

Generating User-friendly Identification Tools  
From High Resolution Images of Herbarium  
Specimens of *Sapotaceae* From the Sangha  
Trinational



David A. Purvis

August 2012

Thesis submitted in partial fulfilment of the requirements for the degree of MSc in the  
Biodiversity and Taxonomy of Plants.



Royal  
Botanic Garden  
Edinburgh



THE UNIVERSITY of EDINBURGH

## **Acknowledgements**

With great thanks to my supervisors David Harris, Elspeth Haston and Hannah Atkins, for all their help, knowledge and enthusiasm throughout my project. To all RBGE staff who offered their guidance and advice through my project and my years at RBGE, especially Phil Lusby and the legend, Greg Kenicer.

To all my identification tool testers David, Hannah, Peter Wilkie, Richard Whittet, Jane Droop and Linda Neaves and anyone who gave their opinions or help through the building of all the tools, especially Clíodhna Ní Bhroin and Carl Berthold.

An enormous thanks to all of my fellow MSc students for their friendship and support throughout the whole year.

Finally a special thanks to my parents, Jeanette and Gordon, without whom my MSc and whole higher education would not have been possible, and for their support and guidance through everything, thank you.

### **Abstract**

Past and current developments in the creation of plant identification tools are reviewed, and a study made of the potential use of computer technologies, including high resolution digital images. This project was based on a study of members of the family Sapotaceae from the Sangha Trinational region of West-central Africa, using herbarium specimens held in the collections of the Royal Botanic Garden Edinburgh. Written descriptions for all 23 taxa studied, and a character matrix and dichotomous keys for the identification of genera and species are provided. Digital photographs of all studied specimens are used to assemble a character glossary and to illustrate the taxa studied.

These building blocks are used to create a range of identification tools based on both dichotomous and multi-access key methods. The latter is implemented using Lucid software. Additionally, the Scratchpads online taxonomy tool is used to create an integrated, interactive website containing all assembled information for the studied specimens. The practical use of the assembled tools is evaluated by testers, commissioned to provide feedback on their relative usefulness and effectiveness. This process was used to amend and improve the tools created. A discussion of the lessons learned and recommendations for the building of user-friendly taxonomic tools is provided.

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## 1. Introduction

### 1.1 Development of Tools in Taxonomy

Many methods for plant identification have been created over the centuries. Perhaps the simplest approach, is visual comparison of an unknown specimen with a known one, or with a written description of a known species. In 1778, Lamark was one of the first to recognise the use of contrasting statements describing plant characteristics as a basic means to teach botanical science, and was the first to formalise rules for the construction of dichotomous keys (cited in Voss, 1952).

In Britain, one of the earliest taxonomic tools created for plant identification was the *The Student's Flora of the British Isles* written by Sir Joseph Dalton Hooker in 1884. This author was one of the most influential botanists of the late nineteenth century. His taxonomic work for students was the first standardised and widely available plant identification tool, which followed an earlier landmark work in three volumes, the *Genera Plantarum*, published in collaboration with George Bentham in 1876. The *Genera Plantarum* had presented a formalised system for describing plants, which grouped species by their shared morphological characteristics. At the time, and for many decades afterwards, the works of Hooker were thought to be the most practical and accurate means of plant identification. Today, however, the classification system adopted in the *Genera Plantarum* is regarded as having little relevance to the past evolutionary history of plants, or our greatly expanded and improved understanding of their phylogeny. The modern-day equivalent of Hooker's *Student's Flora*, is probably the *New Flora of the British Isles* (Stace, 2010).

Both Hooker (1884) and Stace (2010), and nearly all taxonomic works published in the intervening period, use the dichotomous key as the preferred method of plant identification. Historically, such keys draw on natural morphological characters. All characters can be used, but in botanical identification, floral and vegetative characters predominate. Other features relating to structures such as roots, bark and fruit may be included, but their utility may be limited as they are not always present in available material, or herbarium collections. The most important characters to be included are those of vegetative states, as these are almost always available. Unfortunately, floral

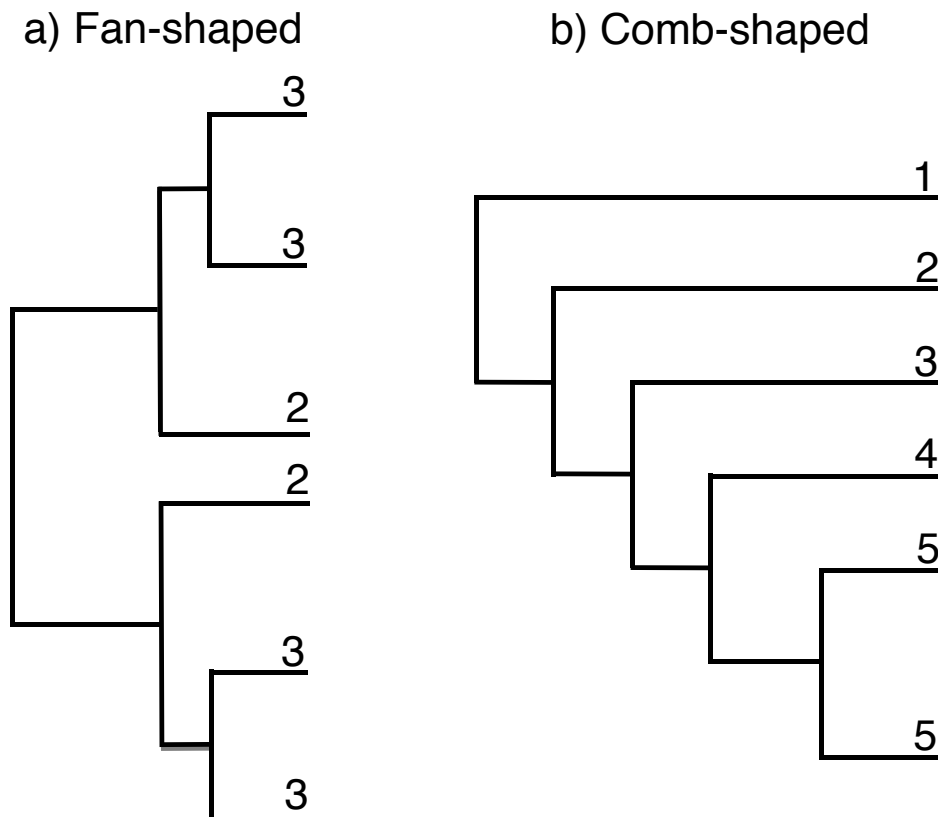
characteristics predominate in angiosperm classifications, but flowers are not always available at the time of specimen collection, and hence in herbarium material. Other information that can usefully be included in the creation of a key, include details of geographical distribution and ecological preferences, which can be helpful in excluding unlikely possibilities.

Recent rapid progress in the understanding of molecular biology has revolutionised our approach to the taxonomy of virtually all groups, and seen the development of the concept of DNA barcoding. This has been viewed as the new taxonomic frontier (Hebert *et al.*, 2003). Some have suggested that the bar coding approach might resolve the ‘*taxonomic impediment*’ (Hoagland, 2000) evident in the loss of traditional expertise in descriptive *alpha* taxonomy, and facilitate the widespread documentation of the biological diversity of life (Janzen *et al.*, 2005). However, it has since become apparent that DNA sequencing can enhance, but not replace traditional taxonomy (Rubinoff & Holland, 2005). Irrespective of the technologies developed for distinguishing taxa, there will always be a need for the creation of effective and practical identification tools for use in the real world of ecological studies and conservation (Gotelli, 2004).

### *1.1.1 Strengths and Weaknesses of Dichotomous Keys*

Dichotomous keys present the user with a sequence of contrasting statements, and by following the appropriate branch of each key couplet, a pathway to the correct identification is created. These step-wise choices are both the main strength and the main weakness of the dichotomous key. A strength, because if well constructed, a series of logical choices will provide the most efficient path to a definitive answer; but a major weakness if an incorrect choice is made (the ‘*weakest link*’ issue), or if a specimen is damaged and a critical character cannot be seen (the ‘*dead end*’ issue). Mistakes can be made by the key’s author, for example, by the choice of a variable, or unreliable character state at a particular step; or by the key’s user if a character description is misinterpreted. The greater the number of taxa to be discriminated in a dichotomous key, the greater the risk that any of the above circumstances will cause a key to fail. In constructing dichotomous keys, it is preferable to create a ‘*fan-shaped*’ key (**Fig. 1.1a**) that splits taxa into groups of similar size, rather than a ‘*comb-shaped*’ key that splits off individual taxa one at a time - a process sometimes referred to as

‘chipping’ (Fig. 1.1b). This is because the fan-shaped structure reduces the total number of necessary steps in the identification process.



**Fig. 1.1:** Diagrammatic illustration of: a) ‘fan-shaped’, and b) ‘comb-shaped’ dichotomous key structures (after Walter & Winterton, 2007); note the shorter pathway (number of couplets) that need to be negotiated to the final solution in the former.

### 1.1.2 Multi-Access Keys

A possible solution to the ‘weakest link’ and ‘dead end’ issues of dichotomous keys, is the use of multi-access keys (Walter & Winterton, 2007). These utilise all character states studied on a specimen. Early development of such keys, involved creation of a full character state matrix for all possible taxa. The resulting tabulated character matrix could then be used in a relatively laborious process requiring the user to match all the character states possessed by the specimen. Clearly, a dichotomous key is a much more time efficient identification tool for the user, in that it creates an optimum single path through a limited number of character state choices that need to be negotiated to reach the solution. However, computers are ideally suited to the task of making multiple simultaneous character comparisons, and so in an era of much

greater computer accessibility, the development and use of multi-access keys has become much more prevalent.

## 1.2 Taxonomy in the Computer Era

With increasing interest in the protection and conservation of the world's biodiversity (UNEP, 1992), the critical role of taxonomists in documenting the natural world has become increasingly apparent (Blackmore, 2002; Godfray, 2002a). However, with this recognition has also come an appreciation that world-wide (alpha) taxonomic expertise is declining, and this presents a severe impediment to progress in biodiversity research (Hoagland, 2000; Wheeler *et al.*, 2004). Fortunately, the greatly expanding technical capacities of the computer age offer many new possibilities. These include the development of much more easily accessible taxonomic tools, and taxonomic recording and archiving systems that will greatly facilitate the aims of biodiversity protection (Bisby *et al.*, 2002; Gerwin, 2002; Godfray, 2002b; Thacker, 2003; Wheeler, 2003; Wilson, 2003; Godfray & Knapp, 2004).

### 1.2.1 Use of Computer-based Software for Key Development

A wide variety of computer software had now been developed to aid the creation of taxonomic keys using both the dichotomous and multi-access approach. Lucid Phoenix (Lucid Central, 2012a) is an example of the former. This type of software primarily provides a means to '*computerise*' older printed keys, and add extensive amounts of supporting media such as photographic images and other identification aids through hypertext links (Walter & Winterton, 2007). More recent versions of Lucid Phoenix, have become so sophisticated that they can check over the structure of developed keys for errors and their internal logic. Computers are also the perfect means to create highly sophisticated multi-access keys using software algorithms that can rapidly sift through inputted specimen details and match these against a full character matrix (Dallwitz, 1992; Dallwitz, *et al.*, 2012). Such software can be programmed to assist the user, and shorten the process of identification, by prompting the input of information about the character most likely to hasten the process of final identification. Lucid Professional is an example of this type of software (Lucid Central, 2012b). Such interactive, multi-access keys overcome many of the problems of traditional dichotomous keys, including the '*weakest link*' and '*dead end*' issues. Whether created using the dichotomous or multi-access approach, keys produced

using computer software can be made available to users either as stand-alone applications on CDROM, or accessed as web-based resources.

### *1.2.2 Integration of Taxonomic Resources on the World Wide Web*

Whilst, computer software has been rapidly developed to facilitate the creation and integration of more easily-used identification tools and supporting imagery, the real potential of computers in taxonomy lies in the creation of highly integrated web-based taxonomic resources. Such information systems, can include formal taxonomic descriptions, phylogenetic structures and links to keys created elsewhere on the World Wide Web. Scratchpads is an example of such potential (Scratchpads, 2012). There have been many attempts to standardise the use of taxonomic data in the creation of such systems, including the *Descriptive Language for Taxonomy* (DELTA) format first created in 1971 (Dallwitz, 1993; Dallwitz, 2012). However, many alternative systems have also been developed, which claim to have greater flexibility for the user, such as the Structure of Descriptive Data (SDD) initiative developed by the Taxonomic Databases Working Group (2004). Pankhurst (1991) gives an excellent introduction to the rapidly developing use of computer technologies in modern taxonomy.

### 1.3 Use of Images in Plant Taxonomy

Since the first creation of dichotomous and more recently multi-access keys, there have been many attempts to improve their ease of use, and to incorporate new ideas and technologies into their creation (Pankhurst, 1991). In the earliest development of dichotomous keys, it became conventional to aid the user by illustrating the characters used. In the pre-computer age, illustrations were hand-drawn and the ability to make detailed and accurate drawings for use in keys was an essential skill, therefore a specialist illustrator was employed. Excellent examples of this skill can be seen in many of the taxonomic works of the 19th and early 20th Centuries. For examples, see the publications of Smith *et al.*, 1790-1813 and Ross-Craig, 1979. The use of dichotomous keys based on visual imagery in addition to written couplets, is therefore not a new concept to taxonomy. One of the first records of the creation of such an identification tool, was Richard Waller's '*Watercolours of the Herbs of Britain*' published in 1689 (Griffing, 2011). More recent technologies, including digital

photography and a wide range of computer software for image enhancement and manipulation, are now an important potential tool in taxonomy. Such technologies potentially render drawing skills unnecessary, but have added a completely new dimension and complexity to the skill-sets required in taxonomic work. For a basic introduction to electronic image creation and incorporation into interactive computer-based keys and taxonomic resources, see Dallwitz (2010). For detailed recommendations regarding a range of different aspects of the use of digital imagery in the development of interactive taxonomic resources, see also; Taylor (2005) for specimen photography; Morris (2005) for digital colour management; Crick (2005) for image file management; and Berendsohn *et al.* (2005) for advice on the imaging of herbarium plant specimens.

#### 1.4 Aims and Outline of the Current Study

The aims of the current study were:

- i) To create the resources necessary for construction of user-friendly plant identification tools, including a character matrix for the studied taxa and supporting photographic imagery, from herbarium specimens.
- ii) To use the assembled resources to build a range of identification tools using both the dichotomous and mult-access approach to key development
- iii) To test and compare the practical use of the developed identification tools
- iv) To make recommendations for key development based on the lessons learned.

The chosen plant group for this work were species of the family Sapotaceae Juss. found in the Sangha Trinational region of Africa. This group was chosen because all the known Sapotaceae species from this region are held in the herbarium collection at the Royal Botanic Garden Edinburgh (RBGE) and high quality images of herbarium specimens are available.

### 1.5 The Sangha Trinational Region

The Sangha Trinational comprises a major conservation initiative created by coordinated agreement between three countries, namely, Cameroon, the Republic of Congo and the Central African Republic. The total area involved includes a major portion of all three of these relatively large West-central African countries (**Fig. 1.2**), and includes a core protected area comprising designated nature reserves within each country that bound the Sangha River. This combined nature protection area includes the Nouabalé-Ndoki National Park in the Congo, the Lobéké National Park in Cameroon, and the Dzanga-Sangha Reserve in the Central African Republic (Harris & Wortley, 2008). A total of 10 genera and 23 species of the family are recorded from within the Sangha Trinational region (Harris & Wortley, 2008). These species are listed in **Appendix 1**.



Fig. 1.2 Map of Sangha Trinational, including D.R. Congo, Cameroon and the Central African Republic (map by Anna Dorward).

## 2. Classification, Taxonomic History and Distribution of the Sapotaceae

### 2.1 The Family Sapotaceae

The Sapotaceae is listed by Pennington (1991), as a family of some 54 genera and about 1,200 species. Most species are trees or woody shrubs with one exception of a subscandent liana from West Africa, *Chrysophyllum welwitschii* Engl.. The family is widely distributed in tropical and subtropical areas such as the archipelagoes of the Caribbean and the Pacific with a high incidence of endemic species on Madagascar and New Caledonia (Govaerts *et al.*, 2001). The group mainly occurs in more humid mainland areas, or the fringes of islands, with very few taxa tolerant of temperate conditions. Sapotaceae are usually identified by the combined possession of: latex, alternate leaves that sometimes cluster at the twig apex, unicellular bifid (malpighian) hairs, axillary flowers usually held in fascicles (but occasionally in racemes with basally united parts), and usually indehiscent fruit with one or more large shiny seeds (Stevens, 2001). Floral characters vary in the numbers of parts and general structure, which has led to disputed generic definitions within the family (Govaerts *et al.*, 2001).

Sapotaceae have been long associated with the Ebenaceae Gurke, and in earlier classifications were placed within the same order, *Ebenales*. More recently, the Angiosperm Phylogeny Group III (Stevens, 2001) recognised the two groups as distinct families within the order *Ericales*, in which *Sapotaceae* form a small clade that also contains the *Maesaceae* (A.DC.) Anderb., B.Ståhl & Källersjö, *Theophrastaceae* Link., *Primulaceae* Vent. and *Myrsinaceae* R.Br.. This classification has 100% Bayesian support (Stevens, 2001). As a tropical group, members of the Sapotaceae have a wide variety of economically important uses and properties, including the production of timber, fruit and latex.

### 2.2 Taxonomic History

Antoine Laurent de Jussieu was the first botanist to fully recognise Sapotaceae in his *Genera Plantarum* published in 1789. Previous to this, Linnaeus had recognised four taxa now classified as Sapotaceae (modern-day *Mimusops* L., *Manilkara* Adans., *Chrysophyllum* L. and *Sideroxylon* L.), which he had placed in two pair-groups, *Octandria Monogynia*, and



*Pentandria Monogynia*, respectively. Jussieu compiled a list of genera that along with Linnaeus' work created for the first time a distinct homogeneous group. This included nine described genera: (modern-day classifications in parenthesis) *Sideroxylon*, *Bassia* All. (*Madhuca* J. F. Gmel.), *Mimusops*, *Imbricaria* Sm. (*Mimusops*), *Chrysophyllum*, *Lucuma* Molina (*Pouteria*), *Achras* L. (*Manilkara*), *Jacquinia* L. (*Theophrastaceae*) and *Manglilla* Juss. (*Myrsinaceae*). The last two genera were mistakenly included in Jussieu's list because of their very similar floral characteristics (Pennington, 1991). Jussieu's work included four out of five currently recognised subfamilies of the Sapotaceae and was accurate in correctly recognising nearly all of the important characters for the group, with the exception of their possession of malpighian hairs.

Several subsequent publications attempted to improve upon Jussieu's classification of the Sapotaceae. These included Alphonse de Candolle (1844) and Bentham and Hooker (1876). Both of these works recognised a total of six sub-family groups, but based their ideas on different interpretations of staminodial and corolla lobe characters. De Candolle's four main characters remain of primary importance in modern day generic classification. These were: a) the presence or absence of staminodes, b) number of corolla lobes relative to number of sepals, c) number of stamens relative to number of corolla lobes and d) the presence, or absence of corolla lobe appendages. Bentham & Hooker stressed the importance of floral characteristics, mainly in the form of the uniseriate or biseriate calyx, which would later become a very important character for recognition at supra-generic level (Pennington, 1991).

It wasn't until 1888 that the modern concept of Sapotaceae subfamilies was created, on the basis of the form of staminodial whorls (Radlkofer, 1888). After this important contribution, several further attempts were made to reclassify Radlkofer's subfamilies, based on the form of two other important floral characters, the staminodes and corolla lobes, or a combination of the two. Probably the most important reclassification since that of de Candolle in 1844, was that of Aubréville (1964) who worked for some 30 years on both herbarium and field specimens, mainly in Africa and Asia. Aubréville combined the characters used in previous classifications to create the most up-to-date and generally agreed arrangement of subfamilies and tribes based on purely morphological features (Pennington, 1991). This final classification included 4 sub-families, 15 tribes and 124 genera. Some of the distinguishing features were based on only a single morphological character, or the geographic location of the taxon concerned. This can make Aubréville's classification difficult to use at times.

