial year of exposure. As an outcome, modifications in the root due to exposure are
86 analyzed at the macroscopic level[25], or at the tissue and cellular levels[26–28]. The principal
87 anatomical change present in the exposed roots of conifers is increasing growth ring thickness,
88 as a consequence of a significant number of cells within the earlywood (EW)[26]. A cutback has

89   similarly been found within the lumen area of EW tracheids along with an increased cell wall
90   structure thickness of latewood (LW) tracheids[24,27,29]. These modifications have been described
91   and quantified as beginning when erosion lowers the ground surface over the root to roughly
92   three cm[30]. Less attention was granted to the adequate determination of the E_x parameter. The
93   age of exposed roots was typically connected with the height of the root's center axis of growth
94   over the ground surface[31,32]. The estimation of E_x was consequently corrected considering
95   ongoing secondary growth[30,33]. More recently, these methodological approaches have also
96   integrated the characterization of soil microtopography to obtain reliable erosion rates[34–36].
97
98   We present a laboratory and field protocol to estimate more accurate and reliable sheet
99   erosion rates from dendrogeomorphology. In this particular protocol, we examine the
100   hypothesis that sampling all exposed roots, regardless of orientation relative to runoff path and
101   in conjunction with microtopographical analysis, enables erosion rates to be precisely
102   reconstructed and quantified. Our objective, therefore, is to provide a protocol to estimate
103   erosion rates from maximizing the sample size of exposed roots, using macroscopic and
104   microscopic information found in growth tree-ring series and also high-resolution topographic
105   data.
106
107   **PROTOCOL:**
108
109   **1.   Sampling Strategy**
110
111   1.1)   Geomorphic process identification
112
113   1.1.1) Implement the Hydrologic Response Units approach (HRU)[21]. To this end, identify
114   homogenous areas within the study site, comprising lithology and surface deposits, canopy
115   cover, vegetative residue in contact with the soil surface and slope. Select among all the HRUs
116   those in which the sheet erosion process is predominant.
117
118   [Place **Figure 1** here]
119
120   1.2)   Sampling of exposed roots
121
122   1.2.1) Locate in the study site exposed roots corresponding to tree species useful for tree-ring
123   dating (preferably coniferous)[20].
124
125   1.2.2) Provide a detailed description of the spatial and morphological characteristics of the
126   surroundings of the exposed roots to be sampled. Collect the following information:
127   geographical location (UTM coordinates); altitude; aspect in sexagesimal degrees, both for the
128   hillside and for the particular root location (local aspect); distance of the root section to the
129   tree trunk; hillside slope and slope of the specific root location (both expressed in degrees);
130   orientation of the exposed root with regard to the runoff path.
131

132 1.2.3) Take one soil sample of about 1 kg from the area surrounding each exposed root. The
133 parameters to characterize are texture, percentage of organic matter and soil structure.

135 1.2.4) Measure *in situ* hydraulic conductivity using a single ring infiltrometer under constant
136 head.

138 Note: Implement steps 1.2.2 and 1.2.3 to characterize soil erodibility.

140 1.2.5) Locate exposed roots that are farther than 1.5 m from the trunk. At lesser distances the
141 exposure could be related to tree growth.

143 1.2.6) Cut with a handsaw at least 30 exposed roots, with a diameter greater than 5 cm, into 15
144 cm-long sections. Subsequently, take two slices of approximately 1.5 cm thick.

146 [Place **Figure 2** here]

148 1.2.7) By using a gauging trowel, a handsaw and a measuring tape, sample a subset of buried
149 roots (at least one-third of the total exposed roots sampled) at different soil depths (maximum
150 20 cm) to establish the minimum soil thickness below which roots begin to have an anatomical
151 response due to exposure.

153 **2.   Microtopographic Characterization of Ground Surface and Exposed Roots at Easily**
154 **Accessible Locations**

156 2.1)   Use a Terrestrial Laser Scanning device that can measure up to 50,000 points per second
157 with a precision of 1 mm at a scanning distance of < 120 m.

159 2.2)   Consider at least two different conventional TLS locations to avoid shadow zones.

161 2.3)   Merge the different locations by using a minimum of four high-definition surveying
162 (HDS) targets positioned to cover the entire area.

164 2.4)   In order to obtain highly accurate topographic data, scan an average area of 300 cm^2
165 from the selected locations using a spatial resolution of 1 mm. Include the exposed roots and
166 the surrounding area that is representative of the ground surface.

168 **3.   Microtopographic Characterization of Ground Surface And Exposed Roots, at Locations**
169 **with Difficult and Steep Terrain (Mountain Environments)**

171 3.1)   Place a microtopographic profile gauge perpendicular to the exposed root and,
172 subsequently, level horizontally for all measurements in such a way that different datasets can
173 be compared.

175 3.2)   Draw the profile obtained in step 3.1 on graph paper to be able to infer the amount of
176 eroded soil along the profile with sub-millimeter precision.

178 [Place **Figure 3** here]

180 **4.   Determination of the Timing of Root Exposure**

182 4.1)   Macroscopic analysis

184 4.1.1) Air dry the sections obtained in step 1.2.6 for 2 months.

186 4.1.2) Obtain from the initial sections two slices that are each approximately 2 cm thick.

188 4.1.3) Sand and polish the slices with sandpaper (up to 400 grit) to facilitate recognition of
189 growth rings.

191 4.1.4) Scan slices at a minimum resolution of 2,800 dpi so that they can be accurately analyzed
192 even when rings are particularly thin.

194 4.1.5) Use the increase in latewood percentage and larger growth-ring widths as indicators of
195 stress induced by exposure.

197 4.1.6) Mark at least 4-5 radii along the diameters of the slices that show the highest variability
198 in growth-ring widths.

200 [Place **Figure 4** here]

202 4.1.7) Use an image analysis system or a measuring table to measure tree-ring width.

204 4.1.8) Apply visual cross-dating procedures by comparing variability in growth-ring widths
205 between the different radii, to both improve the dating precision for the first year of exposure
206 to soil erosion and to correctly date subsequent rings and recognize the presence of multiple or
207 discontinuous rings.

209 4.2)   Microscopic analysis

211 4.2.1) For both exposed and non-exposed root samples, use a sliding microtome to obtain
212 radial cross-sections of approximately 1 cm in width and 20 microns thick.

214 4.2.2) Stain cross-sections with safranin (*i.e.,* 1 g of safranin + 50 g of water + 50 g of 96%
215 ethanol) and dehydrate with increasingly richer ethanol-water solution up to 96% ethanol (*e.g.,*
216 50% and 96% ethanol) until the ethanol runs clear. Soak the samples in xylol or a citrus oil
217 clearing agent (*e.g.,* Histoclear).

4.2.3) Mount cross-sections on coated slides, cover-slip with a hardening epoxy (*e.g.,* Eukitt, Canada balsam and dry at ambient temperature (*i.e.,* about 5-8 h for Eukitt, at least 24 h for Canada balsam).

4.2.4) Observe (under 125X magnification) and photograph samples with a digital imaging system under optical microscopy.

4.2.5) Compare under an optical microscope the anatomical footprint of both exposed and non-exposed root samples (steps 1.2.5 and 1.2.6).

4.2.6) Take microscopic measurements using an image analyzer on the digital photographs of the ensuing parameters: a) width of the growth ring; b) number of cells per ring; c) percentage of latewood; and d) lumen area in earlywood.

