Supporting Methods

Protocol for processing fossil leaves

Fossil leaves with perfectly-preserved margins can be processed with the methods developed for extant leaves (see Materials and Methods and Royer et al., 2005) (Fig. SM1). But because fossil leaves are almost always fragmentary and are embedded in rock matrix that can be a similar hue to fossils, additional steps for digitally processing fossil specimens are usually required.

The first step is to digitally extract the leaf from the rock matrix. The leaf outline is traced using the extraction tool in Adobe Photoshop (Adobe Systems, San Jose, California, USA) and copied into a new layer. Similar to processing extant leaves, any minor portion of the leaf margin that is damaged is restored by reconstructing those segments as straight lines (Fig. SM2). Severely-damaged or incomplete leaves are not reconstructed. The petiole, if present, is separated from the rest of the leaf by cutting a line perpendicular to the midvein from the basal-most intersection between the petiole and leaf lamina (Fig. SM1). Inferred leaf area, inferred major axis length, and inferred Feret's diameter are calculated for the subset of leaves whose margins can be reconstructed with confidence (see Table S4 for definitions of variables). If only half of the leaf can be reliably reconstructed and the leaf is symmetrical, leaf area is calculated by doubling the area of the intact half (Figs. SM3, SM4). Leaf perimeter is not calculated for any fossil leaf because the uncertainties in the measurement are deemed too large (especially for toothed leaves).

Additional protocols for toothed leaves

For fragmentary toothed leaves, the damaged part of the leaf needs to be removed from the rest of the blade. This includes any damaged areas that were reconstructed in the earlier step. The minimum preservation necessary for processing a leaf is two contiguous teeth. First, the leaf is copied into a new layer. Each damaged segment of the margin is removed by drawing two lines, each perpendicular to the nearest primary vein (usually the midvein), from the primary vein to the two points along the margin that bound the damaged area (Fig. SM5c). A line (or multiple lines, if the vein is curved) is then traced along the vein to connect these two lines (Fig. SM5c). These straight lines are referred to as the "cut perimeter" (Fig. SM5c, Table S4). A single

fossil leaf may contain multiple polygons (Fig. SM4c, d). If a damaged section contains the leaf base or apex, only one perpendicular line is needed. We consider these polygons to be a simple, reproducible approximation of the leaf blade that is physiologically linked to the damaged margin, and they allow the calculation of variables such as tooth area: blade area and number of teeth: blade area. Importantly, the mean annual temperature and precipitation models that we present do not include these two variables. Thus, if the user's purpose for processing leaves is to apply our climate models, this step (which is often time consuming) can be skipped.

Next, primary and secondary teeth are selected and detached from the leaf blade following the rules of Royer et al. (2005). These teeth and corresponding blade area are copied into a new layer (Fig. SM5d). The complete processing of most toothed specimens results in three layers: 1) the reconstructed leaf extracted from the matrix (Fig. SM5b); 2) the leaf blade with attached teeth and the damaged polygons removed (Fig. SM5c); and 3) the leaf blade with detached teeth and the damaged polygons removed (Fig. SM5d). Both layers 2 and 3 preserve the cut perimeter.

As discussed earlier, inferred blade area, inferred major axis length, and inferred Feret's diameter are measured from layer 1 (Fig. SM5b). Raw blade area and raw perimeter are determined from layer 2 (Fig. SM5c), and raw internal blade area and raw internal perimeter are determined from the non-tooth areas in layer 3 (Fig. SM5d). Tooth area of the intact teeth ("tooth area (total preserved)") is calculated by subtracting raw internal blade area from raw blade area. To calculate the perimeter of the intact sections of the leaf margin ("perimeter (total preserved)"), cut perimeter is subtracted from raw perimeter (in layer 2). The corresponding internal perimeter ("internal perimeter (total preserved)") is calculated by subtracting cut perimeter from raw internal perimeter (in layer 3). From these measurements, perimeter ratio, number of teeth: (internal) perimeter, and tooth area: (internal) perimeter can be calculated.