Today, using both classical morphological and molecular characters, the Sapotaceae are classified into just three subfamilies with rather fewer species than cited by Pennington, 1991. The *Sarcospermatoideae* Swenson & Anderb. includes a single genus and 6 species, which naturally only occur in Asia; the *Sapotoideae* Eaton contains 27 recognised genera and about 540 species and is widely distributed across tropical and subtropical areas; and the *Chrysophylloideae* Luersson contains 25 recognised genera and about 550 species, which are pantropical (Stevens, 2001).

### 2.3 African Sapotaceae

In Africa, the Sapotaceae flora has several endemic genera *Autranella* A. Chev., *Baillonella* Pierre, *Breviea* Aubrév. & Pellegr., *Delpydora* Pierre and *Gluema* Aubrév. & Pellegr, and a somewhat unusual, near temperate genus *Argania* Roem. & Schult. (Govaerts *et al.*, 2001). The centre of Sapotaceae diversity within the African continent appears to be in West-central Africa. However, detailed information on the geographic distribution of taxa is lacking, and no overall treatment of the African flora has been published since the monograph of Engler (1904).

## 2.4 Sapotaceae in Sangha Trinational

The following genus and species descriptions are based on observation of purely the vegetative character states of herbarium specimens largely held in the collections of RBGE, supplemented by information, particularly on growth habit and floral characters, gleaned from published sources (Aubréville, 1963; Bentham & Hooker, 1876; Govaerts *et al.*, 2001; Harris & Wortley, 2008; Hemsley, 1968; Hutchinson & Dalziel, 1931; Oliver, 1877; Pennington, 1991).

### 2.4.1. *Autranella* A. Chev.

*Autranella* is monospecific and *A. congolensis* occurs naturally in West and West-central Africa. The genus is closely allied to *Mimusops*, but differs in that its corolla tube is 2-3 times the length of the lobes. *A. congolensis* is a large forest tree with terminally clustered leaves, fruit with 1-3 large seeds and ultimately with a massive girth up to 45m (Govaerts *et al.*, 2001).

#### *Autranella congolensis* (De Wild.) A.Chev.

Tree to 20m tall. Stipules present and caducose. Leaves alternate, simple; elliptic-obovate; apex rounded-obtuse, rarely acute; acumen very small sub-triangular; base acute. Secondary venation closely spaced (<10mm), parallel forming continuous sub-marginal loops with reticulate tertiary venation. Lower lamina glabrous; scattered short hairs on midrib; petiole glabrous. Calyx to 2.5mm long, tomentose. Fruit ovoid 5 x 7cm. Single seed 4.5 x 3cm wide, 2-2.3cm thick.

### 2.4.2. *Brevia* Aubrév. & Pellegr.

A genus with only one species, *B. sericea*, found naturally in West and West-central Africa. This large semi-deciduous forest tree is found throughout a very large range and prefers seasonally humid areas (Govaerts *et al.*, 2001). *B. sericea* is unique amongst the Sapotaceae found in the Sanga Trinational, in that it is the only species with characteristically elongated and near parallel-sided leaves with cordate base, sericeous abaxial (lower) leaf surface and very prominent secondary venation.

*Breviea sericea* Aubrév. & Pellegr.

Tree to 45m tall; slash cream with milky juice. Stipules present. Leaves alternate, simple, elongate with sub-parallel sides; apex obtuse; acumen elongate sub-triangular (length 2-3 times basal width); base cordate-rounded. Secondary venation closely spaced (<10mm) parallel, forming continuous sub-marginal loops; tertiary venation reticulate, obscured below. Lower lamina with silvery hairs; midrib and petiole with felt-like pubescence. Inflorescences in fascicles at leaf axils. Calyx to 3.5mm long. Corolla tube to 3mm long, lobes to 2mm long. Stamens up to 3mm long, subulate staminodes rarely present. Ovary 5-locular, pilose. Fruit depressed globose, glabrescent.

2.4.3. *Chrysophyllum* L.

*Chrysophyllum* is one of the larger genera distributed across the world with 81 accepted species (Govaerts, *et al.*, 2001). This genus is represented across all of the tropics, mostly in tropical America and Madagascar, but also in the Asia-Pacific region. Nearly all are trees, a few such as *C. welwithschii* are climbing shrubs. Six species are known to occur in the Sangha Trinational area. The species of *Chrysophyllum* vary in many vegetative characters, but within the Sanga region can be grouped by a unique combination of characteristics, including possession of a distinct acumen, and the *combined lack of stipules, random reticulate tertiary leaf venation and decurrent leaf-base*.

A nomenclatural problem came to light during this project concerning the naming of *Chrysophyllum ubangiense*. This species was first recognised as a *Chrysophyllum* species by Govaert in 1999, and named *C. ubangiense* (*World Checkl. Seed Pl.* 3(1): 15. 1999). Subsequently, the same author miss-spelt the name as *C. ubanguiense*, an error perpetuated in other publications such as Tropicos and IPNI. This has caused considerable confusion, which was successfully corrected only after the current writer (DAP) tracked down the original protologue for the basionym *Mimusops ubangiensis*, which had been first described by De Wildeman (Mission Emile Laurent 1903-1904). This made it clear that De Wildeman had originally named the species after a river in the region in which it was found. The name of this river has two alternative spellings, *Oubangui* and *Ubangi*. Since De Wildeman originally spelled the specific name with a u, and not an o, the correct spelling for the specific epithet of this species now included in the genus *Chrysophyllum*, should therefore be *ubangiense*.

*Chrysophyllum beguei* Aubrév. & Pellegr.

Tree to 30m tall; slash pale yellow with white streaks. Stipules absent. Leaves alternate, simple, elliptic; apex acute; acumen elongate parallel-sided, blunt emarginated tip; base asymmetric. Secondary venation widely spaced (>10mm) parallel, forming continuous sub-marginal loops; tertiary venation scalariform, but can occasionally loop backwards from midrib to previous secondary. Lower lamina with sparse long red hairs; midrib and petiole with long hairy pubescence. Inflorescences clustered at leaf axils or at old nodes. Calyx to 2.5mm long, pubescent. Corolla tube to 1mm long, lobes to 0.5mm long. Stamens short, anthers mucronulate, no staminodes. Ovary 5-locular, hirsute. Fruit subglobose, 2-3cm long and 3-4cm in diameter, glabrous.

*Chrysophyllum boukokoense* (Aubrév. & Pellegr.) L.Gaut.

Tree to 20m tall. Stipules absent. Leaves alternate, simple, elliptic-oblongate; apex obtuse-acute; acumen elongate sub-triangular (length 2-3 times base width); base acute. Secondary venation widely spaced (>10mm) parallel, forming continuous sub-marginal loops; tertiary venation scalariform. Lower lamina with dense white felt-like pubescence; midrib with short hairs. Inflorescence without staminodes. Fruit 2cm in diameter.

*Chrysophyllum lacourtianum* De Wild.

Tree to 20-35m tall; slash dark red with white latex. Stipules absent. Leaves alternate, simple, obovate; apex obtuse; acumen small to large sub-triangular; base cuneate. Secondary venation widely spaced (>10mm) parallel, forming continuous sub-marginal loops; tertiary venation scalariform. Lower leaf surfaces glabrous. Inflorescences on branches. Calyx 3.5-4mm long, pubescent. Corolla tube to 3.5mm long, lobes 1mm. Stamens shorter than corolla lobes, no staminodes. Ovary 5-locular. Fruit ovoid, 7cm in diameter and 10 cm long, borne on branches high in the crown.

*Chrysophyllum perpulchrum* Mildbr. ex Hutch. & Dalziel

Tree to 40m tall, slash with white latex. Stipules absent. Leaves alternate, simple, elliptic; apex obtuse-acute, sometimes rounded; acumen very small sub-triangular; base acute sometimes rounded. Secondary venation widely spaced (>10mm), parallel, forming continuous sub-marginal vein; tertiary venation tightly scalariform. Lower lamina with dense curly red hairs; midrib and petiole with felt-like pubescence. Inflorescences sessile at leaf axis or old nodes. Calyx to 4mm long, pubescent. Corolla tube ~2.5mm long, lobes 3-4mm

long. Stamens 2-3mm long, filaments flattened, no staminodes. Ovary 5-locular, densely pilose. Fruit sessile, globose, 3-4cm in diameter, rusty tomentose.

*Chrysophyllum pruniforme* Pierre ex Engl.

Tree to 30m tall; slash cream. Stipules absent. Leaves alternate, simple, asymmetrically-ovate; apex acute; acumen very elongated sub-triangular (length usually >4x basal width, occasionally only 2-3x); base asymmetric. Secondary venation closely spaced (<10mm) parallel, forming a continuous sub-marginal vein; tertiary venation parallel, indistinguishable from secondary. Lower leaf surfaces with sparse long red hairs, becoming glabrous. Inflorescences very small, greenish, clustered in leaf axils. Calyx up to 2mm long, pubescent. Corolla tube up to 1mm long, lobes to 1.5mm long. Stamens up to 2mm long, filaments flattened, no staminodes. Ovary 5-locular, tapers into a short thick style. Fruit depressed, globose, yellows when ripe.

*Chrysophyllum ubangiense* (De Wild.) Govaerts

Tree to 25m tall; slash with white latex. Stipules absent. Leaves alternate, simple, obovate; apex blunt with elongate parallel-sided; acumen parallel-sided, blunt with emarginated tip; base asymmetric. Secondary venation closely spaced (<10mm) parallel, forming a straight and continuous sub-marginal vein; tertiary venation parallel, indistinguishable from secondary. Lower lamina with sparse long red hairs, becoming glabrous; midrib and petioles glabrous. Inflorescences small, clustered in current leaf axils. Calyx to 2mm long. Corolla tube to 1mm long, lobes to 1mm long. Stamens to 2.5mm long, filaments flattened, staminodes absent. Ovary 5-locular. Fruit sub-globose, up to 11cm long and 8.5cm in diameter.

2.4.4. *Englerophytum* K. Krause

*Englerophytum* comprises a genus of eight species found in tropical and Southern Africa. Gabon and neighboring countries of Central Africa comprise the main centre of diversification. Growth habit various, but most specimens are medium-sized forest trees. The fruits of some species are edible and are used to make jellies and wine. Most species are considered to be attractive decorative plants, and their timber is quite often used in light construction. Their separate generic status is not completely clear, and they are often considered to be closely allied to *Synsepalum*; but differ primarily in foliage insertion, venation and the presence of fused filaments. No revision of the group has been carried out

since Aubréville work in the 1960's. According to Pennington (1991), the genus is variable, poorly defined and its acceptance somewhat provisional. Only one species, *E. oubanguiense*, occurs naturally in the Sangha Trinational area.

*Englerophytum oubanguiense* (Aubrév. & Pellegr.) Aubrév. & Pellegr.

Tree to 20m tall. Stipules present. Leaves alternate, simple, oblanceolate-obovate; apex emarginated-mucronate with no acumen; base acute, sometimes cuneate. Secondary venation closely spaced (<10mm) parallel, forming continuous sub-marginal loops; tertiary venation open parallel. Lower lamina with dense curly red hairs; mid-rib and petiole with felt-like pubescence. Inflorescences in fascicles on main stem and branches. Calyx 5(-6) to 4mm long. Corolla tube to 5-6mm long. Stamens 5(-6) with short filaments, anthers connivent covering ovary. Ovary 5-locular. Fruit 3cm diameter, tomentose, clustered on trunk.

2.4.5. *Manilkara* Adans.

A widely-distributed genus of 82 species of generally small to medium-sized, evergreen trees found in various types of forest. The group is pan-tropical and most speciose in the Americas. One of the more commercially better-known species is the chicle tree (*M. zapota*), widely grown as a source of both fruit and latex, which is the principle raw material used in the manufacture of chewing gum (Govaerts et al., 2001). Closely allied with *Mimusops*, it is sometimes difficult to tell these genera apart. At species level, it is also difficult to define individual taxa, as there has been no published revision on the genus since the work of Aubréville (1964). However, regional accounts are available from Cronquist (1945), Pennington (1991), and van Royen (1959). Only three *Manilkara* species occur naturally in the Sangha Trinational region.

*Manilkara dawei* (Stapf) Chiov.

Tree to 25m tall. Stipules absent. Leaves alternate, simple, slightly clustered, obovate; apex obtuse-acute; acumen very small sub-triangular; base acute. Secondary venation widely spaced (>10mm) parallel, forming continuous sub-marginal loops; tertiary venation open parallel, sometimes reticulate. Lower leaf surfaces glabrous. Inflorescences in fascicles of 6-8 held in leaf axils. Calyx to 8mm long, pubescent. Corolla tube to 6mm long, lobes to 5mm long. Stamens up to 7.5mm long, staminodes up to 4mm long. Ovary 5-locular. Fruit subglobose, with very pale mealy indumentum.

*Manilkara mabokeensis* Aubrév.

Tree to 25m tall; slash with white latex. Stipules present, caducose. Leaves alternate, simple, clustered, obovate; apex rounded; acumen may be absent, or very elongate, sub-triangular (length >4x basal width); base cuneate-acute, sometimes rounded. Secondary venation closely spaced (<10mm) parallel, forming continuous sub-marginal loops, barely visible below; tertiary venation open parallel-reticulate. Lower surface with dense white felt-like pubescence; midrib and petiole glabrous. Fruit ellipsoid, pale yellow.

*Manilkara pellegriniana* Tisser. & Sillans

Tree to 20m tall. Stipules present and persistent. Leaves alternate, simple, clustered at leaf tips, oblanceolate; apex obtuse-rounded; acumen very small, sub-triangular; base acute. Secondary venation closely spaced (<10mm) parallel, but barely visible, forming continuous sub-marginal loops; tertiary venation open parallel-reticulate, but barely visible. Lower leaf surfaces glabrous. Inflorescences below terminal leaf clusters. Calyx up to 7mm long, pubescent. Corolla characters not available. Stamens and staminodes 2.5-3mm long. Ovary 12-locular. Fruits unknown.

2.4.6. *Mimusops* L.

*Mimusops* is a genus of 50 recognised species, all but three occur naturally in Africa, or surrounding islands, and are small to medium-sized trees found in wet or dry forests. As mentioned above in *Manilkara* they are similar, but these taxa can be clearly defined by their fine lateral venation. The species are widely used as timber, essential oils, fruit and in amenity. Only one species, *Mimusops andongensis*, occurs naturally in the Sangha Trinational region.

*Mimusops andongensis* Hiern

Tree to 20m tall; slash red with white marks. Stipules absent. Leaves alternate, simple elliptic; apex acute-obtuse; acumen very small, sub-triangular; base acute. Secondary venation closely spaced (<10mm) parallel, forming continuous sub-marginal loops; tertiary venation reticulate. Lower leaf surfaces glabrous. Fruit up to 2.5cm long and 2cm in diameter.



#### 2.4.7. *Omphalocarpum* P. Beauv.

*Omphalocarpum* is a genus of considerable uncertainty, with between 6 and 27 recognised species (Govaerts *et al.*, 2001). All are medium to large-sized forest trees with very large fruit containing many large flattened seeds that are known to be dispersed by mammals, including elephants. The problems of classification within the group, including the uncertainty regarding species number within the genus, stem from very limited collector information leading to poor field knowledge, and the fact that collected material is widely dispersed. A revision of *Omphalocarpum* (*Omphalocarpeae*) by Y. B. Harvey (RBG-Kew) is currently ongoing in an attempt to rectify this uncertainty. Three described species are found within the Sangha Trinational region, of which two (*O. elatum* and *O. procerum*) are a sought-after source of quality timber resulting in the exploitation of natural populations in Cameroon and neighboring countries (Vivien & Faure, 1985).

#### *Omphalocarpum elatum* Miers.

Tree to 25m tall; slash pink-brown with white latex. Stipules absent. Leaves alternate, simple, clustered at twig tips, tapering-oblongate; apex obtuse-rounded; acumen large sub-triangular (length approximately equal to basal width); base long decurrent. Secondary venation widely spaced (>10mm) parallel, forming continuous sub-marginal loops; tertiary venation scalariform with some looping backwards linking midrib to secondary. Lower leaf surfaces glabrous. Inflorescences in fascicles, 4-6 flowers per fascicle. Calyx 5, 5-12mm long. Corolla tube and lobes 9-17mm long. Stamens to 12mm long. Ovary 5-locular. Fruit subglobose, up to 15cm in diameter and 8cm long, yellow-green maturing to dull brown.

#### *Omphalocarpum pachysteloides* Mildbr. ex Hutch. & Dalziel

Tree to 20m tall; bark grey; slash whitish oxidising to orange. Stipules present. Leaves alternate, simple, tapering-oblongate; apex obtuse-acute, sometimes rounded; acumen very elongated sub-triangular (length >4x base width); base decurrent. Secondary venation widely spaced (>10mm) parallel, forming continuous sub-marginal loops; tertiary venation reticulate and impressed above. Lower leaf surface glabrous, pubescent when young. Inflorescences in fascicles, 8-20 flowers per fascicle. Calyx 5-lobed, 7-10mm long, tomentose. Corolla subtending calyx, 8-11mm long. Stamens to 8mm long. Ovary 5-locular, stigma subtending corolla by 2mm. Fruit subglobose, pale orange in colour.

*Omphalocarpum procerum* P.Beauv.

Tree to 20m tall; slash pinkish with white juice. Stipules absent. Leaves alternate, simple, clustered at twig tips, tapering-obovate; apex rounded-obtuse; acumen either large sub-triangular (length approximately equal to basal width) or elongate sub-triangular acumen (length 2-3x basal width); base long decurrent. Secondary venation widely spaced (>10mm) parallel forming continuous sub-marginal loops; tertiary venation loops backwards from midrib joining secondary. Lower leaf surfaces glabrous. Inflorescences sessile. Corolla tube to 9mm long, lobes to 2.5mm long. Fruit flattened globular up to 18cm diam.

2.4.8. *Pouteria* Aubl.

A large genus of 304 species globally, *Pouteria* species are mainly pan-tropical and native to the Americas and the Asian-Pacific. Economically important uses include timber production in the form of both light and heavy hard woods. Asian and American *Pouteria* species are also valued producers of edible fruit, with that of *P. caimito* from the Central Americas said to taste like pears (Popenoe, 1920). Only five *Pouteria* species occur naturally in Africa, and only one, *P. altissima*, widely known as an Ivorian timber species (Govaerts *et al.*, 2001) occurs within the Sangha Trinational.

*Pouteria altissima* (A. Chev.) Baehni

Tree to 50m tall; slash pinkish. Stipules absent. Leaves alternate, simple, elliptic; apex acute-obtuse, with no acumen; base rounded. Secondary venation widely spaced (>10mm) parallel, looped to form a continuous marginal vein; tertiary venation scalariform. Lower leaf lamina glabrous, pubescent when young; mid-rib and petiole with felt-like pubescence. Inflorescences in fascicles. Calyx to 3.5-5.5mm long. Corolla tube to 3.5mm long, lobes 2mm long. Stamens 2mm long, staminodes subulate, to 2mm long. Ovary 5-locular, densely pilose. Fruit ovoid to sub-globose.

2.4.9 *Synsepalum* (A. DC.) Daniell

*Synsepalum* is a genus with 23 known species (Govaerts *et al.*, 2001), of which five occur naturally within the Sangha Trinational. Members of the genus vary in stature from small shrubs to large trees over 50m in height, and occur varied habitats from savanna to forests, and often in swampy or riverine locations. *Synsepalum* species are similar to *Englerophytum* both in their morphology and their distribution within Gabon and surrounding countries.