4.2.7) Test with the image analyzer (step 4.2.6) the occurrence of resin ducts and take measurements for each growth ring.

4.2.8) Perform a one-way analysis ANOVA with multiple range tests (method: 95% LSD –Least Significant Difference) for the anatomical variables considered (step 4.2.6) to verify the existence of statistically significant differences between the two groups of measurements (pre-exposed vs exposed roots).

5.   Estimation of the Thickness of the Soil Layer Eroded Since Initial Exposure (*Ex*)

5.1)   Scenario 1: exposed roots that run parallel to the runoff path.

5.1.1) Based on the data obtained in step 2.4, use inverse distance weighting as the interpolation method to obtain highly accurate digital elevation models (DEMs) with a spatial resolution of 3 mm.

5.1.2) Use GIS tools to extract from the DEM perpendicular profiles of the exposed root with a rough distance of 150 cm.

5.1.3) Perform steps 5.1.1 and 5.1.2 at easily accessible locations (step 2).

5.1.4) Use the perpendicular profiles of the exposed root obtained in step 3.2 when the study site is located in areas where the terrain is difficult and steep (mountain environments) (step 3).

5.1.5) In the profiles obtained in steps 5.1.2 and 5.1.3 use visual interpretation to locate the threshold distance (*TD*), defined as the distance between the root and the knickpoint at the ground surface. This establishes the lowering of ground surface for the profiles due to sheet erosion.

[Place **Figure 5** here]

263

264 5.1.6) Estimate the thickness of the soil layer eroded, by measuring the height between the top
265 of the root and the knickpoint at the ground surface estimated in step 5.1.5.

266

267 5.1.7) Correct the measurement obtained in step 5.1.6 by subtracting it from the ongoing
268 secondary growth (*i.e.,* growth of the root since the year of exposure) and the bark thickness on
269 the upper/lower side of the root. See Corona *et al.* [30] for a detailed description.

270

271 5.2)   Scenario 2: exposed roots that run perpendicular to the runoff path

272

273 5.2.1) Implement steps 5.1.1 to 5.1.4 as stated under step 5.1.

274

275 5.2.2) Using the raster calculator available in any Geographic Information System (GIS)
276 software, for each perpendicular profile measure the height between the top of the root and
277 the ground surface using the knickpoint at the ground surface as a reference. At this point
278 measurements of E_x are not influenced by sedimentation and/or scour erosion and, therefore,
279 it is possible to measure soil erosion.

280

281 [Place **Figure 6** here]

282

283 5.2.3) Correct the measurement obtained in step 5.2.2 using the procedure in step 5.1.7.

284

285 **6. Sheet Erosion Rate Estimation**

286

287 6.1) Depending on the soil mechanic characteristics of the study site, apply equation 1 (*i.e.,*
288 hypothesizes that the radial growth pressure applied by the root is lower than shear strength of
289 the soil), or equation 2 (*i.e.,* supposes stability of the root axis through time)[30]:

290

291 $$E_R = \frac{E_X - (G_{r1} - G_{r2}) + \left(\frac{B_1 + B_2}{2}\right) + \varepsilon}{NR_{ex}}$$ (1)

292

293 $$E_R = \frac{E_X - (G_{r1}) + \frac{B_1 + B_2}{2} + \varepsilon}{NR_{ex}}$$ (2)

294

295 Where:

296

297 E_R (mm·yr^{-1}), is the sheet erosion rate to be estimated.
298 E_X (mm), is the thickness of the soil layer eroded since initial exposure. This is obtained by
299 performing steps 5.1.1 to 5.2.3.
300 G_{r1} and G_{r2} (mm) represent the secondary (subsequent) growth on the upward/downward part
301 of the root after exposure. It is obtained after performing step 5.1.7.

302   B_1 and B_2 (mm) are the bark thickness on the upper/Lower part of the root. It is obtained with
303   the procedure in step 5.1.7.
304   ε (mm), is defined as the minimal depth of soil below which root begin to change its anatomical
305   configuration.
306   NR_{ex} (yr), is the number of tree-rings developed after the year of exposure. It is obtained using
307   steps 4.1.1 to 4.2.8.
308
309   **REPRESENTATIVE RESULTS:**
310   Samples of exposed roots suffer serious cambial deterioration due to the impact of exposure
311   (*e.g.,* modifications in temperature, incidence of light) plus the physical stress, due to trampling
312   by hikers or animal grazing and browsing that the roots undergo after they are exposed.
313   Determining the existence of discontinuous rings, as well as precisely dating the first year of
314   response to exposure was accomplished in the lab as in Protocol 4 (steps 4.1.6 to 4.1.8). We
315   chose the increase of latewood percentage and the presence of tree-ring significantly wider
316   than the average as indicators of first exposure.
317
318   114 sections of exposed *Pinus uncinata* Ramond ex DC, *Fagus sylvatica* L., *Pinus pinaster* Ait.
319   and *Pinus sylvestris* roots were used for this purpose. As a result of the death of the cambium
320   on the top part of the root, we found severe changes in the tree-ring growth pattern, which
321   shifted from concentric to eccentric growth (**Figure 7**), as well as discontinuous tree-rings or
322   even some that had been completely destroyed in the outer tree-rings. The above suggests that
323   the approach we implemented was successful in determining with enough accuracy the age of
324   the roots and the particular year in which the first exposure ring was formed.
325
326   [Place **Figure 7** here]
327
328   A lab experiment was conducted as in protocol 4 (steps from 4.2.1 to 4.2.8) to determine how
329   roots anatomically respond to exposure. To this end, the same exposed roots sample described
330   above was used. Samples were examined below optical microscopy and photographed with a
331   digital imaging system. Microscopic images were analyzed at 50× magnification with an
332   accuracy of 1 μm in the measurements. The first time of exposure can be seen in the
333   characteristic anatomical changes. Tree-rings show evident increased growth (particularly
334   recognizable in two or three succeeding rings), which is as a result of an increase in both
335   tracheid number and their size. An increase in the number of vessels was also noticeable. Resin
336   ducts usually appear in tangential rows in earlywood. Latewood is readily observable as it has
337   several rows of thick-walled tracheids. A significant decline in the tracheid lumen of earlywood
338   once root is exposed also occurs. With respect to the anatomical footprint of the ten buried
339   roots sampled, results indicate that this sample group starts to react according to the behavior
340   described above when the edaphic cover fall below 3 cm (**Figure 8**).
341
342   [Place **Figure 8** here]
343
344   Characterization of surface microtopography variability plays a critical role in obtaining reliable
345   sheet erosion rates derived from dendrogeomorphology (**Figure 9**). To this end, we designed an