References

Royer DL, Wilf P, Janesko DA, Kowalski EA, Dilcher DL. 2005. Correlations of climate and plant ecology to leaf size and shape: potential proxies for the fossil record. *American Journal of Botany* **92**: 1141-1151.

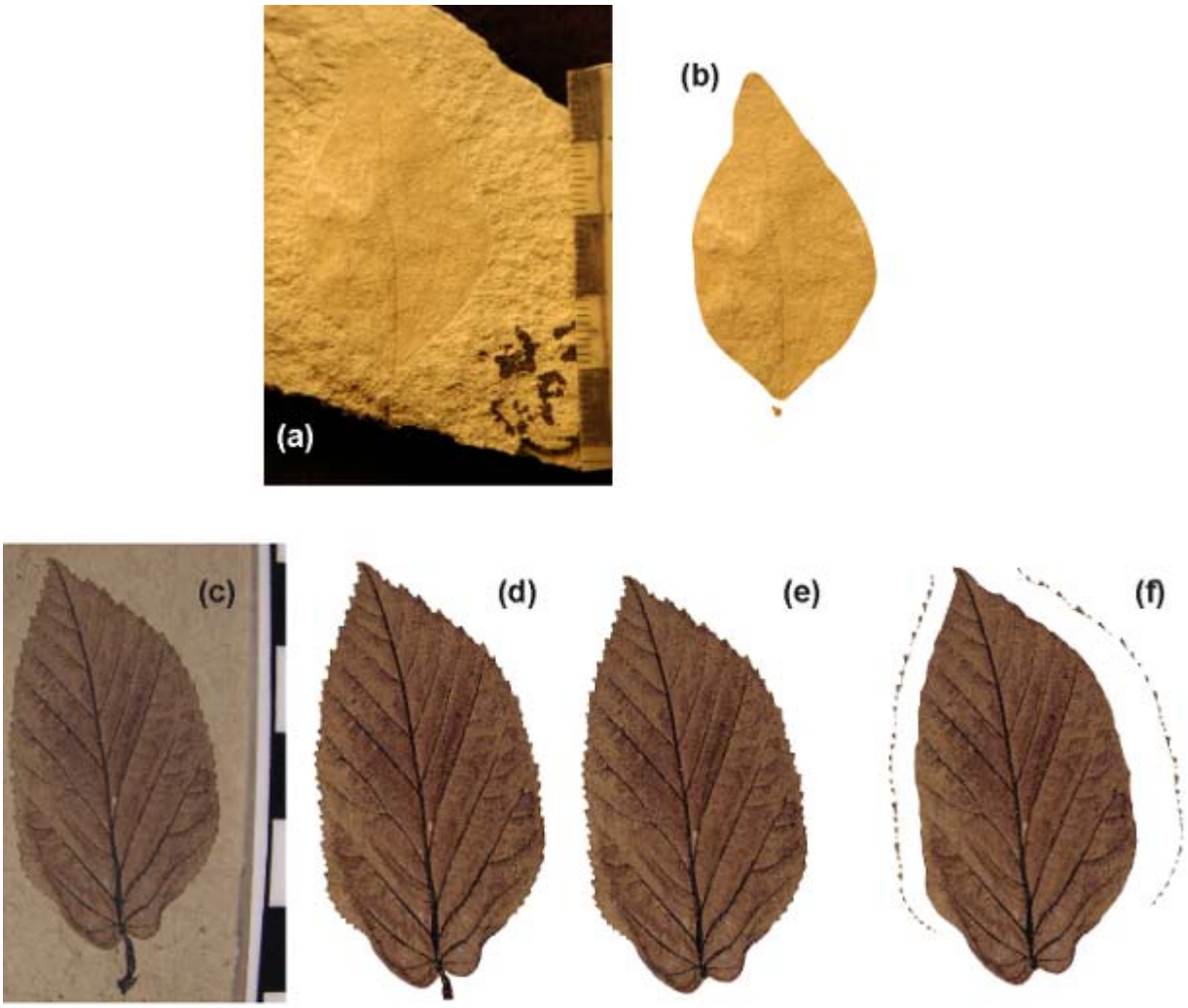

Fig. SM1 Representative complete fossil leaves that can be processed following the extant leaf methodology (see materials and methods in Royer *et al*., 2005), with cm ruler for scale. (a - b) Untoothed leaf (*Zizyphoides flabella*, YPM80119a, WBII). (a) Unprocessed specimen. (b) Leaf extracted from matrix with petiole removed. (c - f) Toothed leaf (*Betula leopoldae*, rp22 25068 19, Republic). (c) Unprocessed specimen. (d) Unprocessed leaf extracted from matrix. (e) Leaf with petiole removed. (f) Leaf with teeth separated from leaf blade.

Fig. SM2 Representative untoothed fossil specimen (*Caesalpina pecorae*, DMNH9896, Bonanza), with mm ruler for scale. (a) Unprocessed specimen. (b) Processed specimen with leaf extracted from matrix and damage to margin reconstructed with straight lines connecting the edges of the damaged portion of the lamina.