Species within the genus show highly variable character states, and the taxonomic integrity of the group is by no means definitive (Pennington, 1991).

*Synsepalum brevipes* (Baker) T. D. Penn.

Tree to 35m tall; slash pink. Stipules present and persistent. Leaves alternate, simple, obovate-oblanclate; apex rounded, sometimes obtuse-blunt, acumen elongate, sub-triangular (length 2-3x basal width); base decurrent. Secondary venation widely spaced (>10mm) parallel, but barely visible, curved near margin but not forming continuous sub-marginal loops; tertiary venation reticulate, obscured below. Lower leaf surfaces glabrous, but pubescent when young. Inflorescences in fascicles. Calyx to 4mm long. Corolla tube to 2mm long, lobes 4.5mm long. Stamens to 6mm long. Ovary 5-locular. Fruit ellipsoid, edible.

*Synsepalum laurentii* (De Wild.) D.J.Harris

Tree to 20m tall. Stipules present. Leaves alternate, simple, obovate; apex obtuse with no acumen; base acute. Secondary venation widely spaced (>10mm) parallel, forming continuous sub-marginal loops; tertiary venation reticulate. Lower leaf lamina glabrous; midrib and petiole with felt-like pubescence. Fruit 2cm long by 1 cm wide, yellow when mature.

*Synsepalum longecuneatum* De Wild.

(Syn. *S. stipulatum* (Radlk.) Engl.)

Tree to 20m tall; slash pinkish with white latex. Stipules absent. Leaves alternate, simple, oblanceolate; apex acute; acumen elongate sub-triangular (length 2-3x basal width); base long decurrent. Secondary venation widely spaced (>10mm) parallel, forming continuous sub-marginal loops; tertiary venation scalariform-reticulate, but barely visible. Lower leaf surfaces glabrous. Inflorescences in short axillary fascicles. Calyx lobes short. Corolla tube to 3mm long, lobes to 2mm long. Stamens slightly exceeding lobes. Fruit ellipsoid, shiny, green and cherry red.

*Synsepalum revolutum* (Baker) T. D. Penn.

Small tree to 2-3m tall, slash deep pink, fibrous with white latex. Stipules present. Leaves alternate, simple, obovate; apex obtuse; acumen large sub-triangular (length approximately equal to base width), but sometimes absent; base acute. Secondary venation widely spaced (>10mm) parallel, forming continuous sub-marginal loops; tertiary venation reticulate, but

obscure below. Lower leaf lamina glabrous, but pubescent when young; mid-rib and petiole with long hairy pubescence. Inflorescences in fascicles, 8-20 flowers per fascicle borne on 1-2 year old branches. Calyx almost free, short, pubescent. Corolla tube very short, lobes to 2.2mm long. Stamens and staminodes nearly free up to 2mm long. Ovary 5-locular, densely hairy. Fruit unknown.

*Synsepalum subcordatum* De Wild.

Tree to 20m tall; slash pinkish with white juice. Stipules absent. Leaves up to 65cm long, alternate, simple, strongly clustered at twig tip, large obovate; apex obtuse; acumen large sub-triangular (length approximately equal to base width); base rounded/cordate and decurrent. Secondary venation widely spaced (>10mm), parallel forming continuous sub-marginal loops; tertiary venation reticulate, but sometimes scalariform. Lower leaf lamina with long silvery hairs; mid-rib and petiole with felt-like pubescence. Fruit unknown.

2.4.10 *Tridesmostemon* Engl.

This is a relatively small genus with only two accepted species (and 3 synonyms), which are only known to occur in West Central Africa (Cameroon, D. R. Congo and Gabon) and grow to form large forest trees with often-fluted boles. In Cameroon, such trees are much sought-after sources of timber (Vivien & Faure, 1985). The species are closely allied to *Omphalocarpum*, but differ in having solitary flowers, which develop in the axils of fallen leaves, and much smaller fruit. Only one species, *Tridesmostemon omphalocarpoides*, occurs within the Sangha Trinational region.

*Tridesmostemon omphalocarpoides* Engl.

Tree to 25-30m tall; slash white with orange/red streaks. Stipules absent. Leaves alternate, simple, obovate, clustered at twig tip; apex obtuse-rounded; acumen elongate, sub-triangular (length 2-3x basal width); base decurrent. Secondary venation widely spaced (>10mm), parallel, forming continuous sub-marginal loops; tertiary venation reticulate, impressed above. Lower leaf surfaces glabrous. Inflorescences either solitary or paired at base of petioles. Calyx red, to 6mm long. Staminodes 6-7mm long shorter than corolla lobes. Ovary 5-locular. Fruit subspherical, borne below branches, 10-12cm diameter.

## 2.5 Taxa Protologues

The following listing gives details of protologues for the taxa studied in this project:

- Austranella congolensis* (De Wild.) A.Chev. *Veg. Ut. Afr. Trop. Franç.* 9: 268, 271 1917.
- Breviea sericea* Aubrév. & Pellegr. *Bull. Soc. Bot. France* 81: 793 1934 publ. 1935.
- Chrysophyllum beguei* Aubrév. & Pellegr. *Bull. Soc. Bot. France* 81: 795 1934 publ. 1935.
- Chrysophyllum boukokoense* (Aubrév. & Pellegr.) L.Gaut. *Énum. Pl. Fl. Afr. Trop.* 4: 27 1997.
- Chrysophyllum lacourtianum* De Wild. *Miss. Ém. Laurent* 1: 425 1907.
- Chrysophyllum perpulchrum* Mildbr. Ex Hutch. & Dalziel *Fl. W. Trop. Afr.* 2: 9 1931.
- Chrysophyllum pruniforme* Pierre ex Engl. *Monogr. Afrik. Pflanzen-Fam.* 8: 42 1904.
- Chrysophyllum ubangiense* (De Wild.) Govaerts *World Checkl. Seed Pl.* 3(1): 15. 1999.
- Englerophytum oubanguiense* (Aubrév. & Pellegr.) Aubrév. & Pellegr. *Notul. Syst. (Paris)* 16: 255 1961.
- Manilkara dawei* (Stapf) Chiov. *Italia, Mem. Cl. Sci. Fis.* 11: 46 1940.
- Manilkara mabokeensis* Aubrév. *Adansonia n.s.*, 4: 373 1964.
- Manilkara pellegriniana* Tisser. & Sillans *Rev. Int. Bot. Appl. Agric. Colon.* 33: 558 1953.
- Mimusops andongensis* Hiern *Cat. Afr. Pl.* 1: 646 1898.
- Omphalocarpum elatum* Miers. *Trans. Linn. Soc. London, Bot.* 1(1): 16. 1875.
- Omphalocarpum pachysteloides* Mildbr. ex Hutch. & Dalziel *Fl. W. Trop. Afr.* [Hutchinson & Dalziel] ii. 13 (1931)
- Omphalocarpum procerum* P.Beauv. *Fl. Oware* 1: 10 1805.
- Pouteria altissima* (A. Chev.) Baehni *Candollea* 9: 292 1942.
- Synsepalum brevipes* (Baker) T. D. Penn. *Gen. Sapotac.* 248 1991.
- Synsepalum laurentii* (De Wild.) D.J.Harris *Kew Bull.* 54: 80 1999.
- Synsepalum longecuneatum* De Wild. (Syn. *S. stipulatum* (Radlk.) Engl.) *Repert. Spec. Nov. Regni Veg.* 13: 377. 1914.
- Synsepalum revolutum* (Baker) T. D. Penn. *Gen. Sapotac.* 249 1991.
- Synsepalum subcordatum* De Wild. *Spec. Nov. Regni Veg.* 13: 377 1914.
- Tridesmostemon omphalocarpoides* Engl. *Bot. Jahrb. Syst.* 38: 99 1905.

### 3. Creation of Identification Tools

#### 3.1 Building Blocks

Irrespective of form, all taxonomic identification tools made in this study depend on the initial assembly of a number of basic elements, or building blocks, that can subsequently be customised and incorporated into the final delivery system. There are four basic building blocks;

- a character matrix that collates details regarding taxa and character states and facilitates construction of a key
- a key that enables the systematic exclusion of incorrect taxa, and final recognition of the correct specimen identity
- visual images to illustrate specific character states and assist the user of the key
- a glossary of terminology and character details to assist the user of the key.

The current project is based on the creation of identification tools for a plant group (Sangha Trinational Sapotaceae) accessible only as specimens held in herbarium (mainly RBGE) collections. Since these specimens often don't include structures other than foliage, the tools developed are limited to the use of vegetative characters visible in dried material. In particular, details relating to flower morphology are not available for the vast majority of specimens. This introduces a quite serious limitation when constructing a key capable of identifying taxon levels higher than species, such as genera, since in angiosperms floral characters are usually the primary basis of group differentiation.

#### 3.2 Character Matrix

As a first step in constructing a suitable character matrix for the material to hand, existing literature describing the relevant taxa was consulted, and a detailed study was made of the vegetative characteristics of all available specimens (see **Appendix 1** for a collated list of all studied material). Relevant consulted literature included; Pennington (1991), Harris & Harris (2001) and Harris & Wortley (2008). There is a relatively limited range of purely vegetative characters that can be used to describe leaf morphology in dried herbarium specimens. These were; stipules, basic leaf shape, leaf base, leaf apex, acumen (extended leaf tip), secondary venation, tertiary venation, and abaxial (lower leaf) pubescence. Character states used to create a character matrix for Sangha Trinational Sapotaceae are listed in **Table 3.1**. Initially,

an additional secondary venation character state of ‘parallel’ was included in the matrix, but subsequently dropped since all taxa within the Sangha Trinational were found to possess this feature.

**Table 3.1:** Characters and character states used to create a Character Matrix for herbarium specimens of Sapotaceae from the Sangha Trinational

Character	Character State
a) <i>Stipules</i>	
	i) Present
	ii) Absent
b) <i>Leaf shape</i>	
	i) elliptic (longitudinally symmetrical)
	ii) obovate (widest in apical third)
	iii) oblanceolate (widest in apical third)
	iv) laterally asymmetrical
	v) straight tapering from mid-point to base
	vi) elongate with sub-parallel sides
c) <i>Leaf base</i>	
	i) acute (curved)
	ii) rounded
	iii) cordate/sub-cordate
	iv) asymmetrical
	v) cuneate (acutely tapered & straight)
	vi) decurrent (leaf margin narrowly extended in parallel to petiole)
	vii) long decurrent (leaving less than 1cm of free petiole)
d) <i>Leaf apex</i>	
	i) curvature acute (less than 90°)
	ii) curvature obtuse (more than 90°)
	iii) blunt (with obvious shoulder)
	iv) broadly rounded
	v) emarginate
	vi) mucronate
e) <i>Leaf acumen</i> (extended leaf tip)	
	i) absent
	ii) very small, sub-triangular
	iii) large, sub-triangular (length sub-equal to basal width)
	iv) elongate, sub-triangular (length 2-3 times basal width)
	v) very elongate, sub-triangular (length more than 4 times basal width)
	vi) elongate, parallel-sided, with blunt emarginate tip

**Table 3.1 (cont.):** Characters and character states used to create a Character Matrix for herbarium specimens of Sapotaceae from the Sangha Trinational

---

f) *Secondary leaf venation*

- i) curved near margin but not forming continuous submarginal loops
- ii) forming continuous submarginal loops
- iii) forming a straight & continuous sub-marginal vein
- iv) looped to form a continuous marginal vein
- v) widely spaced (more than 10mm)
- vi) closely spaced (less than 10mm)
- vii) barely visible

---

g) *Tertiary venation (in basal half of the leaf)*

- i) reticulate (forming random web-like pattern)
- ii) tertiaries looped backwards from mid-rib to join secondaries
- iii) scalariform (forming ladder-like rungs between secondaries)
- iv) open parallel (coming off mid-rib parallel to but distinguishable from secondaries)
- v) compact parallel (closely parallel to and indistinguishable from secondaries)
- vi) clearly impressed on adaxial leaf surface
- vii) indistinct on abaxial (lower) surface

---

h) *Pubescence on abaxial (lower) leaf surface*

- i) lamina glabrous
- ii) lamina with long silvery hairs
- iii) lamina with dense white, felt-like pubescens
- iv) lamina with dense curly red hairs
- v) lamina with sparse long red hairs
- vi) centre of midrib glabrous
- vii) mid-rib pubescent
- viii) petiole with felt-like pubescence
- ix) petiole with long hairy pubescence

---

During the process of evaluating character states, it was found that some were variable between different specimens of the same species, and occasionally between leaves of the same specimen. To recognise this fact in constructing a character matrix in a spreadsheet, the *normal* character state was indicated with an X, and less common states with an S (= sometimes). Definitions of characters and their states were revised as the project progressed, until it was felt that an optimum means of discriminating between taxa had been achieved. The finalised character matrix created in Microsoft Excel is presented in **Fig. 3.1**.





### 3.3 Character Images

#### 3.3.1 Image Capture

There are several steps to image processing. Firstly, images of the required specimens have to be captured. In the current study, images were provided by the ongoing RBGE Herbarium Digitization Project using a 56 megapixel digital camera (Cambo 45 Repro 4x5 with Leaf Aptus II-10 camera back: fitted with an Apo digitar macro f5.6/80mm copal 0 lens). In taking a photograph, the specimen is held flat on a horizontal platform with measuring scale (mm) and standard colour palate to one side (**Fig. 3.2**).

A single, constant light source (Bowens sl855 studiolute starter kit 55w 5400k), and three surrounding foil reflectors are used to illuminate the specimen. This lighting arrangement overcomes a previous ‘halo-effect’ problem encountered when using two independent lighting sources. The image capture process ideally involves two people working together. The first takes charge of arranging the specimen and lighting reflectors, including the specimen label and any additional loose material held in an associated capsule, and then captures the image by releasing the manual camera shutter. The second person operates the connected computer (Apple Mac, Quad-core Intel Xeon (2.66 GHz processor and 6 GB Ram, running Mac OS X version 10.6.8) to upload the recorded image into the software application Leaf Capture 11.3 (Leaf Imaging Ltd., 2012). The computer operator checks that the image recorded is optically flat (two dimensional) and cropped to the ideal image form, before saving it in RAW format as a MOS file of approximately 115MB. The image is then processed, including slight sharpening, and saved as a TIFF file of approximately 150MB. For both these files, the camera operator scans the specimen barcode, which is used to name the files, linking them with corresponding specimen data held in BG-BASE. The image files are stored in one of three archives held on the main RBGE computer server. Tiled file formats of approximately 35MB are created and served online using Zoomify software. Smaller, (approx. 1.5MB) JPG files of all images are then made available for download on the RBGE website.



**Fig. 3.2:** Specimen prepared for image capture: red and green rectangles indicate the approximate areas magnified in Figs. 3.3 and 3.5. [↗](#)

### 3.3.2 Image Editing in Adobe Photoshop

In the current study, JPG files (~1.5mb) were used in illustrating whole specimen characters such as overall leaf shape, and TIF files (~150mb) for the preparation of more detailed images of smaller structures, such as finer leaf venation and pubescence (**Fig. 3.3**).

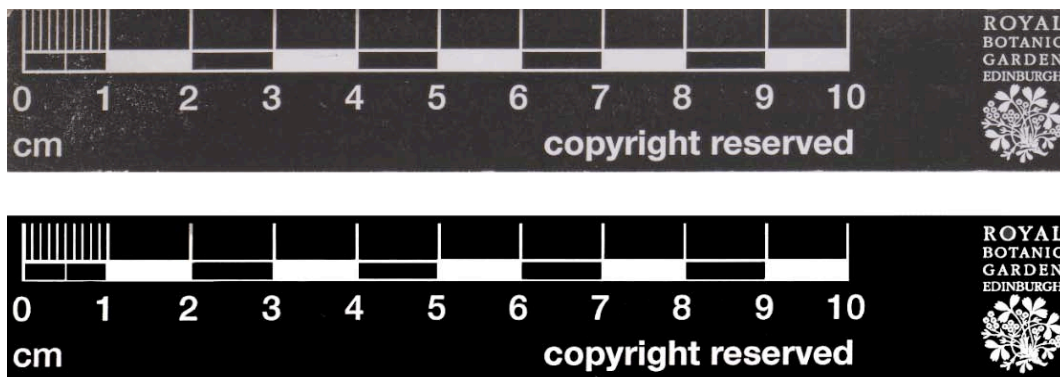


**Fig. 3.3:** JPG and TIF files of *Breviea sericea* (left and right, respectively); note the greater clarity of venation and pubescence in TIF image file.

Images of the different states of each important character used in the subsequent taxonomic key were prepared using images of the herbarium specimen that best illustrated that character state. For example, secondary leaf venation has seven possible character states in the Sapotaceae from the study area (**Table 3.1**). These include a variety of vein patterns including; curved near margin, but not forming continuous sub-marginal loops, continuous sub-marginal loops, straight and continuous sub-marginal loops, and looped to form a continuous marginal vein. A representative example of each of these patterns was selected from the specimen that most clearly illustrated the character state. Selected images were then edited to maximize the detail and clarity of the image using Adobe Photoshop Elements 10

software running on an Apple MacBook Pro laptop (2.3 GHz processor and 8 GB Ram) running Mac OS X (version 10.7.4).

The first step in this process was to add a new layer to the image and copy the linear measurement scale (mm) at exactly its correct size and the RBGE logo from the original image into this layer, arranging its position (including rotation where needed) to align with the character state of interest. The whole image was then cropped to include only the required character and the scale/logo. To further emphasize the character of interest and remove any distracting image detail, the magic wand, paintbucket and paintbrush tools were used to, respectively, select and then fill the background of the main image layer with black. In this step, the original measurement scale-bar and logo were removed. Similarly, the layer with the re-positioned measurement scale and logo was manipulated to remove any distracting dust and improve the contrast of the white scale and logo on its black background (**Fig. 3.4**).



**Fig. 3.4:** Scale bar and logo before (above) and after (below) manipulation in Adobe Photoshop Elements 10 to improve contrast and clarity.

Some images required further editing to highlight the character of interest when this was unclear, even in the high-resolution TIF files. This was achieved by selecting only one half of the main image layer (excluding the re-positioned measurement scale and logo) using the Rectangular Marquee tool, and applying the *Find Edges* filter (*Filter >> Stylize >> Find Edges*). This filter highlights edges within an image, which makes hairs and venation more apparent. However, an undesirable effect of the filter is that highlighted edges are given unrealistic ‘colour fringing’. This artificial colour was removed by selecting *Enhance >> Adjust Colour >> Remove Colour* from the menu bar. Finally, the default setting of the *Enhance >> Adjust Colour >> Adjust Colour Curves* command was used to maximize the clarity and contrast within the delineated image detail. In order to avoid any possible

confusion when using such manipulations to emphasize important character states, only 50% of the image was so manipulated, leaving the remainder in its original form (**Fig. 3.5**).



**Fig. 3. 5:** Image edited using the Find edges filter in Adobe Photoshop to highlight the looping sub-marginal venation on 50% of the abaxial (lower) surface of *Brevia sericea*.