346   experimental and field experiment aimed at capturing highly accurate microtopographic
347   surface profiles to be analyzed using protocol 5 on 114 samples of exposed roots. We utilized
348   the distance between the root and the knickpoint, from which the profile defines the lowering
349   of ground surface due to sheet erosion as a criterion to estimate the thickness of the soil layer
350   eroded since initial exposure (E_x). Concerning sampled exposed roots running parallel to the
351   runoff path, all profiles analyzed showed a concave configuration on both sides of the exposed
352   roots that were characterized. This morphological pattern ends at a specific distance (TD), from
353   which ground surface is only shaped by sheet erosion, determining, therefore, the location
354   where E_x has to be measured. Concerning exposed roots that run perpendicular to the runoff
355   path, our procedure made it possible to systematically determine the height between the
356   topside of the root and a virtual plane tangential to the ground surface. It also allowed locating
357   small-scale impacts of sedimentation and scour erosion and, hence, ensuring that sheet erosion
358   is accurately estimated.
359
360   [Place **Figure 9** here]
361
362   Estimates of sheet erosion rates have been obtained according to the equation included in
363   protocol 6 (**Figure 10**). As regards the 114 samples analyzed, the year of very first root exposure
364   fluctuates from 1900-2012, which enables the medium-term (multidecadal) characterization of
365   the erosion rates. Additionally, we examined ten buried roots, which were still protected by a
366   thin soil cover. Results showed that buried roots began to anatomically respond to the
367   exposure effects when they were 2.3 ± 1.1 cm below the ground surface (**Figure 11**). We
368   considered this specific soil level as a value to be added to the thickness of the soil layer eroded
369   (E_x).
370
371   [Place **Figure 10** here]
372   [Place **Figure 11** here]
373
374   **FIGURE AND TABLE LEGENDS:**
375
376   **Figure 1: Example of HRUs associated to a sandy gully.** Regarding the protocol proposed here,
377   the sampling of exposed roots must be conducted in an HRU in which the effective erosive
378   process is sheet erosion (in this figure legend corresponding to exposed sand with moderate
379   slopes). This figure has been modified from Bodoque *et al.* [21].
380
381   **Figure 2: Example of how to conduct field sampling.** At least 30 exposed roots are selected
382   and, subsequently, cut with a handsaw.
383
384   **Figure 3: Example of characterization of ground microtopography using a microtopographic
385   profile gauge.** (A) Illustration of exposed roots as observed along a hiking trail; (B)
386   measurements of soil microtopography using a microtopographic profile gauge; (C) estimation
387   of E_x through the acquisition of microtopographic profiles by drawing them on a graph paper to
388   allow inference of the amount of eroded soil along the profile and with sub-millimeter
389   precision.

390

391 **Figure 4: Example of how to prepare a section of an exposed root to accomplish**
392 **dendrochronological dating of growth ring series.** In each section, four or five radii are marked
393 along the directions that show the highest variability regarding tree-ring width.

394

395 **Figure 5: Example is illustrating how to place *TD* when the exposed roots sampled are**
396 **orientated according to the runoff path.** This figure shows a common microtopographic
397 transversal profile of uncovered root and its immediate vicinity. E_{x1} is the location applied to
398 the traditional dendrogeomorphical approach to determine the eroded soil thickness; E_{x2}
399 belongs to the position where this parameter needs to be assessed. *TD* is taken as a guide
400 position from which the ground surface is changed by sheet erosion only. This figure has been
401 modified from Bodoque *et al.* [34]

402

403 **Figure 6: Example drawing how to proceed when the exposed roots sampled are orientated**
404 **according to the perpendicular to the runoff path.** This figure shows a schematic view of a
405 ground surface profile related to an exposed perpendicular root concerning the runoff path.
406 Eroded soil thickness (E_x) is quantified at the knickpoint coinciding to prevailing sedimentation
407 and scour erosion processes nearby the root. This figure has been modified from Ballesteros-
408 Cánovas *et al.* [35]

409

410 **Figure 7: Examples of eccentric tree-ring pattern in roots due to exposure.** This figure shows a
411 view of a polished section of a root exposed in the absence scars (A) and with scars (B). In both
412 cases, it is feasible to observe the pattern of eccentric tree-rings as a clear reaction to soil
413 erosion.

414

415 **Figure 8: Example of anatomical response of roots to exposure.** Wood anatomy of *Pinus*
416 *uncinata* Ramond ex DC roots: (A) anatomy of buried roots (200 µm); (B) anatomy of exposed
417 wood (500 µm). Wood anatomy from roots of *Fagus sylvatica* L.: (C) anatomy of a buried root
418 (500 µm); (D) anatomy of exposed wood (500 µm). This figure has been modified from Bodoque
419 *et al.* [36]

420

421 **Figure 9: Example of outputs of ground surface microtopography characterization obtained**
422 **from TLS and a microtopographic profile gauge.** (A) Hillshade model achieved using
423 microtopographic profiles and (B) raster of slopes derived from the hillshade model; (C)
424 hillshade model obtained from TLS and (D) resulting raster of slopes. Slopes are expressed in
425 sexagesimal degrees. In plots B and D, dashed lines indicate the *TD* at which E_x must be
426 measured. This figure has been modified from Bodoque *et al.* [36]

427

428 **Figure 10: Example of sheet erosion rates estimated from dendrogeomorphology.** Graph
429 linking erosion rates and years of exposure of the exposed roots. Erosion rates inside the
430 square are those used for quantification purposes. This figure has been modified from Bodoque
431 *et al.* [21]

432

433 **Figure 11: Example of anatomical response in buried root sections.** *Dark grey circles* show
434 buried roots with exposure evidence. The size of *circles* shows root diameter, whereas the
435 numbers indicate root depths. This figure has been modified from Ballesteros-Cánovas *et al.* [35]
436
437 **DISCUSSION:**
438 The protocol deployed demonstrates the value of detailed and proper characterization of
439 ground surface microtopography, as it enables to measure trustworthy sheet erosion rates
440 from dendrogeomorphology. Our methodological approach focuses on the importance of
441 characterizing the microtopography in the surroundings of exposure roots to improve erosion
442 rate estimation. This factor has been largely ignored in previous studies, resulting in a
443 misinterpretation of soil erosion rates derived from dendrogeomorphology[34].The inclusion of
444 microtopography allows erosion rates to be estimated regardless of root orientation, which
445 favors the replicability of the methods[35]. The acquisition of microtopography may be performed
446 using different techniques. Therefore, we recognize differences between the DEM produced
447 from microtopographic profiles (step 5.2.1) and TLS (steps 5.1.1 to 5.1.2). Despite these
448 differences sometimes being even within the order of up to 50% of the variance of the
449 measures[36], we highlight that the reliability of our protocol based on microtopographic profiles
450 (step 5.2.1) is comparable to that achieved with TLS (~mm).
451
452 This study also demonstrates that the protocol deployed here can be used in mountainous
453 areas as an alternative approach to TLS. The use of TLS in this specific geographic context is not
454 practical due to the size and weight of the device, which hinder its transport through
455 inaccessible areas. The application of the *TD* criteria as an indication of the distance at which
456 ground surface is not changing as a result of axial and radial pressures exerted by the root[37, 38],
457 or where there is no sedimentation (upslope of the root) or scour erosion (downslope of the
458 root)[35] is illustrated as well (steps 5.1.5 and 5.2.2). We determined that this particular distance
459 must be utilized in future work involving the definition on the point at which E_x shall be
460 measured.
461
462 Macroscopic and microscopic observations (steps 4.1 and 4.2) are essential to decipher the
463 environmental signal in tree-ring records. The only use of tree-ring width measurements might
464 not be enough to determine the moment of exposure, since anatomical changes are more
465 sensitive[39] and could even be produced when root are still buried by a thin soil layer[30]. Thus,
466 existing studies suggest that the coniferous tree species used in this paper (*i.e., Pinus uncinata*
467 Ramond ex DC, *Pinus pinaster* Ait. and *Pinus sylvestris*) react to exposure with eccentric growth
468 and a significant development of latewood tracheids, which is congruent with former findings
469 on other conifer species [21, 27, 29, 30]. Reactions start happening when the soil coverage of the root
470 declines below 2.3 ± 1.1 cm and therefore agrees with the observation from marly badlands in
471 France in which the analysis was focused on *Pinus sylvestris and Pinus nigra*[30].
472
473 The first exposure reaction is translated as a reaction to boosting temperature variability as well
474 as drought stress that will happen more quickly in the top of the detrital level of loose sediment
475 close to the soil surface[29, 30, 40, 41]. This anatomical modification may also be viewed as a
476 predictable response of the root to lessen the chance of dysfunctional tracheids due to

477   cavitation, caused by the development of ice crystals in the sap[42], or even due to mobile
478   embolism associated with water stress[43]. Our observations, consequently, verify the hypothesis
479   of Corona *et al.*[30] and also propose that previous assessments that did not consider this bias
480   could have undervalued erosion rates. In the case of *Fagus sylvatica* L., we can confirm
481   similarities in the patterns and reactions between this particular species and other deciduous
482   species discussed in the literature[26, 28, 29].