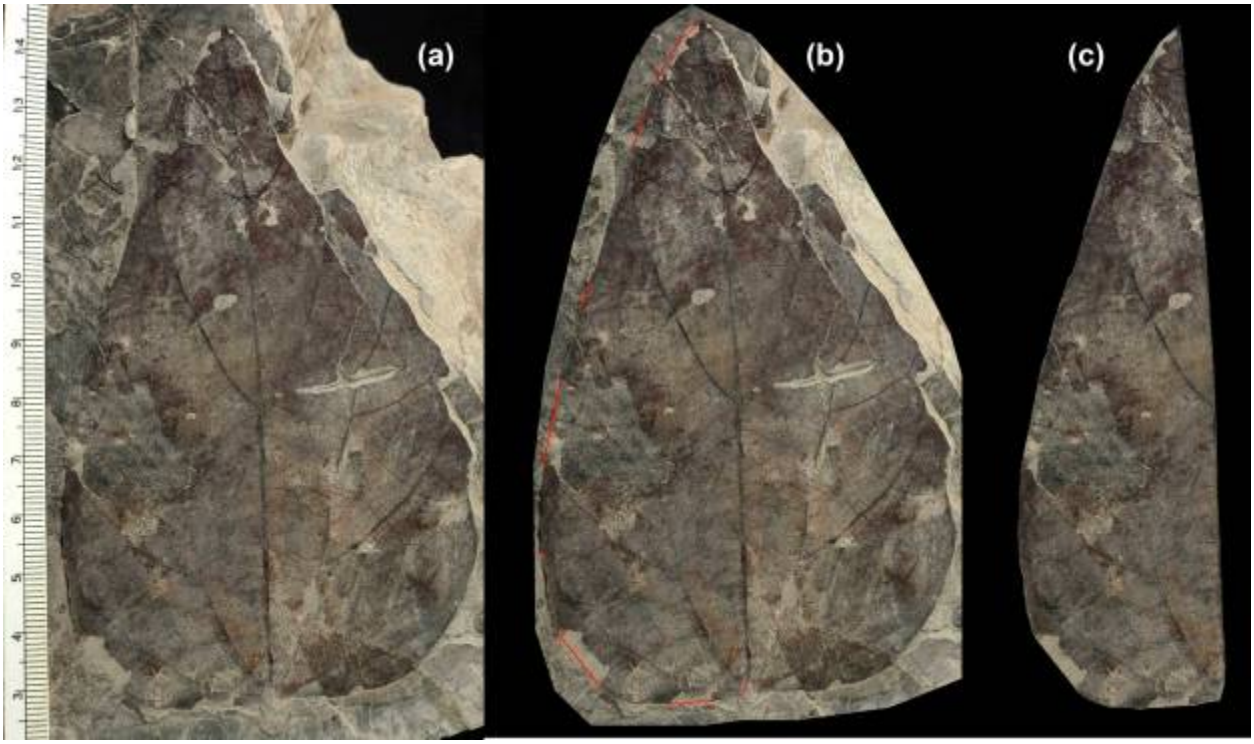

Fig. SM3 Representative fragmentary untoothed fossil specimen that is symmetrical and has one half well-preserved (*Menispermites cerrejonensis*, ING-0907, Cerrejón Flora), with cm ruler for scale. (a) Unprocessed fragmentary leaf. (b) Reconstructed leaf. Red lines indicate locations where margin was reconstructed. (c) Reconstructed half of leaf extracted from rock matrix. The blade area of this leaf half is doubled to calculate leaf area.

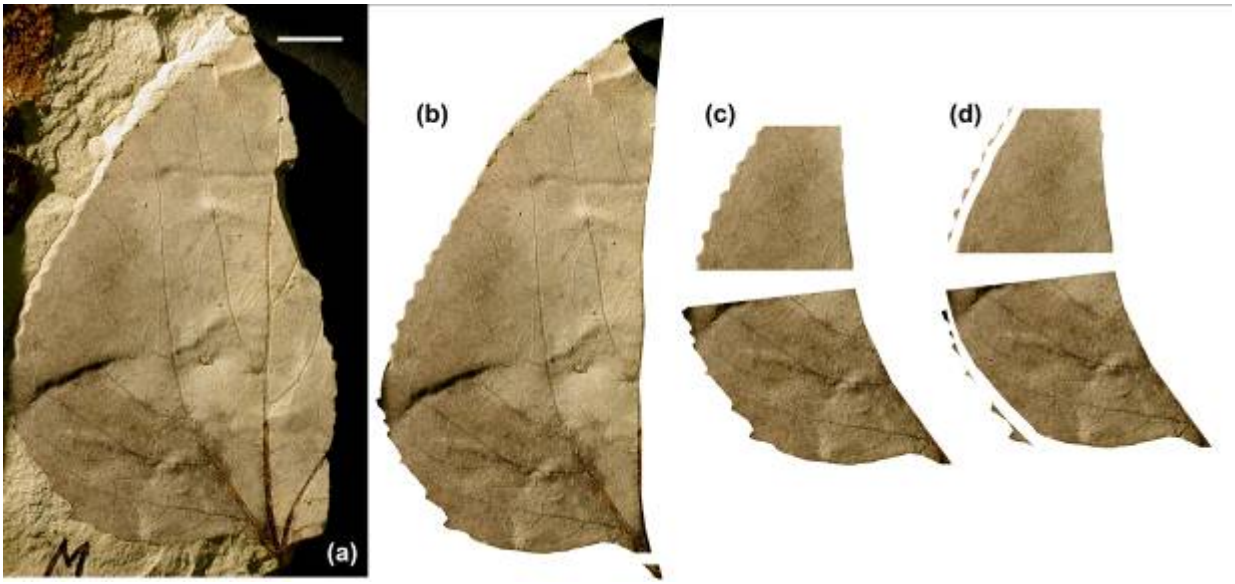

Fig. SM4 Representative fragmentary toothed fossil specimen that is symmetrical and has one half well-preserved ("*Vitis*" *stantonii*, ND03-1.41, Fox Hills). Scale bar is 1 cm. (a) Unprocessed leaf in matrix. (b) Reconstructed leaf extracted from matrix with petiole removed. Inferred leaf area, inferred major axis length, and inferred Feret's diameter are calculated from this layer. (c) Leaf reconstructed portions removed and with cut perimeters. This leaf has two measurable polygons. (d) Leaf with teeth separated from the leaf blade.