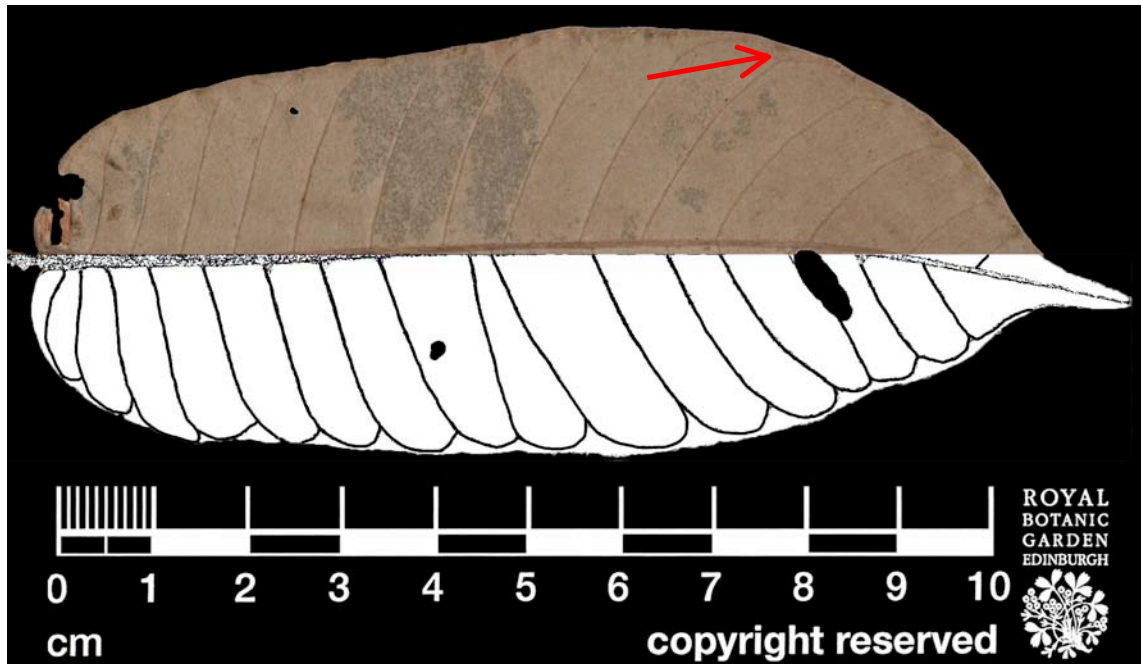
To further highlight the linear secondary venation pattern, the manipulated half of the image was cropped as a second image file, converted to a black and white bit map format, and the inter-vein detail removed user the Photoshop *Eraser* tool. The resulting black and white line drawing was then pasted back into the original file as a new layer, and the image flattened to create **Fig. 3.6**.



**Fig. 3. 6:** Image edited after converting into black and white bitmap format in Adobe Photoshop to highlight the looping sub-marginal venation on 50% of the abaxial (lower) surface of *Brevia sericea*.

### 3.3.3 Final Image Output

To emphasise important character details, a red arrow was inserted within the processed image before its multiple layers were flattened by selecting *Layer >> Flatten Image* from the menu bar. Finalised images (**Fig. 3.7**) were saved as both TIFF and JPG files for subsequent use in identification tools.



**Fig. 3.7:** Finalised image created from the original photograph of *Brevia sericea* (**Fig. 3.2**) to illustrate the looping sub-marginal character state visible on the abaxial leaf surface.

### 3.4 Creation of Dichotomous Keys

#### 3.4.1 Key to Genera

As pointed out in section 3.1, the herbarium material that formed the basis of this study included few plant structures other than foliage. This introduces a quite serious limitation when constructing a key to genera, since discrimination of the latter is primarily based on floral characters (Pennington, 1991). The simplest way to create a user-friendly and maximally effective key would therefore have been to ignore generic status, and construct a simple dichotomous key with single character couplets to distinguish between groups of individual taxa. The fact that the studied material did not provide a comprehensive selection of all the known taxa within the studied genera lent further support for such a strategy. However, construction of an initial key to genera was decided for the project, as a key straight to genera can be useful when dealing with geographic areas. This has the potential for users outside the studied area to key out additional species to their genus, decreasing the possible options for a correct identification. The original character matrix was invaluable in finding the final best solution to creating this a key genera (**Fig. 3.8**). The character matrix was rearranged to identify the most effective means to split all members of the single largest and highly variable genus, *Chrysophyllum* represented by six species, as an intact group with the first couplet of the key.

This couplet was necessarily complex involving; the *absence* of stipules, *absence* of random-reticulate tertiary venation; and *absence* of decurrent leaf base. Consequently, this initial couplet in the genus key needed very careful wording **Table 3. 2**. As illustrated in **Fig. 3.8**, the subsequent structure of the key splits the ten studied genera into essentially three groups; *Chrysophyllum*, *Pouteria* and *Manilkara* (in part) (couplets 1-3); *Omphalocarpum*, *Synsepalum* and *Tridesmostemon* (couplets 4-7); and *Austranella*, *Breviea*, *Englerophytum*, *Manilkara* (in part) and *Mimusops* (couplets 8-11). Note, however, that even with the help of the rearranged character matrix to summarise character states within genera, it was not possible to split out all genera cleanly in single couplets. Because of the highly variable character states present in the studied *Manilkara* spp., this genus could only be identified in part, at two separate points (couplets 2 & 9) in the developed key. Similarly, *Synsepalum* species could only be discriminated in part via couplets 6 and 7 (see **Table 3.2** and **Fig. 3. 8**).



**Table 3.2:** Initial key developed for identification the Sapotaceae genera found in the Sangha Trinational, with the aid of the rearranged character matrix shown in **Fig. 3. 8.**

---

**INITIAL KEY TO GENERA**

---

<b>1a</b>	Stipules absent; tertiary leaf venation running parallel to secondary, scalaform (linearly linking secondary veins) or looping backwards from the mid-rib to secondary; and leaf base <i>not</i> decurrent.....	2
<b>1b</b>	<i>Either</i> stipules present; tertiary leaf venation forming a randomly reticulate pattern with quaternary; <i>or</i> leaf base clearly decurrent.....	3
<b>2a</b>	Leaf apex with a distinct acumen (extended leaf tip).....	<i>Chrysophyllum</i>
<b>2b</b>	Leaf apex acutely to obtusely rounded, without a distinct acumen.....	<i>Pouteria</i>
<b>3a</b>	Secondary venation widely spaced – at least 15mm apart.....	4
<b>3b</b>	Secondary leaf venation closely spaced – less than 10mm apart.....	8
<b>4a</b>	Leaf base decurrent with a winged petiole.....	<i>Tridesmostemon</i>
<b>4b</b>	If leaf base decurrent, the petiole is not winged.....	5
<b>5a</b>	Stipules present.....	6
<b>5b</b>	Stipules absent.....	7
<b>6a</b>	Leaf base decurrent.....	<i>Omphalocarpum</i>
<b>6b</b>	Leaf base not decurrent.....	<i>Synsepalum</i>
<b>7a</b>	Leaf outline strongly obovate-oblongate, with a markedly broader apical third tapering in an almost straight line to an acutely angled & decurrent leaf base.....	<i>Omphalocarpum</i>
<b>7b</b>	Either leaf base distinctly rounded and sub-cordate, or if acute and decurrent, the leaf shape is much less markedly wider in the apical third.....	<i>Synsepalum</i>
<b>8a</b>	Abaxial mid-rib glabrous along its centre.....	9
<b>8b</b>	Abaxial mid-rib pubescent along its centre.....	10
<b>9a</b>	Leaf shape strongly elliptic, longitudinally symmetrical and widest at the mid-point, tertiary and quaternary leaf venation in the basal part of the leaf randomly reticulate.....	<i>Mimusops</i>
<b>9b</b>	Leaf shape either or obovate or oblongate, widest in the apical third and clearly narrowed towards the leaf base, tertiary leaf venation rarely randomly reticulate – usually clearly parallel to secondary in the basal part of the leaf.....	<i>Manilkara</i>
<b>10a</b>	Leaf elongate with sub-parallel sides and clearly rounded & cordate base.....	<i>Breviaea</i>
<b>10b</b>	Leaf obovate/oblongate with continuously curved leaf margins and acutely angled base.....	11
<b>11a</b>	Abaxial leaf lamina with dense red pubescence.....	<i>Englerophytum</i>
<b>11b</b>	Abaxial leaf lamina glabrous.....	<i>Austranella</i>

---





### 3.4.2 Keys to Species

A similar approach, rearranging the character matrix, was taken in finding the final best solution to discriminate between species within studied genera (**Fig. 3. 9**). In all cases, the most easily observed characters were chosen for discrimination in developing the keys shown in **Tables 3.3-6**.

### 3.5 Character Glossary

To assist the user, pdf files with a pictorial glossary of all the character states featured in the character matrix were created. Images of all possible states for each character were placed on a single landscape orientated page. This allows a direct comparison of all character states used in the keys. In this process, character states were labeled using the same terminology as that used in development of the character matrix and dichotomous keys. Individual image pages were then labeled to indicate their character category (see **Figs. 3.10-17**).

**Table 3.3:** Key for *Chrysophyllum* species found in the Sangha Trinational developed using the rearranged character matrix illustrated in **Fig. 3. 9**.

---

<b>KEY TO <i>Chrysophyllum</i></b>	
<b>1a</b>	Leaf base asymmetric ..... 2
<b>1b</b>	Leaf base symmetric ..... 4
<b>2a</b>	Secondary venation widely spaced (>10mm)..... <i>C. beguei</i>
<b>2b</b>	Secondary venation closely spaced (<10mm) ..... 3
<b>3a</b>	Leaf asymmetrically ovate, broadest below the mid-point; leaf mid-rib and petiole pubescent .. <i>C. pruniforme</i>
<b>3b</b>	Leaf obovate, broadest in apical third; leaf mid-rib and petiole not pubescent ..... <i>C. ubangiense</i>
<b>4a</b>	Abaxial leaf lamina glabrous ..... <i>C. lacourtianum</i>
<b>4b</b>	Abaxial leaf surface with dense pubescence..... 5
<b>5a</b>	Abaxial pubescence red ..... <i>C. perpulchrum</i>
<b>5b</b>	Abaxial pubescence white ..... <i>C. boukokoense</i>

---

**Table 3.4:** Key for *Manilkara* species found in the Sangha Trinational developed using the rearranged character matrix illustrated in **Fig. 3. 9**.

---

**KEY TO *Manilkara***

---

**1a** Stipules absent ..... *M. dawei*

**1b** Stipules present ..... 2

**2a** Abaxial leaf surface with dense white, felt-like pubescens ..... *M. mabokeensis*

**2b** Abaxial leaf surface glabrous ..... *M. pellegriniana*

---

**Table 3.5:** Key for *Omphalocarpum* species found in the Sangha Trinational developed using the rearranged character matrix illustrated in **Fig. 3. 9**.

---

**KEY TO *Omphalocarpum***

---

**1a** Acumen very elongate sub-triangular, length  $\geq 4$  times basal width ..... *O. pachysteloides*

**1b** Acumen relatively shorter, length only 2-3 times basal width ..... 2

**2a** Leaf-shape oblanceolate; in the basal half of the leaf tertiary leaf venation loops backwards from the mid-rib to meet with secondary veins ..... *O. elatum*

**2b** Leaf-shape obovate; in the basal half of the leaf tertiary venation forming a randomly reticulate pattern with quaternary ..... *O. procerum*

---

**Table 3.6:** Key for *Synsepalum* species found in the Sangha Trinational developed using the rearranged character matrix illustrated in **Fig. 3. 9**.

---

**KEY TO *Synsepalum***

---

**1a** Stipules present ..... 2

**1b** Stipules absent ..... 4

**2a** Abaxial mid-rib glabrous ..... *S. brevipes*

**2b** Abaxial mid-rib pubescent ..... 3


**3a** Petiole with felt-like pubescence ..... *S. laurentii*

**3b** Petiole with hair-like pubescence ..... *S. revolutum*

**4a** Leaf base long-decurrent, distinctly sinuous and narrow ..... *S. longecuneatum*

**4b** Leaf base rounded or sub-cordate ..... *S. subcordatum*

---




 Sapotaceae of the Sangha Trinational

David A. Purvis (RBGE 2012)

**KEY CHARACTERS**

Stipules

Absent Present

Images not to same scale  
Lines across images are tape holding herbarium specimens, also key features are indicated by red arrows.