483

484   Dendrogeomorphology has competitive advantages compared to other methods of direct
485   estimation. So, the analysis based on exposed roots enables to be ambitious in terms of
486   characterizing soil erosion even at the basin scale, providing representative erosion rates of the
487   last decades. In contrast, the use of direct methods, as Gerlach troughs[2], water collectors[3] or
488   gauging stations[44], is usually limited to a few years and to the use at the hillslope scale, due to
489   the high cost of maintenance and operation of these devices[21]. Similar thinking could also be
490   applied to models aimed at estimating soil erosion[45], since they require gauges located in the
491   field to allow their validation and calibration[46]. Concerning the analysis of soil erosion in
492   recreation trails, our protocol is much more easily applied than standard protocols, *i.e.,* cross-
493   sectional area (CSA), variable CSA, maximum incision to the trail or topographic surveys[47–49],
494   particularly if the trail is positioned in mountainous areas. In this particular geographic context,
495   it is a challenge to use the protocols above owing to the heavy equipment required, which is
496   difficult to move in such environments. This limitation can restrict the number of transects
497   collected and can consequently impact spatiotemporal estimates of soil erosion[50]. Furthermore,
498   it is a challenge to accurately determine the horizontal position and guarantee that the same
499   height above the fixed points is considered, as soil creep tends to play a role in such
500   environments[49].

501

502   The limitations of erosion rates derived from dendrogeomorphology are related to the fact that
503   the age of exposed roots is usually limited to a few decades. Nevertheless, this time window is
504   usually larger than the one defined by erosion rates obtained from direct techniques. Cross-
505   dating, the basic principle of dendrochronology, also has proven difficult to be implemented in
506   roots, even though they pertain to the same tree[51, 52]. Besides, the consistency of root-based
507   estimation of erosion rates is probable to be affected by restrictions similar to those noted for
508   documentary sources or approaches based on radioisotopes[53]. Concerning the above, soil
509   erosion will be a consequence of a non-linear response to rainfall. Average erosion rates
510   obtained from dendrogeomorphology might be, therefore, less reliable to characterize soil
511   erosion in areas where this process is mostly due to a few heavy rainfall events, since under this
512   circumstance erosion rates could be skewed[55]. Additionally, the sampling of large exposed roots
513   may lead to underestimate erosion rates since it has been demonstrated that erosion rates and
514   root thickness has an inversed proportional relationship[19].

515

516   The results produced from the protocol deployed here offer useful information on soil
517   degradation. In that sense, dendrogeomorphology may aid decision makers to design long-term
518   management plans, due to the spatiotemporal representativeness of erosion rates derived
519   from exposed roots.

520

521 **ACKNOWLEDGMENTS:**

526

527 **DISCLOSURES:**

528 The authors have nothing to disclose.

529

530 **REFERENCES:**

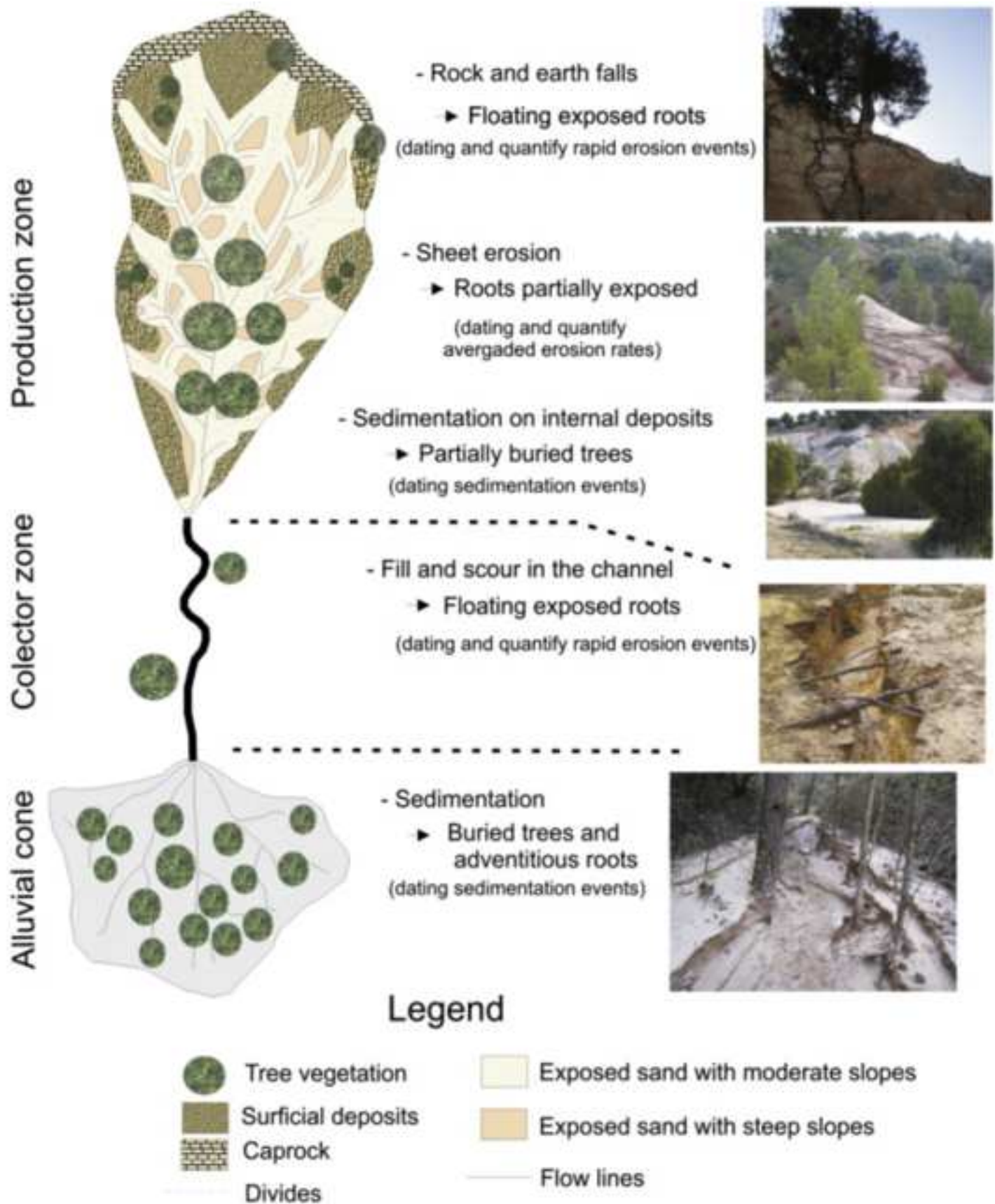531 1.   Montgomery, D.R. Soil erosion and agricultural sustainability. *Proceedings of the*
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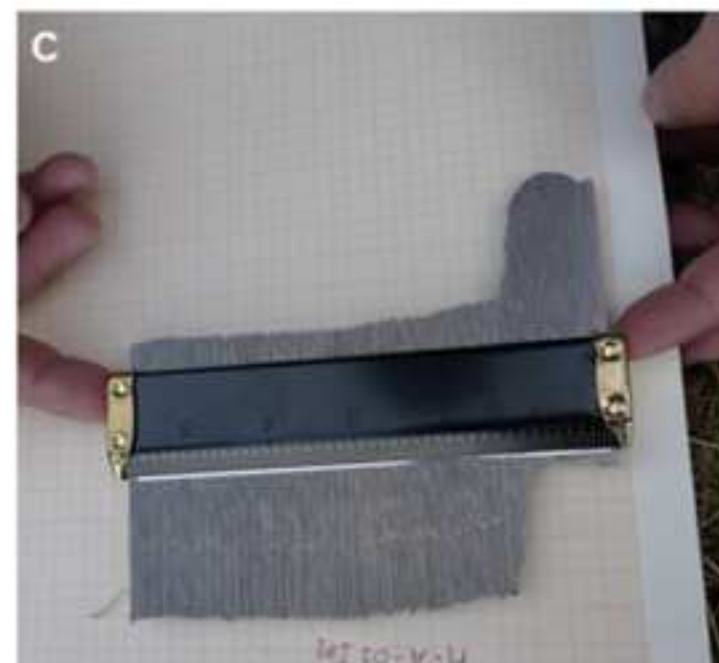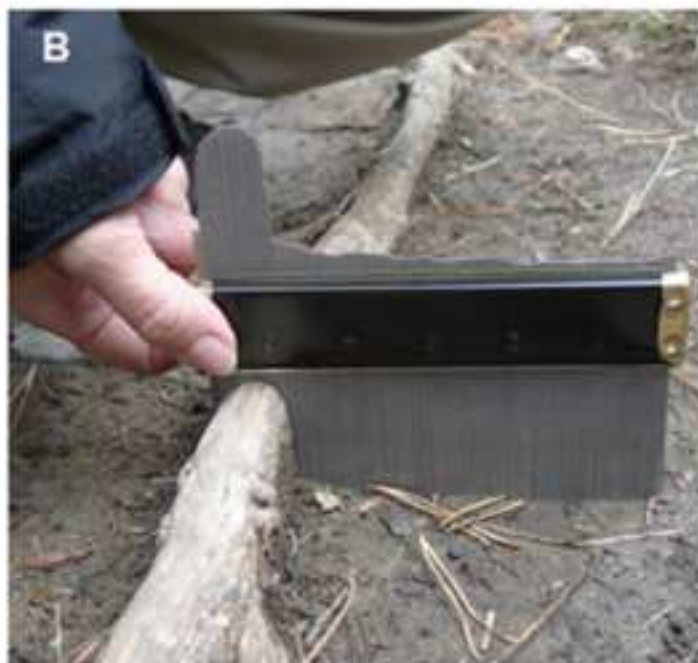564 10.1016/j.jhydrol.2011.03.045 (2011).