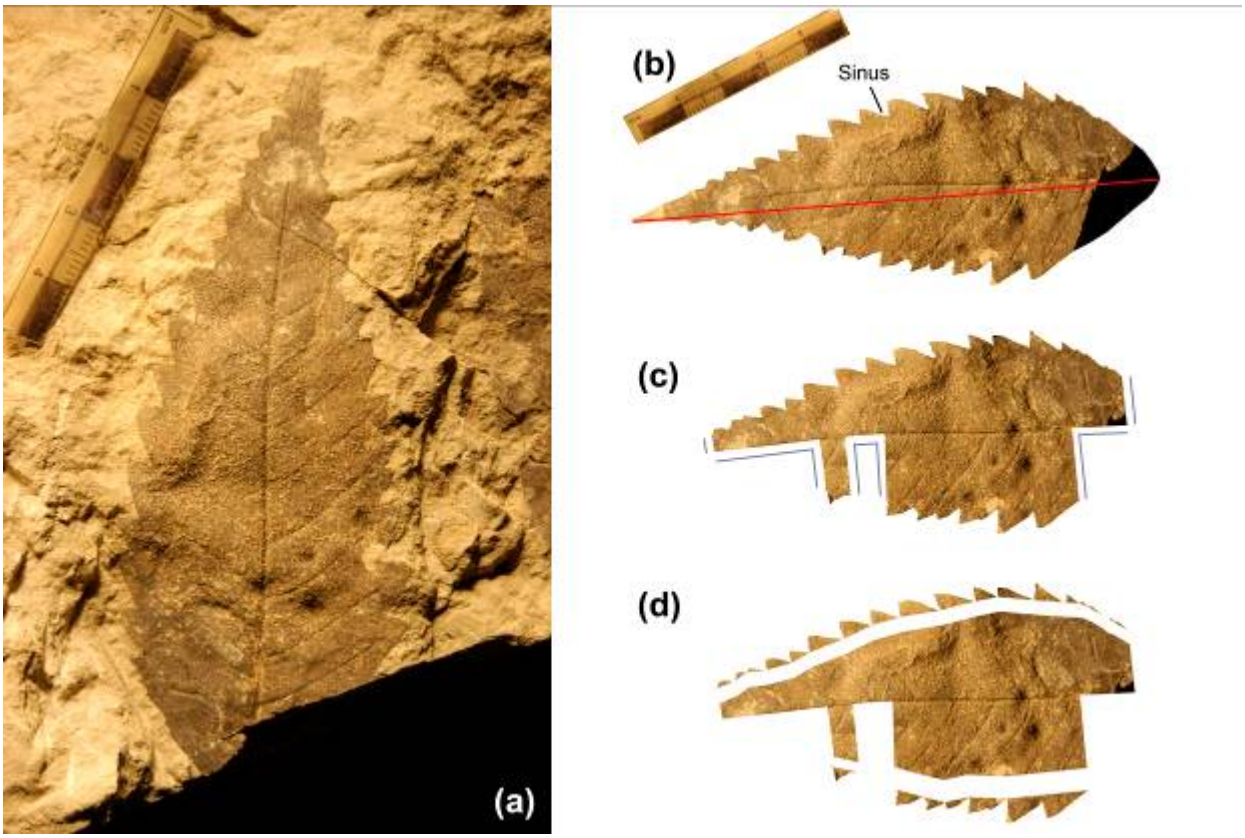

Fig. SM4 Representative toothed specimen from the Fort Union Formation (*Fagopsiphyllum groenlandicum*, YPM78649, WBII), with mm ruler for scale. (a) Unprocessed leaf in matrix. (b) Reconstructed leaf extracted from matrix (layer 1 in discussion). Red line indicates the major axis length. (c) Leaf with damaged portions of leaf margin removed (layer 2 in discussion). The sum of the gray lines is the "cut perimeter". (d) Leaf from panel (c) with teeth separated from the leaf blade (layer 3 in discussion).