Fig. 3.10: Image glossary page created for stipule character states

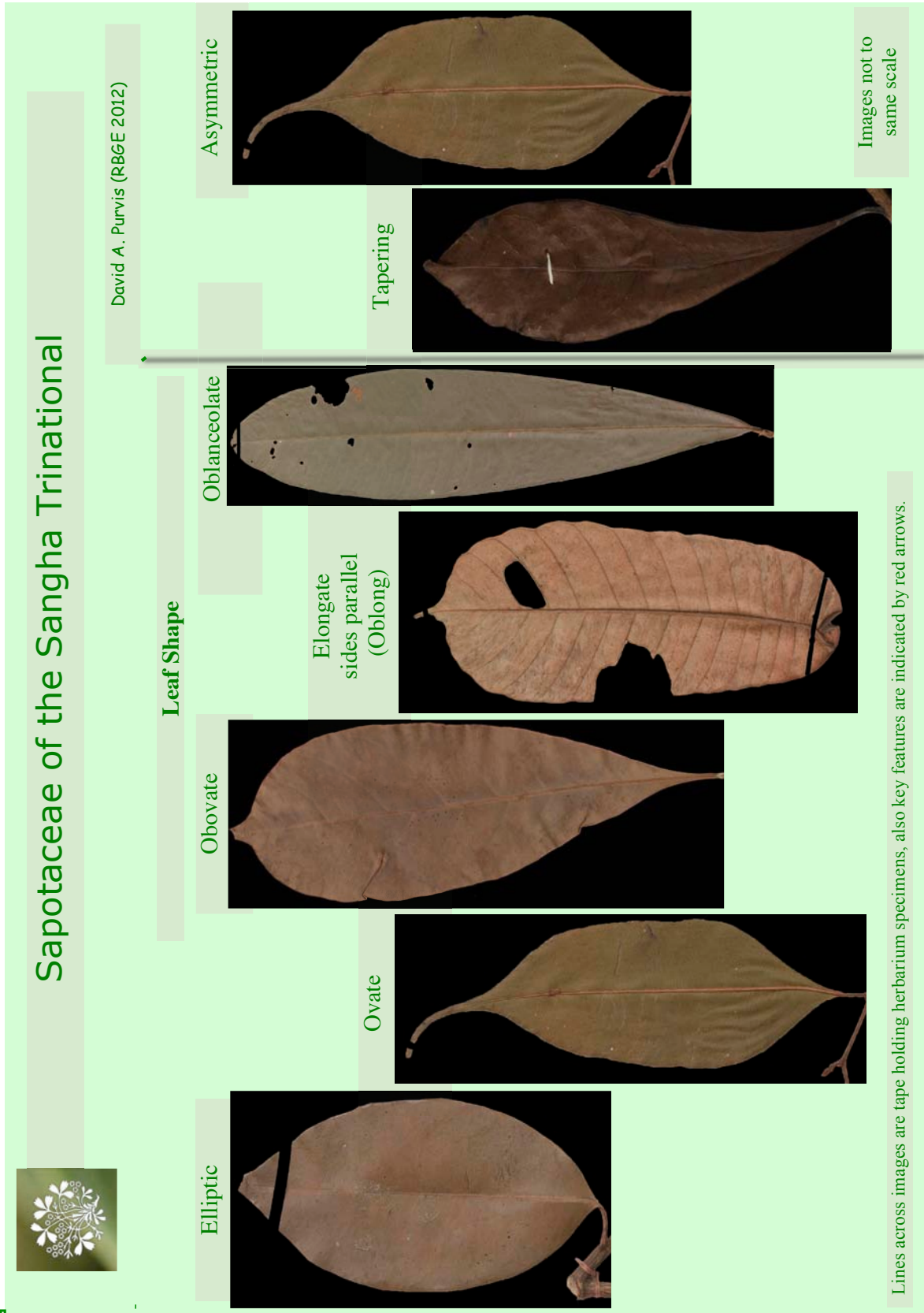


Fig. 3.11: Image glossary page created for leaf shape character states

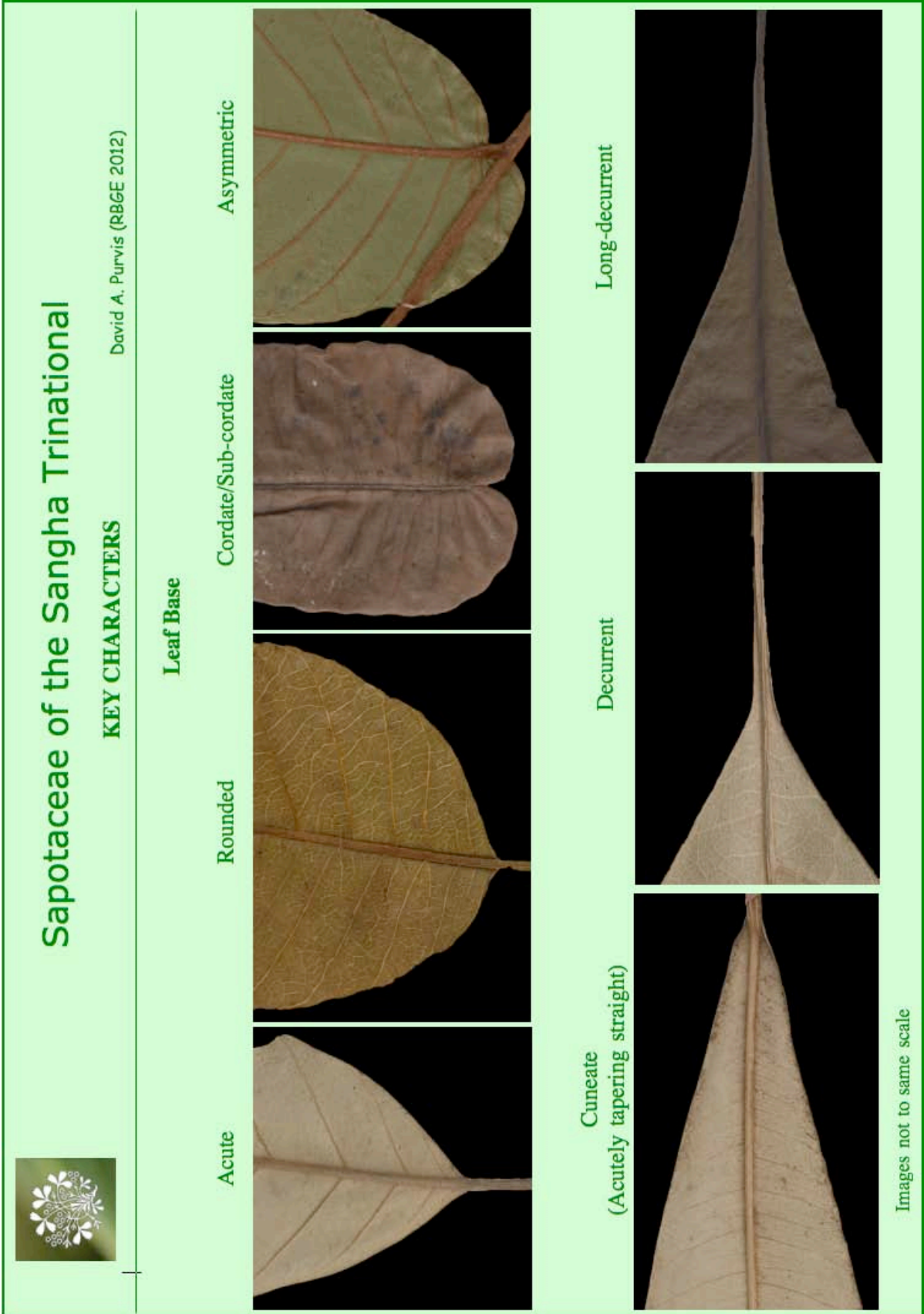


Fig. 3.12: Image glossary page created for leaf base character states



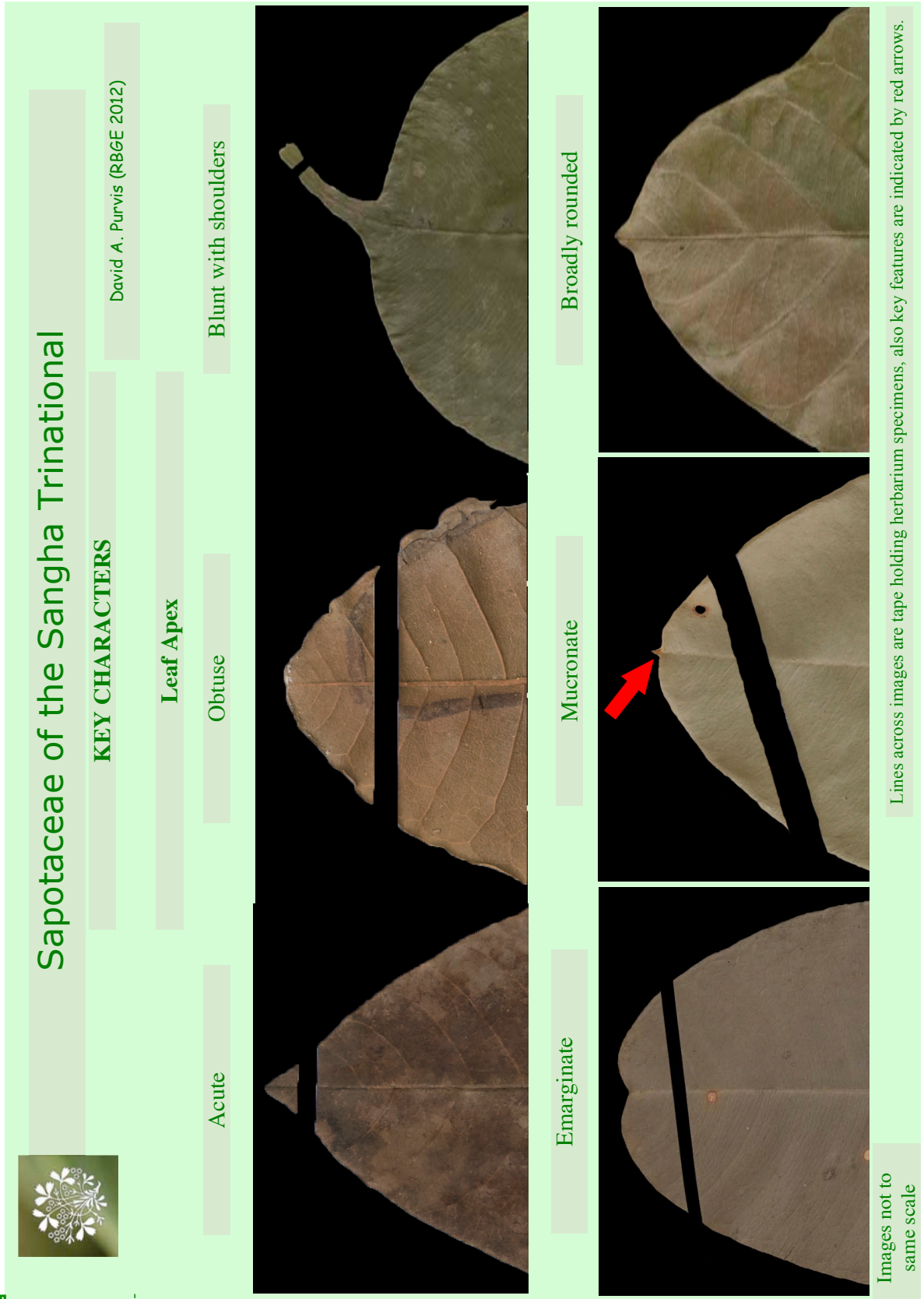




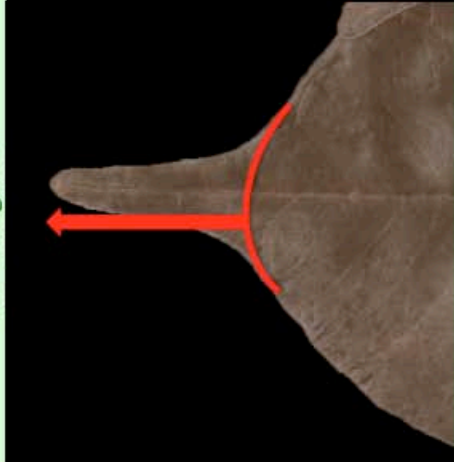




Fig. 3.13: Image glossary page created for leaf apex character states

 Sapotaceae of the Sangha Trinational  
KEY CHARACTERS  
David A. Purvis (RBGE 2012)

	Leaf Acumen	
Absent	Very small	
		
		
Elongate (x 2-3) sub-triangular	V. elongate (x ≥4) sub-triangular	
		
		

Images not to same scale

Fig. 3.14: Image glossary page created for leaf acumen character states

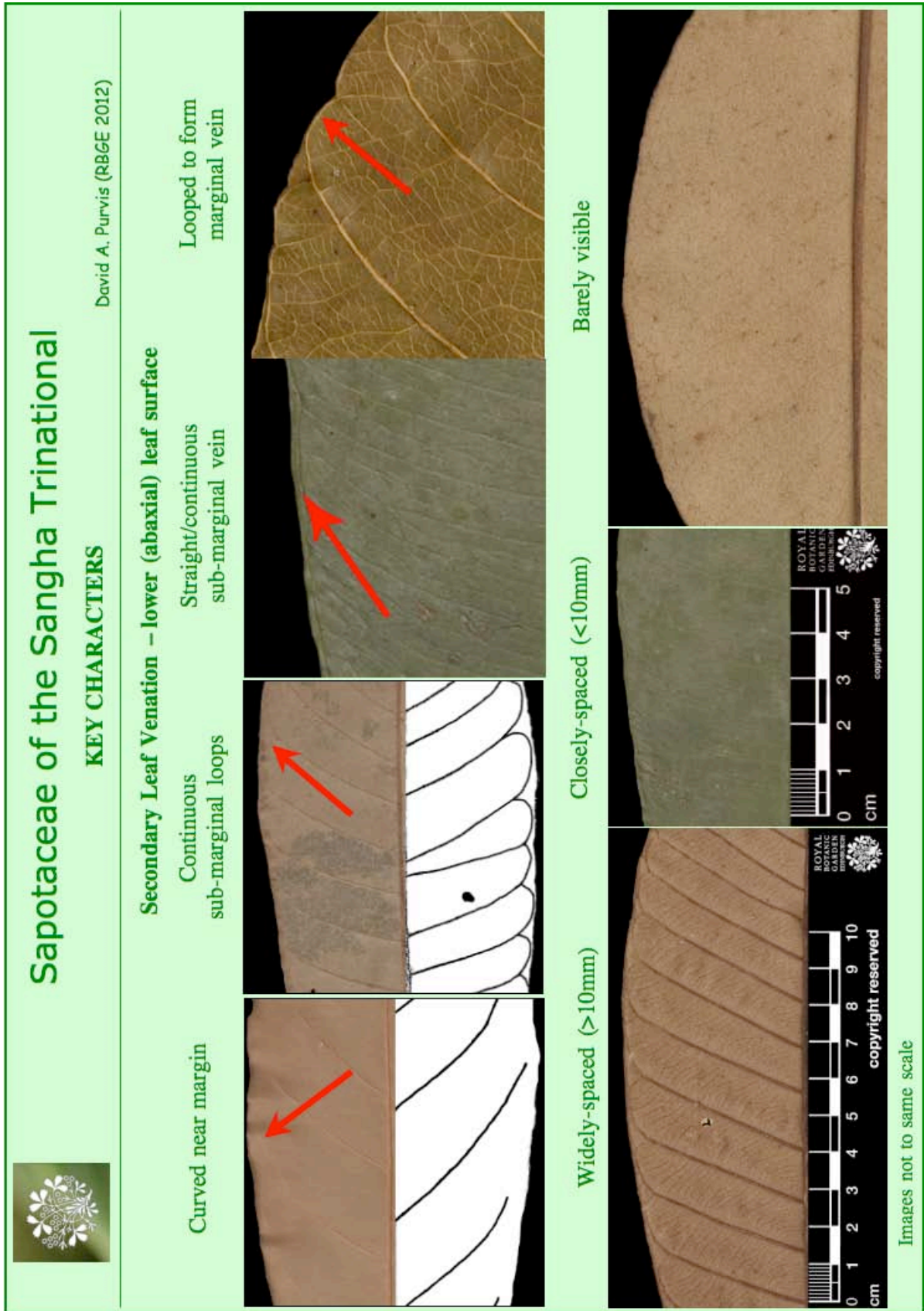


Fig. 3.15: Image glossary page created for secondary leaf venation character states

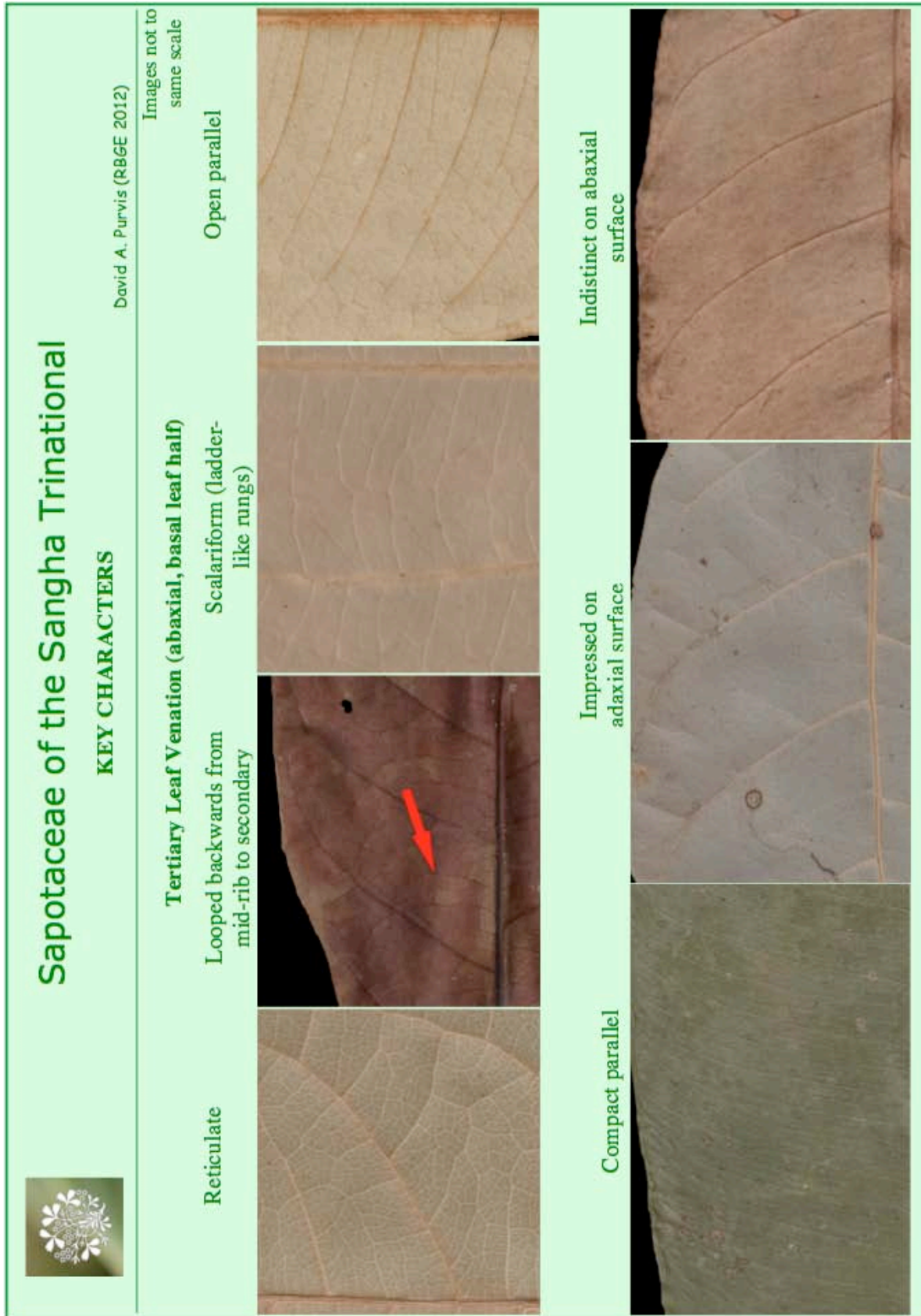








Fig. 3.16: Image glossary page created for tertiary leaf venation character states







## Sapotaceae of the Sangha Trinational

David A. Purvis (RBGE 2012)

### KEY CHARACTERS

Pubescence (abaxial)	
Lamina glabrous	
Lamina with silvery hairs	
Lamina with white felt-like pubescence	
Lamina with curly dense red hairs	
Lamina with sparse long red hairs	

Centre of mid-rib glabrous	
Mid-rib pubescent	
Petiole with felt-like pubescence	
Petiole with long hairs	

Images not to same scale

Fig. 3.17: Image glossary page created for abaxial (lower) leaf pubescence character states

## 4. Delivery Systems

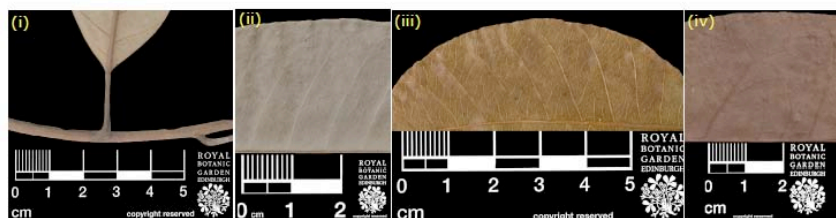
Having prepared the necessary building blocks including character matrices, dichotomous keys and a character image glossary, a range of alternative tools for the identification of Sapotaceae from the Sangha Trinational were assembled.

### 4.1 Dichotomous Image-based Keys for Sapotaceae of the Sangha Trinational

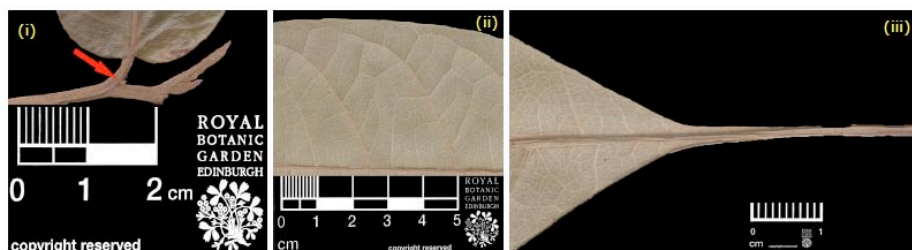
#### *Assembly of the Components*

Using the dichotomous keys created in section 3.4 and the images prepared for an illustrated glossary of important character states created in section 3.5, an image-based key to the Sapotaceae of the Sangha Trinational was created. This was done by inserting relevant character state images between each set of key couplets. To aid the user, images were labeled with small roman numerals, and these referenced in parenthesis within the key text (**Fig. 4.1**). A similar process was used to assemble a key to the genera studied, and to species within individual genera. A complete set of the prepared Image-based keys is provided in **Appendix 2**

#### KEY TO GENERA



- 1a** Stipules absent (i); tertiary leaf venation running parallel to secondary (ii), scalariform (iii) (linearly linking secondary veins) or looping backwards from the mid-rib to secondaries (iv); leaf base *not* decurrent ..... 2



- 1b** Stipules present (i) – or if absent, *either* tertiary leaf venation forming a randomly reticulate pattern (ii) *or* leaf base clearly decurrent (iii)..... 4

**Fig. 4. 1:** Example of a key couplet for an imaged-based key with inserted imagery for relevant character states

## 4.2 Key Cards for the Identification of Sapotaceae of the Sangha Trinational

As an alternative to traditional paper-based keys, a set of Key Cards for the identification of the studied Sapotaceae were prepared, with the intention that these could be printed on double-sided durable laminated cards for possible use in the field.

### *Assembly of the Components*

In addition to the inclusion of dichotomous keys and glossary images, copies of the character matrices (**Figs. 3.8 & 3.9**), which had been so helpful in the creation of the keys, were included in card preparation. This was done in the expectation that in the field, a means to check the full range of characters in a specimen against those of the taxon indicated by the key, would provide an additional identification aid, and a readily available alternative to checking formal taxon descriptions. To maximise the printable size of images, image cards were prepared in landscape format. Because the written keys and matching character matrices were not going to be used at the same time, these were printed on opposite sides of the same card. Similarly, the glossary images (as illustrated in **Figs. 3.10 – 3.17**) were printed back-to-back on a total of four image cards, to produce a complete set of 6 (laminated) identification cards (**Appendix 3**)

## 4.3 Construction of a Lucid Key to Sapotaceae of the Sangha Trinational

### *4.3.1 Introduction*

Unlike the dichotomous method of key construction employed in the creation of Image-based Keys (section 4.1) and Key Cards (section 4.2), the Lucid software package facilitates creation of a multi-access key (LucidCentral, 2012). This software allows the user to assemble a wide range of information concerning multiple character states and their relative importance in making a correct identification. The developed tool can be web-based or developed for use in CD format.

The Lucid Professional software (version 3.3), is freely available and can be downloaded for most computer platforms at the following web page:

<http://www.lucidcentral.com/en-us/software/lucid3/lucidv33freeoffer.aspx>.

In the current study, Lucid Professional 3.3 was used on a 13-inch, 2.3GHz Apple MacBook Pro laptop. A more recent version of Lucid (3.5) offers additional features, but costs

approximately 600 AU\$. In addition to facilitating development of a basic identification tool, these further options permit the addition of detailed taxon descriptions and multiple specimen images to aid use of the developed tool.

The downloaded Lucid application includes a *Lucid Builder* application, and a *Lucid player*. In constructing a Lucid key in the *Lucid Builder*, the first step involves naming the tool being developed and providing a short description of its target taxon. This step automatically creates a new application folder containing a *.lk4 file*, which becomes the key being developed, and a *Resources* sub-folder. The latter holds further sub-folders for project *Data* and project *Media*. Use of these folders is automated within Lucid, and the only necessary user step is the addition of project images to an *Images* sub-folder within the *Media* folder.

#### 4.3.2 Creating a Character Hierarchy

To create a Lucid key it is necessary to define the relevant characters, possible character states and rate their relative importance and reliability. Assistance and guidance in the process of defining characters is provided within a folder download with the programme. Perhaps the most important step, is construction of the character hierarchy. This step is critical because it establishes the basis of how the key works. If not done carefully and correctly from the start, it may become necessary to delete substantial parts of the project later, or even start over again. The hierarchy is created within the ‘*Tree view*’ page (**Fig. 4.2**). Within the left-hand column of this page a list of characters and nested character states is created, whilst in the right-hand column a list of taxa (termed ‘*entities*’ within Lucid) is created. This automatically generates a blank character matrix.

#### 4.3.3 Scoring Character States

Once created the character matrix is accessed on the ‘*Spreadsheet scoring*’ page (**Fig. 4.3**). In creating an effective character matrix (termed a ‘*feature matrix*’ within Lucid) for the taxa to hand, character (feature) states must be rated. Within the blank matrix created on the ‘*Spreadsheet scoring*’ page, scoring involves a relatively simple process of ticking spreadsheet boxes in various colours for each taxon entity (termed ‘*entities*’ within Lucid) × feature state combination in the scoring spreadsheet; blue ticks = common state; green = rarer state; red = common and easily misinterpreted state; orange = rare and easily misinterpreted state. Additionally, boxes can be ticked with a question mark to indicate uncertainty. The process of defining feature states and indicating their reliability can take only a matter of minutes if the states are already well established, or can be a process taking many weeks to



finalise if the character matrix is being newly created. The character matrix developed for Sapotaceae taxa in the current study (and previously used in the development of dichotomous keys featured in sections 4.1-4.2) is shown in **Fig. 3.1** .

Once the feature spreadsheet has been developed in Lucid, the ‘*Score Analyser*’ page (**Fig. 4.4**) provides a means to compare taxa using the underlying Lucid algorithm that calculates overall differences in character scores. This step permits the user to gauge how effectively the developed feature matrix distinguishes between taxa. If necessary, the feature matrix can be amended to improve taxon discrimination, or it may be necessary to revisit specimens in a search for additional distinguishing features that would improve the effective separation of ‘difficult’ taxa in the key.