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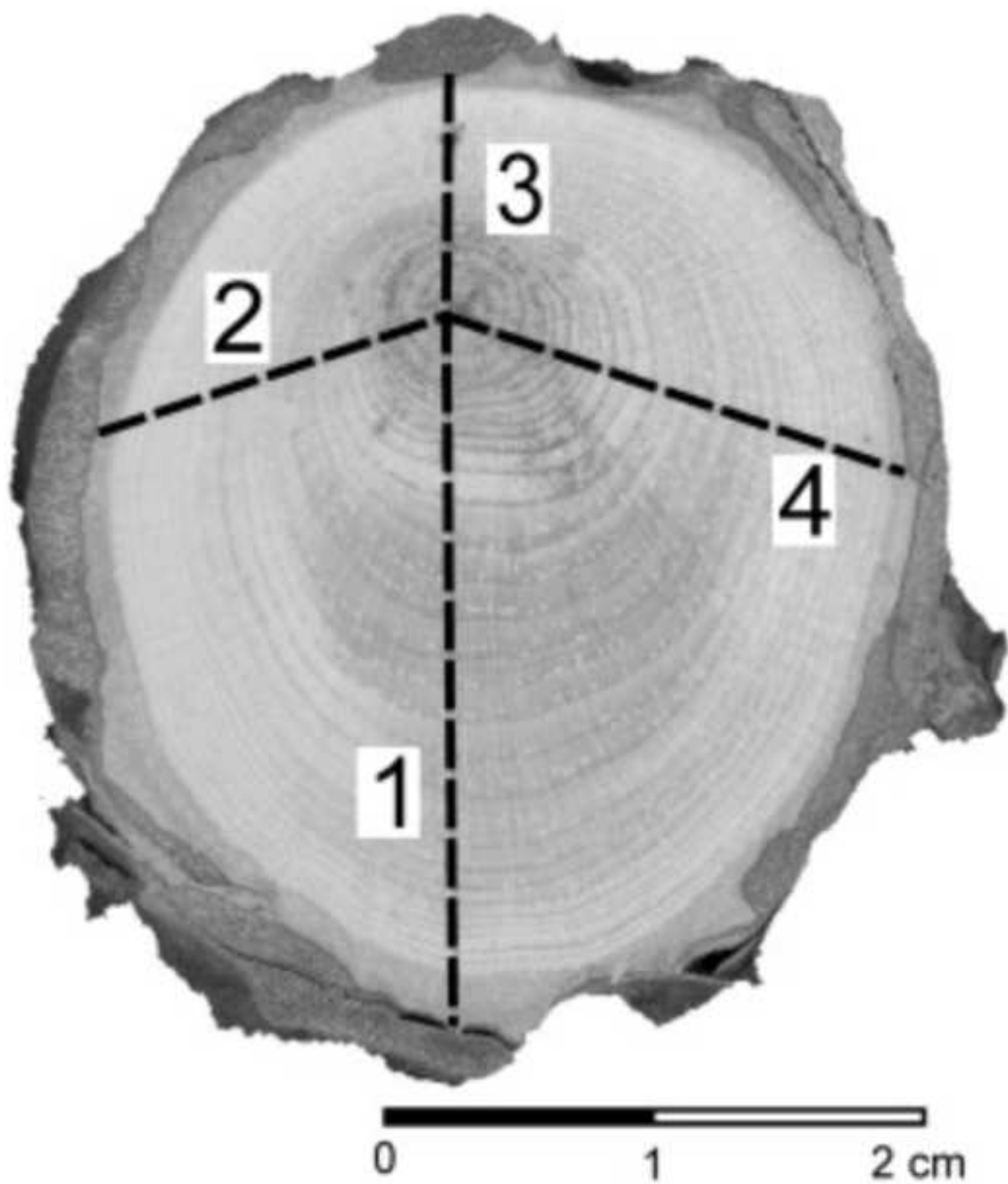608   10.1016/j.catena.2007.05.008 (2008).