#### *4.3.4 Linking Images in Lucid*

Images in Lucid can be any helpful visual aide, ranging from photographs of live plants to traditional line drawings, or digital photographic images of herbarium specimens. Images generated from herbarium specimens (as described in section 3.3) were uploaded to the Lucid *Images* subfolder (see section 4.3.1), initially, as images in gif format. However, these proved to be of insufficient quality. After trying several alternative formats, including png files, it was found that high-quality jpg images (which are the highest quality accepted by Lucid) were the most satisfactory. The linking of images, pre-loaded into the *Images* sub-folder, for both feature states and entities is done via the *Tree view* page. At this stage, additional information concerning the image can be added to an accompanying image caption. When linking images, it was found that Lucid would not accept full-sized herbarium images, even in jpg format. To solve this issue, cropped images of individual leaves were linked to taxon entities, and an url address link to the full-sized image on the RBGE herbarium database was added to the image caption.

File Edit View Search Window Help

Add Feature Add After Sibling

Key Items

Title  
Sangha Trinational Sapotaceae

Description  
A Key of Sapotaceae present in

Authors  
David A. Purvis

Options

Features: 13 States: 54

Leaf acumen

- Absent
- elongate parallel-sided, blunt en
- elongate sub-triangular (length :
- larger sub-triangular
- very elongate sub-triangular (ler
- very small sub-triangular

Leaf apex

- Acute
- Blunt
- Emarginate

Autranella congolensis

Breviea sericea

Chrysophyllum beguei

Chrysophyllum boukokoense

Chrysophyllum lacourtianum

Chrysophyllum perpulchrum

Chrysophyllum pruniforme

Chrysophyllum ubangiense

Englerophytum oubangiense

Manilkara dawei

Manilkara maboakeensis

Manilkara pellegriana

Mimusops andongensis

Omphalocarpum elatum

Omphalocarpum pachysteleioides

Tree View Spreadsheet Scoring Score Analyser

Fig. 4.2: Screenshot from the *Tree View* page of Lucid, used to establish a character hierarchy



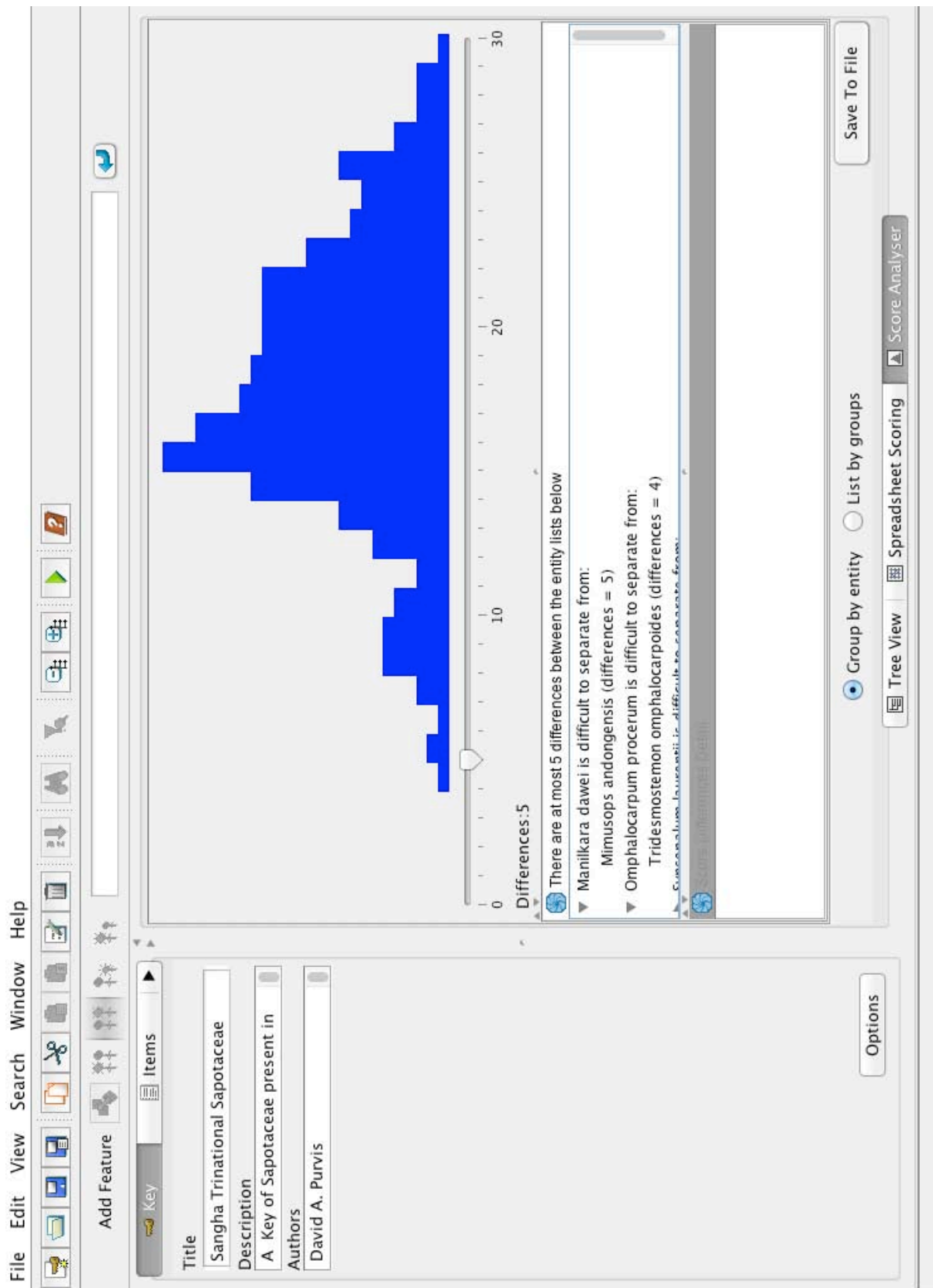


Fig. 4.4: Screenshot from the *Score analyser* page of Lucid, used to gauge how effective the developed feature matrix is in distinguishing between taxa

#### *4.3.5 Deployment of the Lucid Key*

Deployment of completed Lucid projects can be either via the Lucid website, or as a stand-alone application distributed on a CD. The Lucid application developed for Sangha Trinational Sapotaceae is intended to be placed online on the RBGE website PropaGate and is attached on CD as **Appendix 4**.

### 4.4 Construction of a Scratchpad for the Sapotaceae of the Sangha Trinational

#### *4.4.1 Introduction*

Scratchpads is a web-based social networking tool designed to facilitate the building and exchange of information regarding the diversity of life. The Scratchpads web site is accessible at:

<http://scratchpads.eu/>

Strictly-speaking, the Scratchpads facility does not provide taxonomic keys as such. Rather, it is an online location for the publishing of taxonomic information, including details of taxonomic literature, taxon descriptions and visual imagery. It is the intention of the developers of the website that it becomes a formally recognised repository for ‘virtual specimens’. Scratchpad pages frequently provide online links to interactive identification tools, such as those that can be developed using the Lucid software. Scratchpads provide an invaluable source of information for a wide range of taxa. In some ways, however, the Scratchpads goal of providing comprehensive information on the totality of global biodiversity will never be completed, as it can be forever updated and a nearly unlimited amount of additional information added.

Creating a Scratchpads web page initially requires formal registration. Accordingly, a page for Sapotaceae of the Sangha Trinational was created with the following web address:

<http://sapotaceae-sangha-tri-national-area.myspecies.info/>

Once registered, a new page developer is given access to help and guidance on page development. Important steps in the process include:

- i) Adaptation of the generic templates provided for site construction
- ii) Construction/assembly of appropriate page content for:
  - A home page
  - Description of the target group
  - A taxonomic hierarchy
  - A listing of specimens
  - An images gallery
  - A list of relevant literature
  - A description of the author/authoring group

#### *4.4.2 Scratchpads Content Management*

Templates are downloadable for adding detail to the above listed pages. Depending on the project, a wide variety of page content can be added via a '*manage fields*' option for each page. Editing page content to suit personal requirements takes time, but is relatively simple to use. For this project, pages were created containing information for all 23 Sapotaceae taxa studied. The Scratchpad specimens template was populated with specimen label information, which is downloadable with image jpps from the RBGE herbarium database website at:

(URL: [www.rbge.org.uk](http://www.rbge.org.uk))

#### 4.4.3 Use of GUID Numbers

Globally Unique Identifier (GUID) numbers are used to uniquely tag all taxa included in a Scratchpads project. In building the Sapotaceae Scratchpad, pre-existing IPNI taxon identification numbers (available at URL: <http://www.ipni.org/>) were assigned to all taxon levels included in the webpage. In constructing a Scratchpad site, it is important to link the GUID numbers within the taxonomic hierarchy created. As an example, the family Sapotaceae (GUID no. 30000114-2) was linked as the parent of the genus *Breviea* (GUID no. 36678-1), which was linked as the parent of the species *Breviea sericea* (GUID no. 785971-1).

#### 4.4.4 Uploading and Linking Scratchpad Images

Adding images to Scratchpads is relatively simple, but very time consuming because of the large file sizes required. There is no means for the bulk uploading of image files; each jpg image has to be added individually at a high resolution to permit site users to zoom into image detail. Whole specimen images ranging in size from 15 and 20MB, and individual leaf images up to 7MB, were uploaded to appropriate image folders. It was then necessary to link all images to the appropriate taxa via their specified names. This is a lengthy process, but eventually all images are linked not just to their taxa, but also automatically by the underlying software (via the specified GUID numbers) to all other uploaded information, e.g. to the taxonomic hierarchy, species descriptions and details of relevant literature.

#### 4.4.5 The Finalised Scratchpad (incl licensing issues)

Scratchpad pages become active sites (under construction) on the web as soon as they are successfully registered, and in a real sense are never completed as new information can be continuously added. An important, indeed essential detail in site development is the specification of online access licencing agreements. A number of different access arrangements are available, but the most commonly used options include, CC-BY (Creative Commons Attribution By), CC-BY-NC (Creative Commons Attribution By Non-Commercial) (Creative Commons, 2012). For overall access to the scratchpad and the information it contains, a CC-BY agreement was chosen; this allows the copying, distribution and displaying of information, and the generation of derivative works based on the site's content, only if the author or licensor is accredited. A CC-BY-NC agreement was specified

for image content. This additionally requires that any use of images must be 'non-commercial', as these are the property of either the RBGE Herbarium, the specimen collectors, or the site author. The Scratchpad for Sapotaceae of the Trinational is available at:

<http://sapotaceae-sangha-tri-national-area.myspecies.info/>



## 5. Evaluation and Testing of Tools

### 5.1 Introduction and Methods

An essential step in the creation of any taxonomic key, is testing prior to publication. This is necessary because a key that ‘works’ for the developer, is not necessarily effective or usable by others (Walter & Winterton, 2007). The taxonomic tools developed in section 4 were tested individually and comparatively for their effectiveness. A total of six testers collaborated in this process. Testers with a wide range of taxonomic experience were chosen, ranging from three senior taxonomists within the RBGE herbarium, including two Sapotaceae specialists, to PhD and MSc students with no particular knowledge of the family, and a totally inexperienced individual with no background in plant biology.

Each tester was given three herbarium specimens, randomly selected from those studied (**Appendix 1**), and were asked to identify them using:

- i) the Image-based Key (section 4.1)
- ii) the Key Cards (section 4.2)
- iii) the Lucid application (section 4.3)

Testers were allowed to randomly choose any specimen x tool combination. In addition to recording their success rate in using the above tools, testers were asked to comment on:

- i) the clarity of wording in key couplets
- ii) the effectiveness of accompanying imagery
- iii) the relative advantages/disadvantages of the tools provided
- iv) suggestions for improvement of the tools provided

During the testing process, any other comments/observations made by testers were also noted. At the end of testing, each tester was asked to view and comment on the utility of the web-based Scratchpad application created in section 4.5.

## 5.2 Feedback on Use of the Dichotomous Keys

Out of a total of 12 specimens given to the six testers for identification using the dichotomous Image-based and Key Card tools, nine were correctly identified with minimal assistance. The three instances of mis-identification were; *Mimusops andongensis* (mis-identified by a Sapotaceae specialist as a *Manilkara* sp. because of mistaken tertiary venation using the Key Card to genera), *Omphalocarpum pachysteloides* (mis-identified by a Sapotaceae specialist as a *Synsepalum* spp. because of mistaken stipule status using the Image-based key to genera), and *Synsepalum laurentii* (mis-identified by a botany student as an *Omphalocarpum* spp. because of mistaken mid-rib pubescence status using the Image-based key to genera). No errors were made by testers using the keys to species within correctly identified genera. The totally inexperienced tester correctly identified all three of their specimens after being given additional assistance regarding the meaning of morphological terminology, e.g. the meaning of ‘stipule’. In general, non-specialists were more inclined to use the images provided within the dichotomous key tools and to accept character states at face value. On average, botany students took between 5 and 10 minutes per specimen to make an identification using the dichotomous Image-based and Key Card tools. The non-specialist herbarium taxonomist took approximately 15 minutes per specimen, whilst the Sapotaceae specialist took considerably longer. In the latter case, this can be explained by their greater attention to detail in comparing the character states used in the keys.

### 5.2.1 Key Structure and Presentation Format

A major issue raised by several testers related to use of the stipules present/absent character state. This character was found difficult and resulted the mistaken identification of *Omphalocarpum pachysteloides*, because in this and several other species, stipules are caducous i.e. they are non-persistent and can fall off at an early stage of development. Additionally, several comments were received regarding the variable, and often subjective status of many of the characters used in the key to genera, especially those relating to acumen form, tertiary venation, and pubescence. Unfortunately, there is a high degree of variation in these characters, both between specimens and even between leaves of the same specimen. Comments were also received about the use of technical botanical terms, such as abaxial and adaxial, without explanation. Finally, despite attempts to very carefully word the first

complex couplet in the key to genera, several testers still had difficulty in comprehending the fact that the couplet referred to the *combined set* of multiple characters.

To address these issues, the key to genera was revised (**Table 5.1**). In particular, the emphasis previously placed on the stipule character state was greatly reduced, and the key re-organised so that the genus *Omphalocarpum* was keyed out without explicit (and sole) reference to stipule status. In general, couplets were revised to avoid sole dependance on subjective character states, such as acumen form, tertiary venation and pubescence, and the wording of the complex first amended in an attempt to improve clarity. In combination, these changes resulted in a need to key out the genus *Manilkara* at two different points in the revised structure (via both routes of couplet 1). To reflect changes made in the key to genera, a corresponding amendment was made to the form of the supporting character matrix for the key cards tool (**Fig. 5.1**).

**Table 5.1:** Finalised key for Sapotaceae genera found in the Sangha Trinational, to be used in conjunction with a rearranged character matrix illustrated in **Fig. 5. 1.**

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**AMENDED KEY TO GENERA**

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- 1a** Stipules absent; tertiary leaf venation running parallel to secondary, scalariform (linearly linking secondary veins) or looping backwards from the mid-rib to secondaries; leaf base *not* decurrent ..... 2
- 1b** Stipules present – or if absent, *either* tertiary leaf venation forming a randomly reticulate pattern *or* leaf base clearly decurrent ..... 4
- 2a** Tertiary leaf venation open parallel (easily distinguishable from secondary) ..... *Manilkara*
- 2b** Tertiary venation scalariform, or compact parallel and *not* easily distinguishable from secondaries. .... 3
- 3a** Acumen absent ..... *Pouteria*
- 3b** Leaf apex with a distinct acumen (extended leaf tip) ..... *Chrysophyllum*
- 4a** Secondary venation widely spaced – more than 10mm apart..... 5
- 4b** Secondary leaf venation closely spaced – less than 10mm apart ..... 8
- 5a** Leaf margin tapering from mid point in a straight line to the leaf base or if sinuate, acumen very elongate sub-triangular ..... *Omphalocarpum*
- 5b** Leaf margin sinuously curved from mid-point to base, acumen never very elongate sub-triangular ..... 6
- 6a** Tertiary venation forming random reticulate pattern ..... *Synsepalum*
- 6b** Tertiary venation scalariform or looped backwards between mid-rib and secondary ..... 7
- 7a** Tertiary venation looping backwards ..... *Tridesmostemon*
- 7b** Tertiary venation scalariform ..... *Synsepalum*
- 8a** Centre of mid-rib on abaxial (lower) surface glabrous..... 9
- 8b** Centre of mid-rib on abaxial (lower) surface with hairs..... 10
- 9a** Leaf shape strongly elliptic, longitudinally symmetrical and widest at the mid-point ..... *Mimusops*
- 9b** Leaf shape either or obovate or oblanceolate, widest in the apical third and clearly narrowed towards the leaf base ..... *Manilkara*
- 10a** Leaf elongate with sub-parallel sides and clearly rounded & cordate base ..... *Breviea*
- 10b** Leaf obovate/oblanceolate with continuously curved leaf margins and acutely angled base ..... 11
- 11a** Abaxial (lower) leaf lamina with dense red pubescence ..... *Englerophytum*
- 11b** Abaxial (lower) leaf lamina glabrous ..... *Autranella*
-



### *5.2.2 Use of Images*

Most users felt that the supporting images significantly aided use of the developed keys. Several comments, however, were received regarding the size of images provided in the Image-based Key. As a result of the placement of *two* couplets per page (portrait format), image size was thought too small, in comparison to the images provided with the Key Cards. Difficulty was experienced by all testers in seeing pubescence character states. This, however, is not something that can be addressed by a simple increase in printed image size, since the resolution of the original herbarium image files in TIFF format, is insufficient to show the pubescence which is visible only in the actual specimen under a high degree of magnification. To rectify this deficiency it would be necessary to commission the production of specific images of leaf pubescence on relevant taxa at significantly greater magnification. Several testers commented on the fact that in using keys to species within genera, the images provided were more helpful because of their specificity. In comparison, single images provided in support of the key to genera were necessarily 'generic', and therefore were rarely exactly similar to the specimen being identified. The only way to address this issue would be the provision of a comprehensive set of images for all possible taxa, which cause a different, logistical issue. Similarly, some testers commented on the desirability of providing referencing numbers to images in key couplets. This suggestion was not acted upon because it was felt that such figure referencing in key couplets would not materially improve existing verbal image labeling, and would unnecessarily add to couplet length.

### *5.2.3 Comparative Merits of the Image-based Key and Key Cards*

Of the six testers who were asked to use the dichotomous key tools, four (one specialist and all three non-specialists) preferred the Key Card tool with separate image cards, whilst two (specialists) preferred the image-based key with inserted images. Those that preferred the Key Cards expressed the view that the key card was easier to use because it was similar to a conventional dichotomous key and not interrupted by imagery. All testers felt that the images provided on the Key Cards were superior because of their larger printed size. Additionally, at least one non-specialist tester commented positively on the ability to check the complete character set for an identified specimen using the character matrix provided on the reverse of the Key Card.

### 5.3 Feedback on Use of the Multi-access Lucid Key

When the six testers used the multi-access Lucid key to identify a randomly chosen specimen, five made a correct identification. The single mis-identification involved *Omphalocarpum procerum*, mistakenly identified by a Sapotaceae specialist, as *Tridesmostemon omphalocarpoides*. This error resulted from a varying opinion regarding the somewhat subjective tertiary venation status of the specimen. This underlines the difficulty in creating an effective key for the taxa, in this study based only on vegetative characters, even when the key tool is multi-access and utilises the full character set available. None of the testers had had much previous experience of using Lucid keys, and consequently all initially experienced difficulties in its use, which suggests a lack of basic intuitiveness in its interface. This was rapidly overcome through relatively simple initial guidance, although it was noticeable that younger testers seemed to get to grips with the key's functionality more rapidly. Despite these initial problems, the speed of specimen identification by testers using the Lucid key was considerably faster than their use of the dichotomous key tools, with an approximate identification time of 5 minutes per specimen.