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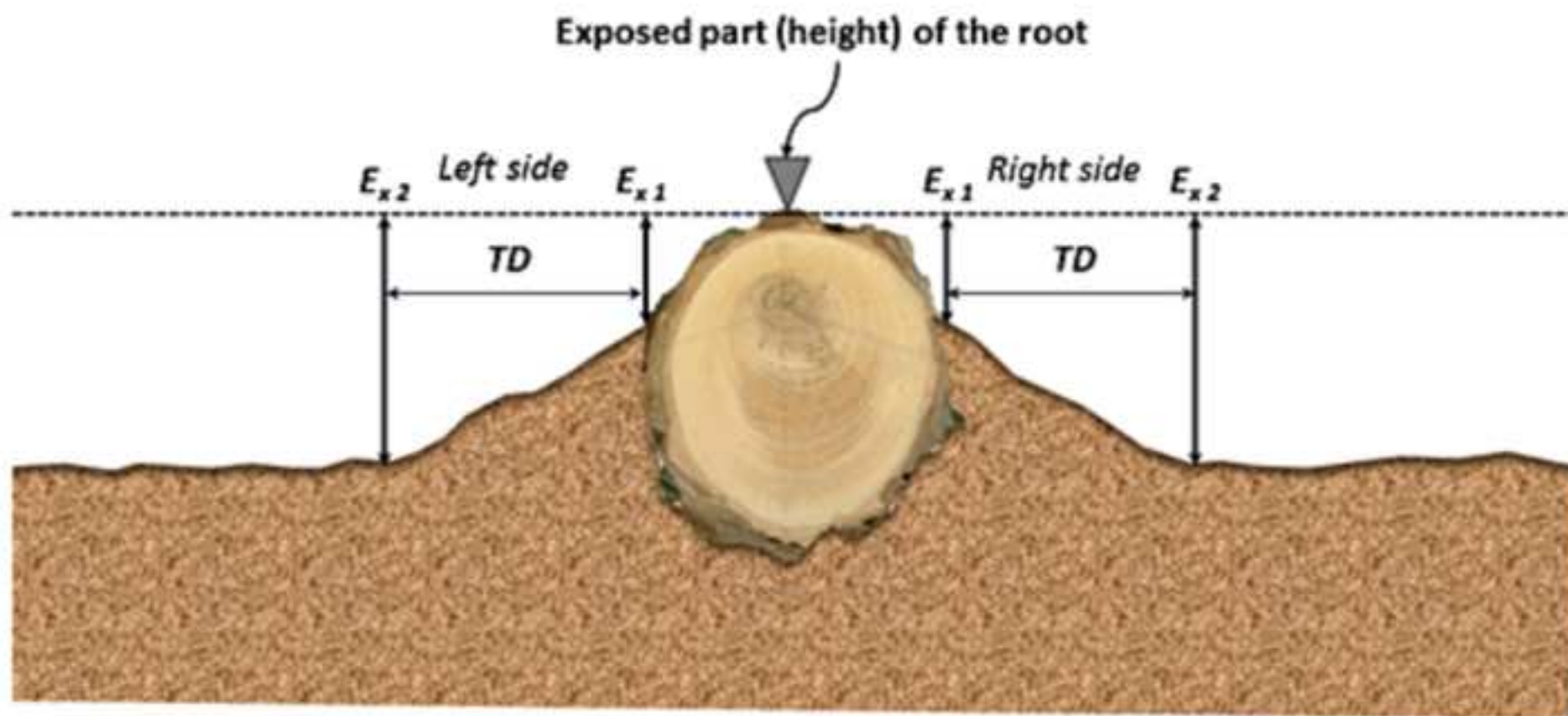
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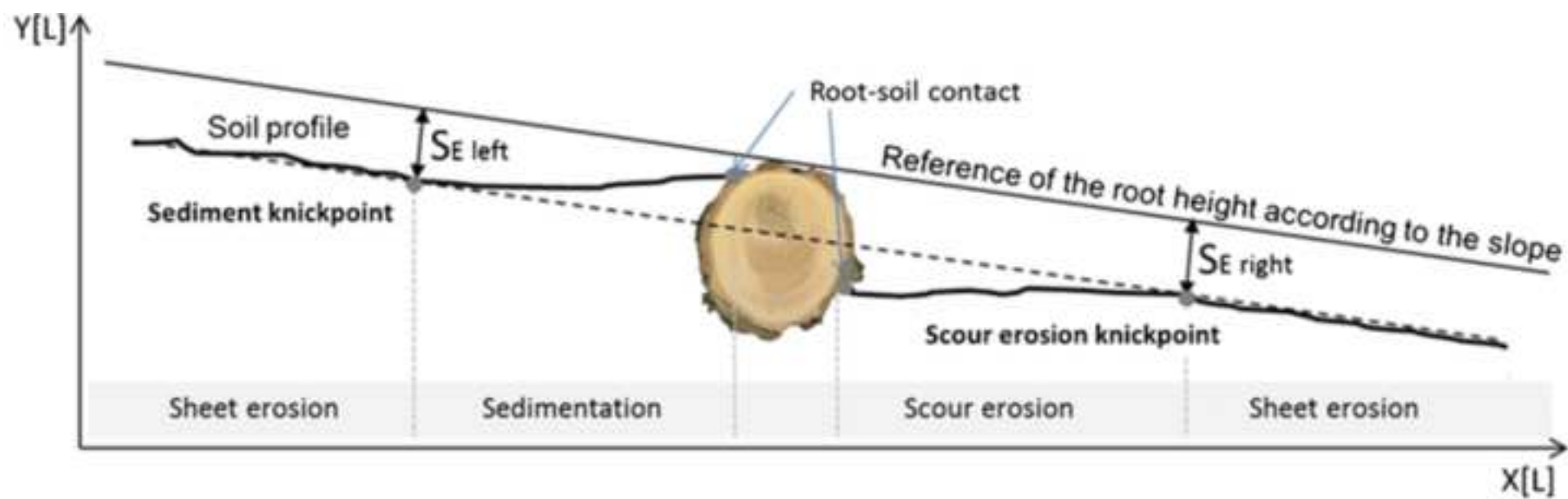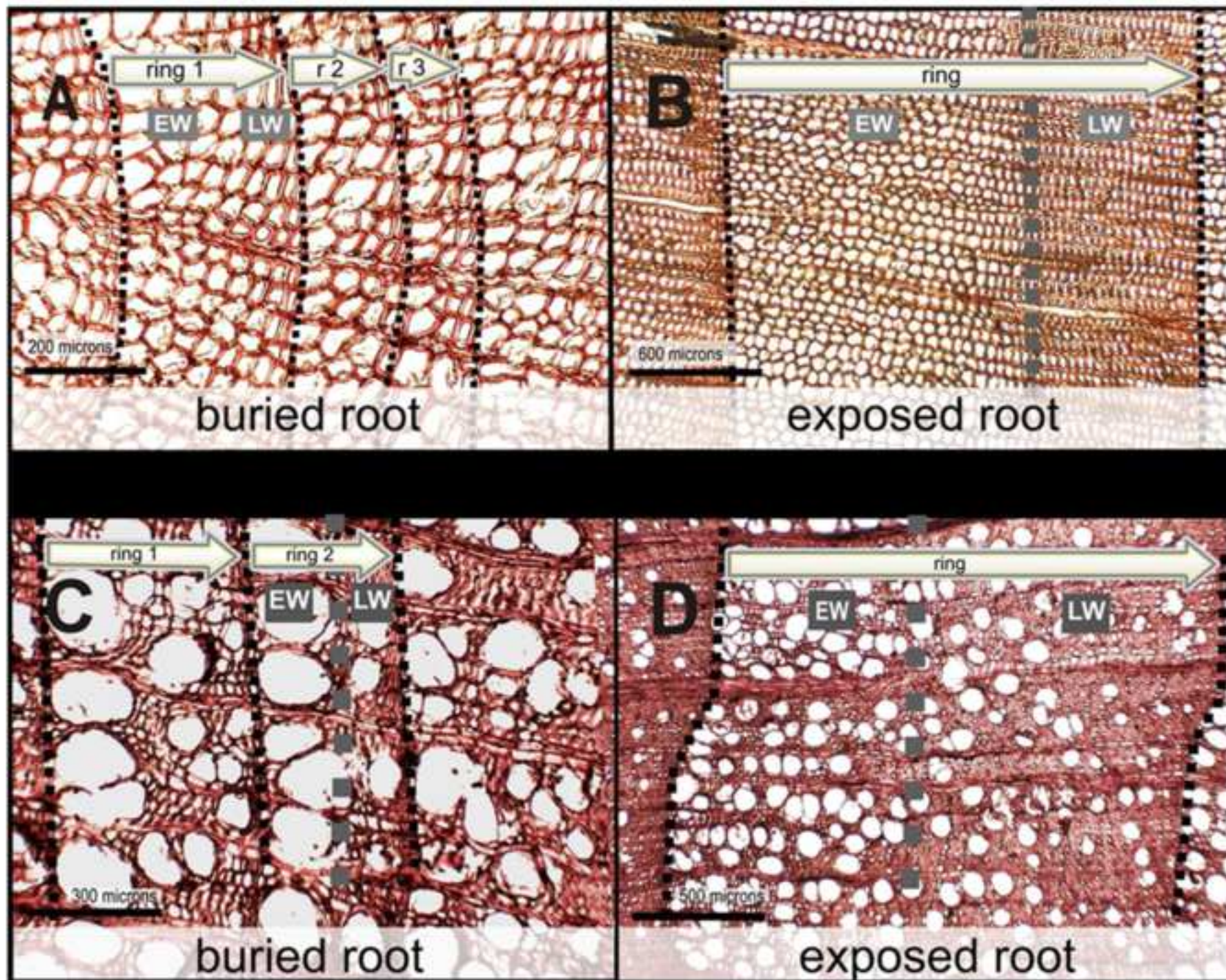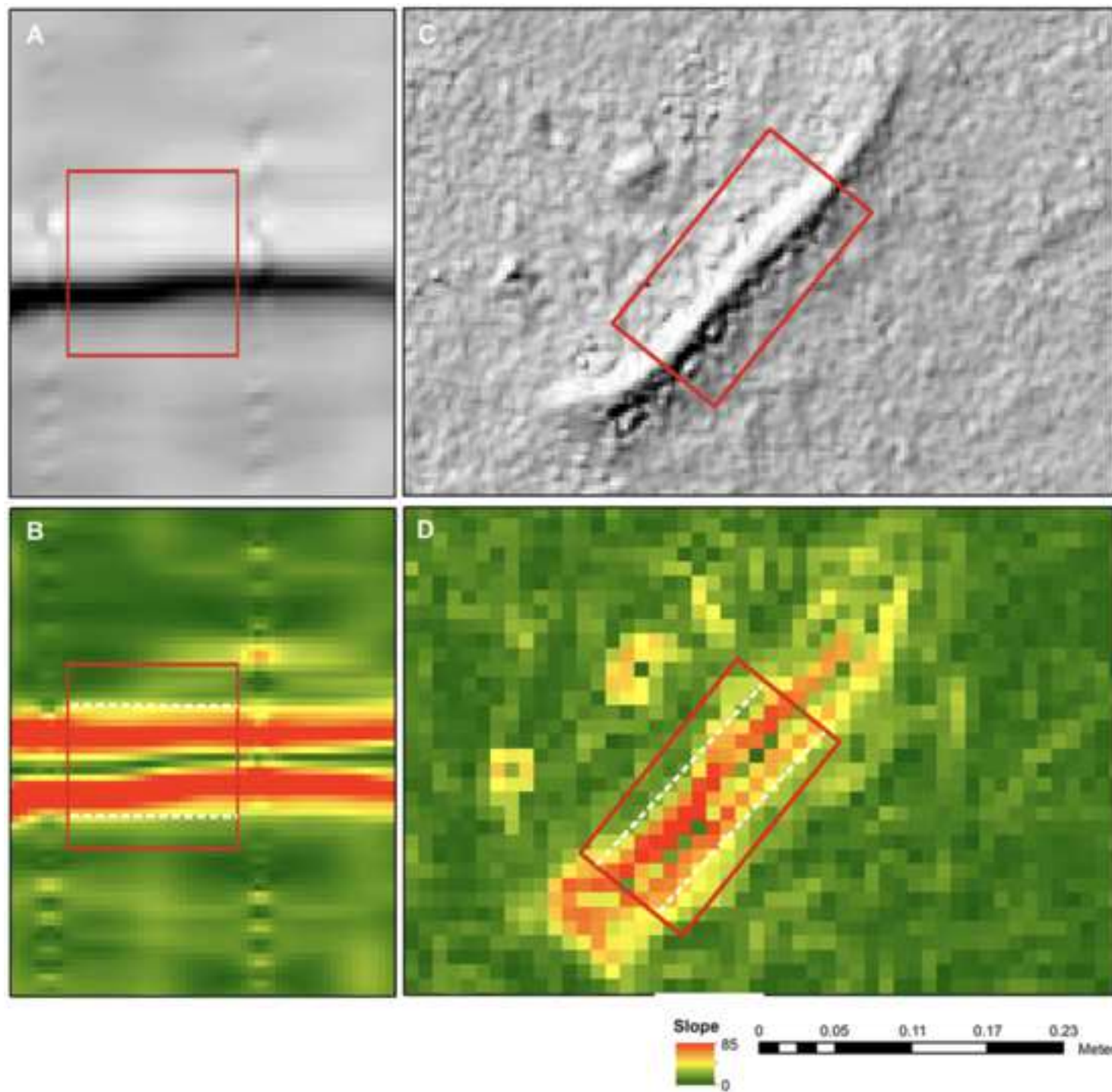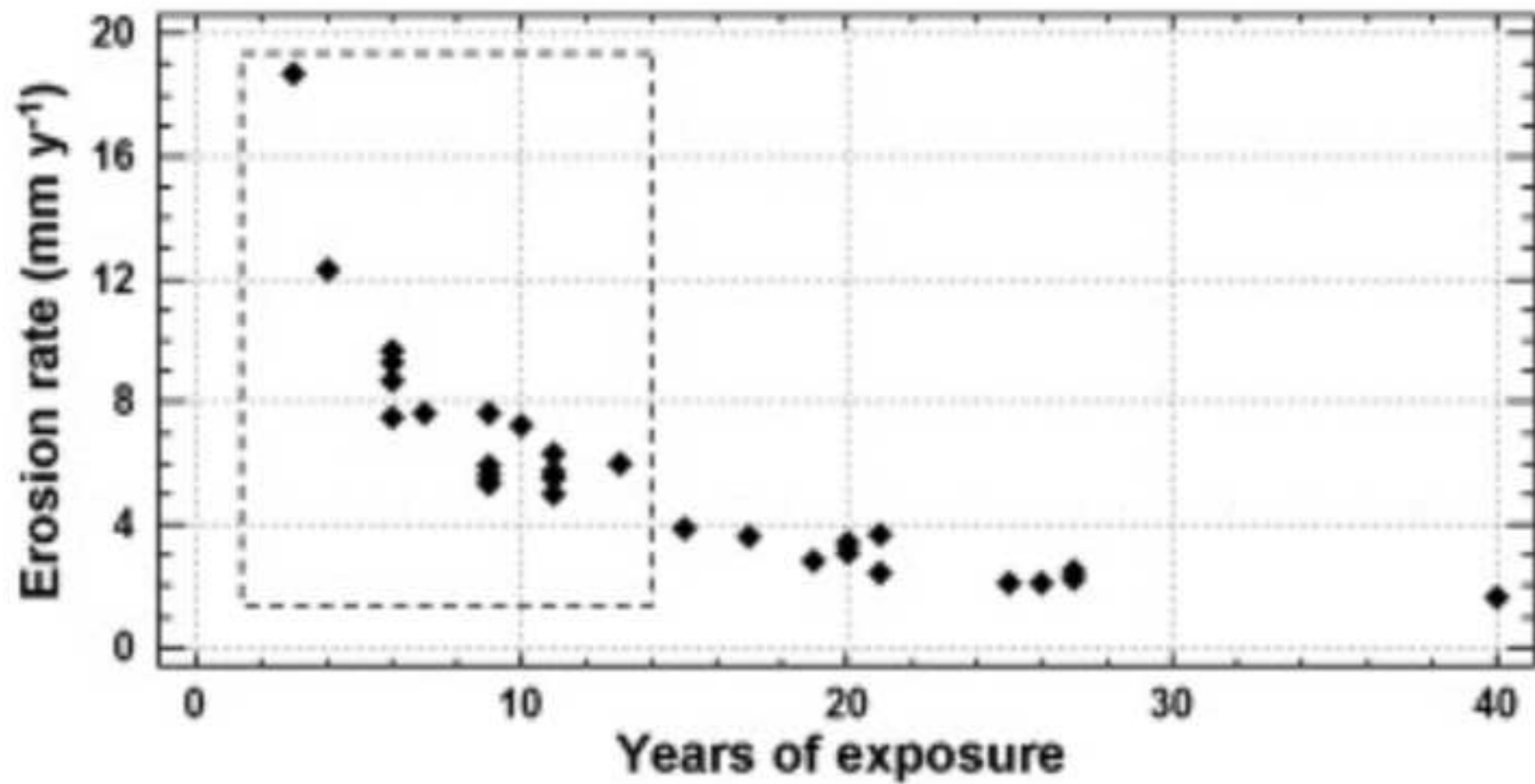692 10.1016/j.catena.2009.06.005 (2009).
693