In the creation of a functional key, a number of relatively minor issues were encountered. These mainly concerned the use of unfamiliar, *alternative* terminology, for which there is no obvious need. For example:

- i) character matrices are termed '*feature*' matrices
- ii) taxa are referred to as '*entities*'
- iii) nested hierarchical (taxonomic) structures are defined using terms like '*parents*', '*siblings*' and '*children*'

Use of these alternative, and often non-intuitive, terms hindered key construction.

#### 5.3.1 Comparative Merits of Lucid vs Dichotomous Key Systems

All testers experienced initial problems with the functionality of the interactive Lucid system. However, these issues did *not* relate to the basic functionality of the created tool; but rather to unfamiliarity with the basic Lucid interface, which is less than fully intuitive. For example, most testers had to be shown that if clicked on, loaded images could be enlarged for easier viewing. Once the basic interface of the Lucid system was understood, all users expressed a preference for its use compared to using the tools based on a dichotomous key. This

preference was largely based on the fact that, in contrast to the use of a dichotomous key, uncertainty about any specific character was not an obstruction to progress and eventual success. Additionally, the Lucid software can help the user by using the information already provided about a specimen's features, to prompt answers regarding further character states that are most likely to enable an identification solution to be reached. Most users found this facility helpful when it was pointed out to them.

All users preferred the larger on-screen image size that Lucid provided, in comparison to the relatively modest printed image size available, even on the Key Cards. Additionally, the image captions that Lucid allows were considered helpful in interpreting image content.

#### 5.4 Feedback on the Scratchpad

As Scratchpads do not provide identification tools as such, the web-page developed for Sapotaceae of the Sangha Trinational was not *tested* in direct comparison with the above tools. Testers were simply asked to view and comment on its content. Most were impressed with its facility to include in particular, much background information, including taxon descriptions, imagery, bibliography and location of existing specimens.

##### 5.4.1 Merits and Limitations of Scratchpad

Relatively few tester comments beyond the above were made. However, in use a number of quite serious practical technical difficulties and limitations in page development were experienced. These included:

- i) The templates provided for data input are quite rigid and inflexible, in some sections there is a limitation as to what can be included.
- ii) Uploaded images are simply cropped to fit existing an existing template, rather than being re-scaled.
- iii) Loaded images can be viewed at multiple page locations, but only viewed in higher detail (by zooming in) at one particular location, which is not intuitively obvious (under the images tab in the specimens table).
- iv) As with Lucid, Scratchpads often uses *alternative* terminology, that is not intuitive to new developers.



## 5.5 Lessons Learned

Whilst traditional dichotomous keys are most familiar to potential users, their construction can be difficult for groups in which the available character states are highly variable and subjective, both between and within taxa. Such keys can be difficult for the user, who is not privy to the insights of the creator. Indeed, it has been stated that; *'keys are compiled by those who do not need them for those who cannot use them'* (Lobanov, 2003). In the current study, it became obvious that the use of simple single-character state couplets (particularly, in the construction of a key to genera) was impossible. In this regard, an optimum solution to the creation of a dichotomous key was found only after careful consideration of a completed character matrix, and the *combination* of multiple characters in the construction of complex couplets, such that developed in couplet 1 of the key to genera (**Table 5.1**). This complexity, required very careful attention to the use of language and grammar to avoid confusion, and feedback from testers to identify potential user difficulties. Additionally, the feedback process provided insight into the need to avoid the use of single, sometimes subjective character states, in order to avoid creating impassible user 'dead-ends' in the key. In delivery of the dichotomous key, all users found photographs evidently helpful for identification. As stated by Walter and Winterton (2007); *"if a picture is worth 10,000 words, then a pair of contrasting characters states is worth more"*. In the current study, the Key Cards were found to be generally the most useful format for the delivery of a dichotomous key tool. As they combine the image and ability to demonstrate character states clearly and therefore provide the most useful identification tool.

Interactive, multiple-access keys that can now be created relatively easily with freely available software, such as Lucid, offer a distinct advantage in actual use, since they avoid the 'bottleneck' of uncertainty about any specific character. They can also be programmed to aid the user, by use of already inputted information to prompt answers regarding features that are most likely to enable a successful identification to be made. Additionally, screen-based imagery has greater utility than printed images, in that zooming into the image to enlarge its detail is possible. The only minor limitation to the use of such software, is initial unfamiliarity of the system on the part of both key developers and users.

## 6. General Discussion

The greatly improved technical possibilities of the computer age offer many new opportunities for the development of taxonomic identification tools, and recording and archiving systems. In many senses, however, the basic requirements of the non-specialist users of identification tools remain unchanged. The fundamental processes of tool construction remain essentially the same, and the first step in the process is the assembly of character state details for the taxa in question. In the current study, this was not an easy process since the basic material studied (herbarium specimens of the family Sapotaceae) comprised almost entirely vegetative material. This limited the choice of characters that could be used in the construction of a character matrix to vegetative features. Many vegetative features that might have been useful in the identification of live specimens, such as the presence of leaf glands, and natural leaf colour, cuticular texture and pubescence of the leaf surface, and in this particular group of plants, the presence and colour of latex secretions, were not useable. It was therefore necessary to use basic leaf morphology characters, such as leaf-shape, venation pattern and to some extent, surviving pubescence characters.

### 6.1 Character State Issues

As in any taxonomic study, the use of essentially subjective character states describing for example, the form of a leaf or pattern of leaf venation, created difficulties even when descriptions were accompanied by images. In describing character states, it is best to avoid the 'invention' of new terminology, and as far as possible to use non-jargon, well recognised terms within botany. Even with the use of such vocabulary, however, particular issues were encountered in the following instances:

#### *Stipules*

The presence or absence of stipules proved to be particularly problematic, because some taxa possess caducous stipules that are lost during early stages of leaf development. This caused the greatest problems for testers of the initial key to genera. The issue was addressed by revising the key's structure to avoid/minimise dependency on this character.

### *Leaf Acumen*

Defining the form of the leaf acumen in the studied specimens proved difficult, largely because of a high degree of variation, often between leaves on the same specimen. However, clear overall differences (ignoring major variations between individual leaves) did exist between the taxa studied. Essentially, six acumen character states could be recognised and supported by accompanying imagery. These were; absent, very small, large sub-triangular (length approximately equal to basal width), elongate sub-triangular (length 2-3 times basal width), very elongate sub-triangular (length at least 4 times basal width); and elongate parallel-sided, with emarginate tip. An alternative approach to describing the form of the leaf acumen, would have been to determine the mean ratio of acumen length:leaf length, and the ratio of acumen length:basal acumen width. Such ratios of linear dimensions are independent of leaf size, which can be highly variable for environmental reasons, and so offer a more quantitative means of defining ‘*shape*’.

### *Tertiary Venation*

This character was found to be particularly variable within species and within specimens, and also between leaves of different age. In addition, the inner basal and apical and marginal parts of the same leaf often showed a different venation pattern. The potential problems were minimised by specifying the venation pattern in the basal half of the leaf, and by careful choice of imagery to illustrate the character state.

### *Pubescence*

The use of pubescence characteristics was greatly limited in herbarium specimens, due to poor visibility of this character in standard herbarium images. This limited the potential usefulness of leaf pubescence in the keys.

## 6.2 Illustration of Character States

Some of the characters chosen, particularly leaf shape, were relatively easy to illustrate using un-manipulated digital images. The intended enhancement of venation characters to improve definition proved rather difficult in practice, and was only really successful in converting secondary venation patterns into simple black and white line illustrations. This was probably better than the use of line drawings, in that if only half of the leaf was so manipulated, the resulting image could clearly assist the user in recognising the appropriate pattern on the un-

manipulated half of the leaf. Image manipulation to illustrate tertiary venation patterns was less successful and offered no real advantage over an un-manipulated photograph. This was not necessarily because of limitations in the capabilities of the image-manipulation software used (in this case Adobe Photoshop). Such software can be extremely effective in image enhancement, but this requires considerable experience in using the software. A major conclusion of the project must therefore be that a mixture of traditional line drawings and un-manipulated photographic images is probably the optimal approach if this software experience is not available. The full potential of digital photographic manipulation can only be fully realised if explicit training in the use of appropriate image manipulation software can be provided. Furthermore, such training probably needs to be customised to the needs of the taxonomic group of interest.

In practice, the imagery provided to support use of keys was generally well-received by testers. However, it was found to be a more useful support to the keys for particular genera, when species specific images were used. When used to accompany the key to genera, testers commented on the potential confusion created by the use of ‘generic’ images that were not necessarily those of the taxon to hand. In this case, generic hand drawings of character states that were not related to any particular taxon would have probably been more useful.

### 6.3 Construction of Dichotomous Keys

The basic issues involved in the development of dichotomous keys are essentially the same, no matter what the taxonomic group of interest. Walter & Winterton’s (2007) paper focuses specifically on insect identification, but never-the-less provides extremely useful guidelines for best practice in the construction of dichotomous keys; **Table 6. 1** is reproduced from this paper. Walter & Winterton’s first guideline, is to avoid the temptation to ‘showcase’ a phylogeny, and not lose sight of the fact that a key is primarily a tool to aid the identification of taxa. Avoiding use of single ambiguous characters, likely to create ‘*dead ends*’ for the user, is also wise. In the construction of dichotomous keys in the current project, many of the leaf characters available were quite variable within taxa, and sometimes variable within the same specimen. This frequently forced the use of *combinations* of characters in couplets, which reduces reliance on features that may be missing, and the possibility that variant forms in the specimen might cause errors.

**Table 6. 1:** Best practices in the construction of dichotomous keys reproduced from Walter & Winterton (2007)

Practice	Rationale
1. Avoid the syntopic pitfall: Keys are for identification, not phylogenetic display.	A key allows the end user to quickly and accurately identify a specimen, not to showcase a phylogenetic hypothesis or a taxonomy. Apomorphies are not necessarily the best characters for identification
2. Avoid the unanswerable couplet: Monothetic couplets are weak.	If a couplet is based around a single character, and that character is obscured on a specimen or lost, then the usefulness of the key ends
3. Remember your end user: Clear, unambiguous characters and limited jargon result in more correct identification.	Couplets with overlapping continuous characters, subtle differences, or exceptions are likely to lead to mistakes. Even specialists use special terms in different ways: Clear descriptive language is better.
4. Construct leads as parallel sets of contrasting characters.	Couplets that use different sets of characters in their leads are likely to seem vague and confusing to a novice.
5. Illustrate contrasting character states and group contrasting character state images together on the same plate.	If “a picture is worth 10,000 words” then a pair of contrasting character state pictures is worth even more.
6. Put illustrations near relevant key couplets.	It is easy to lose one’s place in a dichotomous key.
7. Provide a way out of a dead end; Give links to previous couplets or other means of keeping on the path.	Backtracking is normal during keying and getting lost in a large key is easy.
8. Write couplets that evenly divide the remaining taxa. Fan-shaped keys require fewer steps than comb-shaped keys; the larger the number of taxa in a key, the greater the difference.	The fewer the number of choices an end user must make, the less likely he or she is to make a mistake and the more rapidly he or she is likely to come to a correct identification.
9. Provide comparative diagnoses for end point taxa in keys so that a user may be confident in their determination	Anyone can end up at the end point of a pathway key – but the result should be checked against a description and/or image.
10. Beta-test your key with naïve users before publishing.	We always get the right answer with our own keys, no matter how bad the keys are.

The process of identifying the most appropriate combinations of least-variable characters was greatly aided by the assembled character matrix; the rows of which could be easily rearranged in a spreadsheet to group taxa with similar character combinations. In addition to helping find the most effective path for development of the dichotomous key, the process of re-arranging the character matrix also provided a means to support its use. The re-grouped

character matrices were therefore added to the Key Cards tool. By marking character matrix cards with sequential key couplet numbers, they provide a secondary means to view and even use the key structure. This is not a conventional means to present a dichotomous key to users, and so was probably not fully appreciated by testers. Never-the-less with greater familiarity, this innovation could help key users in better appreciating a key's overall structure and character selection. Ultimately, this could aid users in their knowledge with the plant group involved. Additionally, the Key Card character matrices were useful as a means to check the final identification using the full character set information provided for each taxon. This essentially meets Walter & Winterton's ninth guideline (**Table 6. 1** above), to provide the key user with a means to check and be confident in their determination.

#### 6. 4 Advantages of Lucid and Online Delivery of Resources

The multi-access approach of Lucid Professional offers much greater flexibility in key construction, which may be used to better deal with uncertainty over character states and so aid the user in making the correct identification. Using this system, it would have been possible to address some of the character state issues described in section 6.1 (above). For example, the question of leaf acumen form could have been addressed by creating a hierarchy of nested acumen character states, and scoring these to indicated their degree of reliability. In actual use, testers of the developed identification tools certainly better appreciated the Lucid key, in preference to either of the created dichotomous key tools. Probably the greatest advantage of the Lucid key for testers, was the fact that it avoided the potential road block of '*dead end*' or '*weakest link*' couplets that can occur in use of dichotomous keys. Additionally, the images created as a basic building block for tool construction were much more effective when used as on-screen images in the Lucid application. In Lucid, image detail can be increased by magnifying the displayed image. In comparison, printed images are of a fixed size, which is constrained by simple logistics, and especially when incorporated between the lines of key couplets in the Image-based key. Testers considered the latter approach to be the least effective use of imagery. Using Lucid, it was also possible to incorporate into image captions a web address link to the original, very high quality photographs of specimens held on the RBGE Herbarium database.

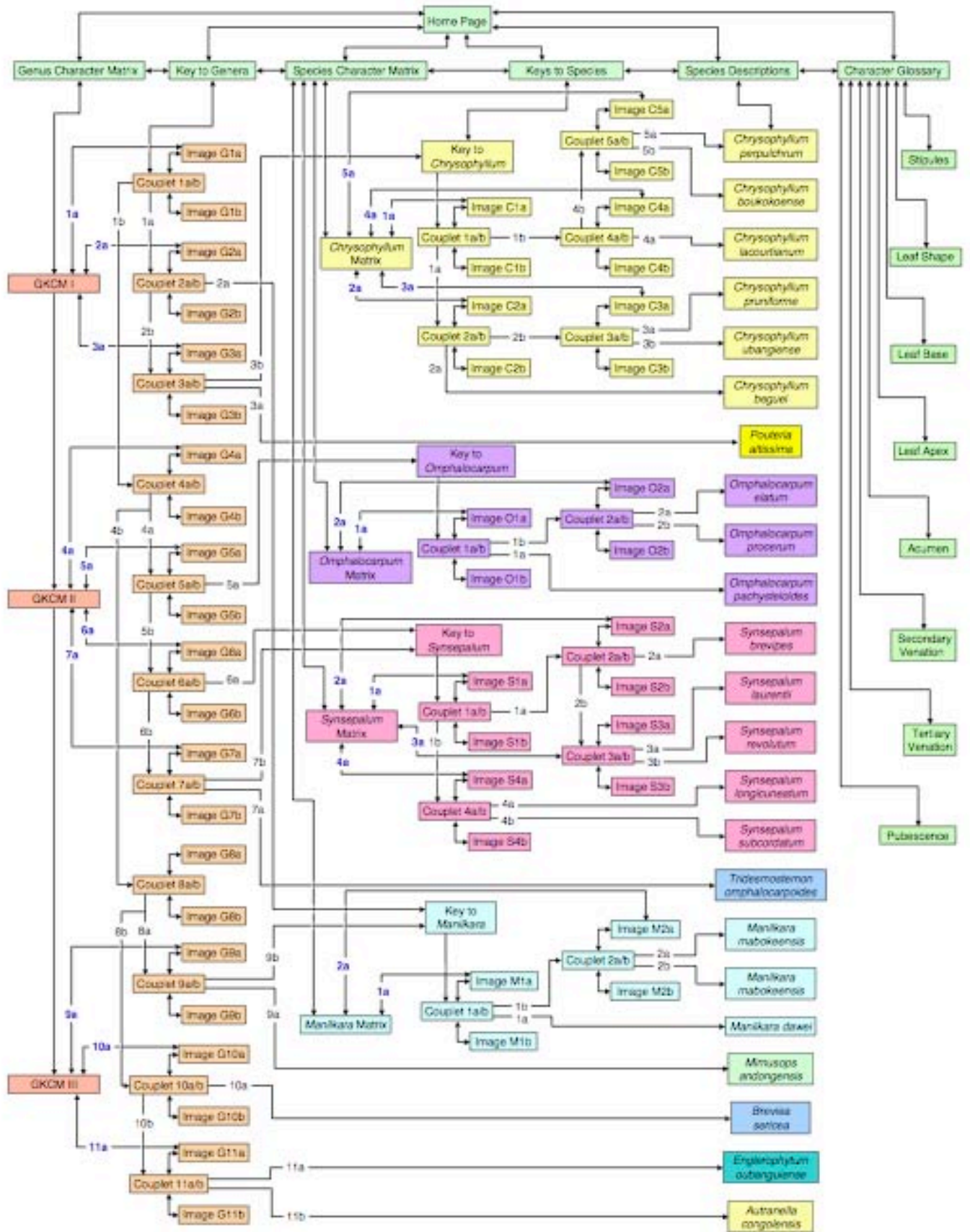
The linking of such taxonomic resources is the single greatest technological advance that has been made possible by computer systems, and particularly by the World Wide Web. Scratchpads provide a good example of what is possible. In the current study, formal descriptions of the studied taxa, collection details and images of all studied specimens, and details of relevant literature were uploaded to a Scratchpad site. A total of 115 specimens were included in the study, so this collectively represented a relatively large amount of information that would have been prohibitively expensive to provide by any other means. It is also intended to create a link from the Scratchpad site to the Lucid key. Such integration possibilities are the real forte of computerised taxonomy. Further advances in the capabilities of personal computers, and development of the almost unlimited data storage capacity promised by ‘cloud’ technology will further enhance these possibilities (Vouk, 2008).

#### 6.5 The Potential Use of Tablet Technology

On the immediate horizon, the most obvious potential new vehicle for the delivery of novel taxonomic tools is ‘tablet technology’. Apple computers currently have the most successful of these new and highly portable web-access tools, the iPad. However, numerous alternatives are quickly transforming the market for such devices, and their memory and operational capacities are continually improving. In theory, it would be perfectly possible to create and deliver taxonomic keys as applications for use on these platforms. Apple computers (2012) are actively encouraging the use of the iPad as the preferred means of delivering third-level educational resources in the US, by making freely available the *iOS Developer University Program* tool for building applications (‘apps’). This software is available at:

<https://developer.apple.com/programs/ios/university/>

The basic building blocks created in the current project are ideally suited to the creation of an interactive key using this software. The process would begin with the construction of a schematic made from the building blocks seen in section 3 for building the application, illustrated in **Fig. 6.1**. Essentially, this illustrates the hypertext links between individual pages of information and other resources such as digital imagery that are built into the application.



**Fig. 6.1:** Schematic for the construction of an iPad application using the basic building blocks for an identification tool created in the current project. Blue numbers signify links between couplet pages with hypertext links to appropriate images, and arrows to links to other project resources, such as character matrices, glossary and species description pages.