Legend

- Tree vegetation
- Surficial deposits
- Caprock
- Divides
- Exposed sand with moderate slopes
- Exposed sand with steep slopes
- Flow lines

Exposed part (height) of the root

E_{x2} Left side E_{x1} E_{x1} Right side E_{x2}

TD TD

A — buried root (200 microns) — ring 1, r 2, r 3, EW, LW

B — exposed root (600 microns) — ring, EW, LW

C — buried root (300 microns) — ring 1, ring 2, EW, LW

D — exposed root (500 microns) — ring, EW, LW

Materials Table

⬇

Name of Material/ Equipment	Company	Catalog Number
Topographic map, soil map, land cover map		
Single ring infiltometer	Turf-Tec International	IN16-W
Handsaw		
Measuring tape		
Terrestrial Laser Scanning (TLS)	Leica-Geosystems	Leica ScanStation P16
Microtopographic Profile Gauge	RS Online	Facom, 19
Sandpaper		
Scanner	EPSON	Perfection V800 Photo
Image analysis system	Regent Instruments Inc.	WinDENDRO
Measuring table	IML	
Sliding microtome	Thermo Fisher SCIENTIFIC	Microm HM 450-387760
Optical microscope	OLYMPUS	MX63/MX63L
Digital camera for microscope	OLYMPUS	DP74
Safranin		
Astrablue		
Alcohol		
Distilled water		
Citrus oil clearing agent		
Coated slides	Thermo Fisher SCIENTIFIC	
Hardening epoxy	MERCK	

Comments/Description
To be obtained from public institutions or generate at the first phase of research
http://www.turf-tec.com/IN16Lit.html
There is noy any specific characteristics to be considered regarding the model
With accuracy of 1 mm
https://leica-geosystems.com/products/laser-scanners/scanners/leica-scanstation-p16
https://www.classic-conservation.com/es/herramientas-para-talla-y-escultura-en-madera/511-galga-medidora-de-perfiles.html
from 80 to 400 grit
https://www.epson.co.uk/products/scanners/consumer-scanners/perfection-v800-photo
http://www.regentinstruments.com/assets/windendro_analysisprocess.html
https://www.iml-service.com/product/iml-measuringtable/
http://www.thermofisher.com/order/catalog/product/910020
https://www.olympus-ims.com/en/microscope/mx63l/
https://www.olympus-ims.com/en/microscope/dc/
Empirical Formula (Hill Notation) C20H19ClN4
Empirical Formula $C_{47}H_{52}CuN_{14}O_6S_3$
Alcohol by volume (50%, 75% and 100%)
H_2O
https://www.nationaldiagnostics.com/histology/product/histo-clear
https://www.fishersci.com/us/en/products/I9C8JXMT/coated-glass-microscope-slides.html
https://www.sigmaaldrich.com/catalog/product/sial/03989?lang=es&region=ES

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Author(s): *Bodoque, Jose Mª; Ballesteros-Cánovas, Juan.A., Rubiales Juan M., Stoffel Markus*

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Dear Editor,

I am submitting a revised copy of our manuscript "Laboratory and field protocol for estimating sheet erosion rates from dendrogeomorphology" (REF.: JoVE57987) by Bodoque et al. We are most grateful to you for the helpful comments to our manuscript. To facilitate the new review, we have modified the document highlighting the changes carried out in blue. Regarding requests carried for you, we have:

- ✓ Reviewed the following lines to avoid previously published text: 54-55, 316-317, 352-355, 439-442, 452-455, 457-461, 488-493, 521-523.

We thank you for the opportunity to resubmit our manuscript to JoVE and hope that it is now suitable for publication. We look forward to hearing from you at your earliest convenience.

At Toledo (Spain), on May 31, 2018

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Author of new article	Jose Maria Bodoque, Juan Antonio Ballesteros, Juan Manuel Rubiales, Markus Stoffel
Expected publication date	Sep 2018

Estimated size of new article (number of pages)	12
Requestor Location	University of Castilla-La Mancha Avda/ Carlos III s/n
	Toledo, Toledo 45071 Spain Attn: Mr
Publisher Tax ID	GB 494 6272 12
Customer VAT ID	ESQ1368009E
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(pages)

Requestor Location	University of Castilla-La Mancha Avda/ Carlos III s/n Toledo, Toledo 45071 Spain Attn: Mr
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Expected publication date	Sep 2018
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