## 6.6 Recommendations for the Development of User-Friendly Tools

- 1) The process of tool building starts with the development of a character matrix. This is the foundation of all subsequent work and should be done carefully with considerable specialist knowledge, ensuring that character state descriptions are clear and do not use ambiguous terminology. The assembled spreadsheet of character matrix data can subsequently be re-arranged to identify the most appropriate characters for the pathway of a dichotomous key.
- 2) When constructing dichotomous keys, it is important to avoid the potential pitfalls of using single characters in couplets that are unreliable, or likely to be mis-interpreted by the user of the key. This is best achieved by using combinations of characters that are as clear and unambiguous as possible. It is also useful to remember that keys are primarily a tool for taxon identification; to this end, it is not necessarily a requirement that phylogenetic relationships are incorporated into the key's structure, although it can be a useful identification tool for surrounding geographical regions with a similar flora.
- 3) Images illustrating the character states used in keys are an important aid to the user. High quality digital photographs are an excellent source of such support, but their use is best incorporated into computer-based and on-line delivery systems in which the user can zoom into greater detail within the image. Software for digital image manipulation has great potential for the enhancement of key characters. However, explicit training in the use of such software is likely to be necessary for this to be maximally effective.
- 4) The most effective way to make use of digital images in support of traditional dichotomous keys, is in the form of Key Cards, created with individual pages of illustrated character states.
- 5) In assembling identification tools from the essential building blocks, software that creates multi-access key systems for computer-based or online use, are likely to be even more effective and preferred by users, compared with traditional dichotomous keys tools. This is because greater and more effective use can be made of supporting resources, such as digital imagery, and possibility of linking to an almost unlimited amount of additional information. Multi-access systems also have the advantage that they can be programmed to give greater assistance to the user, e.g. by suggesting the likely next most effective character for a successful determination.

- 6) The greater use of computer-based, online taxonomic tools is primarily limited by their unfamiliarity to many traditional key builders and users; and by the profusion of different systems that now exist without effective standardisation of their structure or user interfaces.
- 7) Tablet technologies, such as the Apple iPad have great potential for the construction of user-friendly plant identification tools, using highly effective software designed for the creation of teaching resources.

In final conclusion, our knowledge of botanical taxonomy since the days of G. Bentham and J. D. Hooker has been massively improved. However, the job of communicating this specialist knowledge in a practical way for the protection and conservation of global biodiversity has never been greater or more important. Fortunately, in the age of computers there has been a revolution in the technologies available to taxonomists to do this job.

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## 8. Appendices

## 8.1 Appendix 1: Herbarium Specimen List

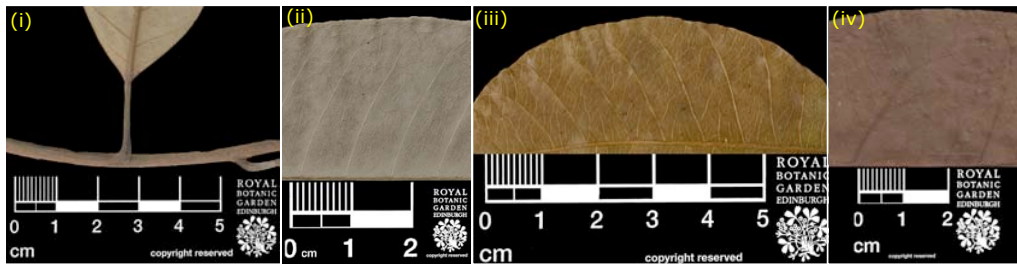
Taxonomic name	Institution code	Barcode Number	Collector(s)	Collection code	Date collected	url to specimen	Location
<i>Aurantiella congolensis</i>	RBGE	E00599584	Fay, J. M. & Harris, David J	8455	20 June 1988	http://data.rbge.org.au/herb/E00599584	Ndakan, gorilla study area
<i>Brevia sericea</i>	RBGE	E00482334	Harris, David J. & Fay, J.M.	503	15 April 1988	http://data.rbge.org.au/herb/E00482334	Ndakan, gorilla study area
<i>Brevia sericea</i>	RBGE	E00482343	Harris, David J.	5285	25 April 1995	http://data.rbge.org.au/herb/E00482343	Likouala
<i>Brevia sericea</i>	RBGE	E00482335	Harris, David J. & Fay, J.M.	1992	6 March 1989	http://data.rbge.org.au/herb/E00482335	Sangha-Mbaere
<i>Brevia sericea</i>	RBGE	E00486321	Harris, David J.	7610	8 May 2001	http://data.rbge.org.au/herb/E00486321	Sangha-Mbaere
<i>Brevia sericea</i>	RBGE	E00599590	Harris, David J.	8164	26 June 2002	http://data.rbge.org.au/herb/E00599590	Nouabal-Ndoki National Park.
<i>Chrysophyllum beguei</i>	RBGE	E00482346	Harris, David J. & Ndolo Ehika, S.T.	9122	6 May 2007	http://data.rbge.org.au/herb/E00482346	Nouabal-Ndoki National Park.
<i>Chrysophyllum boukokoense</i>	RBGE	E00599580	Harris, David J. & Fay, J.M.	1332	5 October 1988	http://data.rbge.org.au/herb/E00599580	Sangha-Mbaere
<i>Chrysophyllum beguei</i>	RBGE	E00599583	Harris, David J.	4741	5 March 1994	http://data.rbge.org.au/herb/E00599583	Sangha-Mbaere
<i>Chrysophyllum beguei</i>	RBGE	E00482336	Harris, David J.	5106	8 June 1994	http://data.rbge.org.au/herb/E00482336	Sangha-Mbaere
<i>Chrysophyllum boukokoense</i>	RBGE	E00482344	Harris, David J.	8136	25 June 2002	http://data.rbge.org.au/herb/E00482344	Nouabal-Ndoki National Park.
<i>Chrysophyllum boukokoense</i>	RBGE	E00599586	Harris, David J.	3447	8 July 1993	http://data.rbge.org.au/herb/E00599586	Sangha-Mbaere
<i>Chrysophyllum boukokoense</i>	RBGE	E00599891	Goldsmith, M.	219		http://data.rbge.org.au/herb/E00599891	Sangha-Mbaere
<i>Chrysophyllum perpulchrum</i>	RBGE	E00290010	Eggleing, W.J.	2089	1 July 1935	http://data.rbge.org.au/herb/E00290010	
<i>Chrysophyllum perpulchrum</i>	RBGE	E00482338	Harris, David J.	8111	24 June 2002	http://data.rbge.org.au/herb/E00482338	Nouabal-Ndoki National Park.
<i>Chrysophyllum perpulchrum</i>	RBGE	E00482337	Carroll, R.W.	1057	15 February 1988	http://data.rbge.org.au/herb/E00482337	Sangha-Mbaere, Bai Hoki Gorilla study area
<i>Chrysophyllum perpulchrum</i>	RBGE	E00482347	Harris, David J. & Fay, J.M.	101	9 January 1988	http://data.rbge.org.au/herb/E00482347	Ndakan, gorilla study area
<i>Chrysophyllum perpulchrum</i>	RBGE	E00599592	Harris, David J., Asonganyi, J.N., Koufani, A. & Onama, J.-M.	5915	16 October 1998	http://data.rbge.org.au/herb/E00599592	Lobeke Reserve.
<i>Chrysophyllum prunifforme</i>	RBGE	E00599594	Harris, David J. & Fay, J.M.	32	30 December 1987	http://data.rbge.org.au/herb/E00599594	West on Sangha river
<i>Chrysophyllum prunifforme</i>	RBGE	E00290011	Klaine, T.J.	283	15 July 1896	http://data.rbge.org.au/herb/E00290011	Gabon
<i>Chrysophyllum prunifforme</i>	RBGE	E00290012	Irvine, F.R.	2152	15 February 1934	http://data.rbge.org.au/herb/E00290012	Ghana
<i>Chrysophyllum prunifforme</i>	RBGE	E00482345	Moukassa, G.	2301	23 January 2007	http://data.rbge.org.au/herb/E00482345	Sangha
<i>Chrysophyllum prunifforme</i>	RBGE	E00599582	Harris, David J.	4241	6 January 1994	http://data.rbge.org.au/herb/E00599582	Sangha-Mbaere, Yandoumbe
<i>Chrysophyllum prunifforme</i>	RBGE	E00599587	Harris, David J. & Fay, J.M.	1822	11 February 1989	http://data.rbge.org.au/herb/E00599587	Sangha-Mbaere
<i>Chrysophyllum prunifforme</i>	RBGE	E00599593	Harris, David J.	4108	20 December 1993	http://data.rbge.org.au/herb/E00599593	Sangha-Mbaere
<i>Chrysophyllum utangense</i>	RBGE	E00482339	Moukassa, G.	617	13 October 2006	http://data.rbge.org.au/herb/E00482339	Sangha
<i>Chrysophyllum utangense</i>	RBGE	E00482342	Harris, David J.	7251	1 December 2000	http://data.rbge.org.au/herb/E00482342	Sangha-Mbaere
<i>Chrysophyllum utangense</i>	RBGE	E00599581	Harris, David J. & Fay, J.M.	50	5 January 1988	http://data.rbge.org.au/herb/E00599581	Ndakan, gorilla study area
<i>Chrysophyllum utangense</i>	RBGE	E00599890	Harris, David J. & Fay, J.M.	831A	2 June 1988	http://data.rbge.org.au/herb/E00599890	Ndakan, gorilla study area
<i>Chrysophyllum utangense</i>	RBGE	E00547225	Fay, J. M. & Harris, David J	8469	24 June 1988	http://data.rbge.org.au/herb/E00547225	Ndakan, gorilla study area
<i>Englerophytum oubangense</i>	RBGE	E00547242	Harris, David J.	4924	23 May 1994	http://data.rbge.org.au/herb/E00547242	Ndakan, gorilla study area
<i>Englerophytum oubangense</i>	RBGE	E00547243	Harris, David J.	5027	1 June 1994	http://data.rbge.org.au/herb/E00547243	Sangha
<i>Englerophytum oubangense</i>	RBGE	E00547257	Harris, David J.	8166	27 June 2002	http://data.rbge.org.au/herb/E00547257	Nouabal-Ndoki National Park.
<i>Englerophytum oubangense</i>	RBGE	E00547256	Harris, David J.	4623	15 February 1994	http://data.rbge.org.au/herb/E00547256	Sangha-Mbaere
<i>Manilkara dawei</i>	RBGE	E00312992	Guignou	2602	30 January 1963	http://data.rbge.org.au/herb/E00312992	Central African Republic
<i>Manilkara dawei</i>	RBGE	E00312996	Letouzey, R.	11630	18 August 1972	http://data.rbge.org.au/herb/E00312996	Cameroun
<i>Manilkara dawei</i>	RBGE	E00547258	Harris, David J.	7707	13 May 2001	http://data.rbge.org.au/herb/E00547258	Sangha-Mbaere
<i>Omphalocarpum pachyscioides</i>	RBGE	E00547222	Nzouam Silaho, F.O.	1956	8 January 2007	http://data.rbge.org.au/herb/E00547222	Sangha
<i>Omphalocarpum pachyscioides</i>	RBGE	E00547221	Harris, David J.	8033	14 June 2002	http://data.rbge.org.au/herb/E00547221	Nouabal-Ndoki National Park.
<i>Omphalocarpum pachyscioides</i>	RBGE	E00547220	Harris, David J.	7111	8 November 2000	http://data.rbge.org.au/herb/E00547220	Sangha-Mbaere
<i>Omphalocarpum pachyscioides</i>	RBGE	E00547219	Harris, David J. & Fay, J.M.	1472	24 October 1988	http://data.rbge.org.au/herb/E00547219	Sangha-Mbaere, Dzanga-Sangha Reserve
<i>Omphalocarpum pachyscioides</i>	RBGE	E00547218	Harris, David J.	5287	25 April 1995	http://data.rbge.org.au/herb/E00547218	Likouala
<i>Omphalocarpum datum</i>	RBGE	E00547270	Fay, J. M. & Harris, David J	8396	30 May 1988	http://data.rbge.org.au/herb/E00547270	Sangha-Mbaere, Ndakan
<i>Omphalocarpum datum</i>	RBGE	E00547212	Harris, David J.	5225	19 April 1995	http://data.rbge.org.au/herb/E00547212	Likouala
<i>Omphalocarpum datum</i>	RBGE	E00547210	Moukassa, G.	1002	28 October 2006	http://data.rbge.org.au/herb/E00547210	Sangha
<i>Omphalocarpum datum</i>	RBGE	E00547209	Nzouam Silaho, F.O.	3109	21 March 2007	http://data.rbge.org.au/herb/E00547209	Nouabal-Ndoki National Park.
<i>Mimuspops andongensis</i>	RBGE	E00547205	Harris, David J. & Fay, J.M.	1450	20 October 1988	http://data.rbge.org.au/herb/E00547205	Sangha-Mbaere, Dzanga-Sangha Reserve
<i>Mimuspops andongensis</i>	RBGE	E00547223	Harris, David J.	4346	29 January 1994	http://data.rbge.org.au/herb/E00547223	Sangha-Mbaere
<i>Mimuspops andongensis</i>	RBGE	E00547247	Harris, David J. Moutsambout, J.-M.	9448	26 June 2007	http://data.rbge.org.au/herb/E00547247	Sangha
<i>Mimuspops andongensis</i>	RBGE	E00547248	Harris, David J. & Fay, J.M.	1050	3 September 1988	http://data.rbge.org.au/herb/E00547248	Sangha
<i>Mimuspops andongensis</i>	RBGE	E00547249	Harris, David J. & Fay, J.M.	880	2 August 1988	http://data.rbge.org.au/herb/E00547249	Ndakan, gorilla study area
<i>Mimuspops andongensis</i>	RBGE	E00547250	Harris, David J. & Fay, J.M.	1533	4 November 1988	http://data.rbge.org.au/herb/E00547250	Kiloua Island
<i>Mimuspops andongensis</i>	RBGE	E00547246	Harris, David J. & Fay, J.M.	1843	12 February 1989	http://data.rbge.org.au/herb/E00547246	Ndakan, gorilla study area
<i>Manilkara mabokensis</i>	RBGE	E00547259	Harris, David J.	7164	11 November 2000	http://data.rbge.org.au/herb/E00547259	Sangha-Mbaere
<i>Manilkara mabokensis</i>	RBGE	E00547260	Harris, David J.	4251	6 January 1994	http://data.rbge.org.au/herb/E00547260	Sangha-Mbaere, Yandoumbe
<i>Manilkara mabokensis</i>	RBGE	E00547261	Harris, David J.	4504	7 February 1994	http://data.rbge.org.au/herb/E00547261	Sangha-Mbaere, Kongana research camp
<i>Manilkara mabokensis</i>	RBGE	E00547263	Harris, David J. & Fay, J.M.	1938	25 February 1989	http://data.rbge.org.au/herb/E00547263	Ndakan, gorilla study area
<i>Manilkara mabokensis</i>	RBGE	E00547264	Carroll, Richard W.	1099	12 March 1988	http://data.rbge.org.au/herb/E00547264	Sangha-Mbaere, Bar Haku



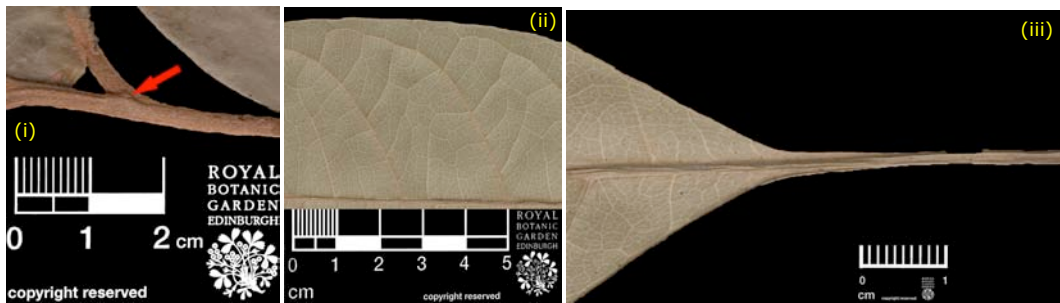
Taxonomic name	Institution code	Barcode Number	Collector(s)	Collection code	Date collected	url to specimen	Location
<i>Manilkara maboceensis</i>	RBGE	E00547265	Harris, David J. & Fay, J.M.	360	24 March 1988	http://data.rbge.org.uk/herb/E00547265	Ndakan, gorilla study area
<i>Manilkara maboceensis</i>	RBGE	E00547266	Harris, David J. & Fay, J.M.	1320	4 October 1988	http://data.rbge.org.uk/herb/E00547266	Ndakan, gorilla study area
<i>Manilkara maboceensis</i>	RBGE	E00547267	Harris, David J. & Fay, J.M.	1481	26 October 1988	http://data.rbge.org.uk/herb/E00547267	Sangha-Mbaere, Dzanga-Sangha Reserve
<i>Manilkara maboceensis</i>	RBGE	E00547268	Harris, David J.	4283	21 January 1994	http://data.rbge.org.uk/herb/E00547268	Sangha-Mbaere
<i>Manilkara maboceensis</i>	RBGE	E00547269	Harris, David J. & Fay, J.M.	932	7 August 1988	http://data.rbge.org.uk/herb/E00547269	Ndakan, gorilla study area
<i>Manilkara maboceensis</i>	RBGE	E00547244	Goldsmith, M.	208	19 May 1995	http://data.rbge.org.uk/herb/E00547244	Sangha-Mbaere, Bai Hoku
<i>Manilkara maboceensis</i>	RBGE	E00547245	Carroll, Richard W.	1004	12 February 1988	http://data.rbge.org.uk/herb/E00547245	Sangha-Mbaere, Bai Hoku
<i>Manilkara maboceensis</i>	RBGE	E00547207	Harris, David J.	5446	13 February 1996	http://data.rbge.org.uk/herb/E00547207	Sangha-Mbaere, Kongana camp
<i>Manilkara maboceensis</i>	RBGE	E00547204	Ndolo Ebika, Sydney Thony	192	20 August 2007	http://data.rbge.org.uk/herb/E00547204	Sangha
<i>Manilkara maboceensis</i>	RBGE	E00547203	Ndolo Ebika, Sydney Thony	191	20 August 2007	http://data.rbge.org.uk/herb/E00547203	Sangha
<i>Manilkara maboceensis</i>	RBGE	E00547202	Ndolo Ebika, Sydney Thony	124	23 June 2007	http://data.rbge.org.uk/herb/E00547202	Sangha
<i>Synsepalum longecuneatum</i>	RBGE	E00547233	Harris, David J.	7168	11 November 2000	http://data.rbge.org.uk/herb/E00547233	Sangha-Mbaere
<i>Synsepalum longecuneatum</i>	RBGE	E00547234	Harris, David J.	5365	1 December 1995	http://data.rbge.org.uk/herb/E00547234	Sangha-Mbaere, Kongana camp
<i>Synsepalum longecuneatum</i>	RBGE	E00547235	Harris, David J.	3992	15 December 1993	http://data.rbge.org.uk/herb/E00547235	Sangha-Mbaere, Kongana camp
<i>Synsepalum longecuneatum</i>	RBGE	E00547236	Harris, David J. & Fay, J.M.	48	4 January 1988	http://data.rbge.org.uk/herb/E00547236	Ndakan, gorilla study area
<i>Synsepalum longecuneatum</i>	RBGE	E00547237	Gentry, A. H. & Harris, David J.	62781	12 May 1988	http://data.rbge.org.uk/herb/E00547237	Sangha-Mbaere, Ndakan
<i>Synsepalum longecuneatum</i>	RBGE	E00547238	Harris, David J.	4400	1 February 1994	http://data.rbge.org.uk/herb/E00547238	Sangha-Mbaere, Kongana research camp
<i>Synsepalum longecuneatum</i>	RBGE	E00547213	Harris, David J. & Fay, J.M.	774	25 May 1988	http://data.rbge.org.uk/herb/E00547213	Ndakan, gorilla study area
<i>Synsepalum laurentii</i>	RBGE	E00547276	Harris, David J. & Fay, J.M.	568	30 April 1988	http://data.rbge.org.uk/herb/E00547276	Sangha
<i>Synsepalum brevipes</i>	RBGE	E00547280	Harris, David J. & Fay, J.M.	1452	20 October 1988	http://data.rbge.org.uk/herb/E00547280	Dzanga-Sangha Reserve
<i>Synsepalum brevipes</i>	RBGE	E00547275	Harris, David J.	7683	12 May 2001	http://data.rbge.org.uk/herb/E00547275	Sangha-Mbaere
<i>Synsepalum brevipes</i>	RBGE	E00217414	Harris, David J., Armstrong, K.E. & Niangadouna, R.	8441	7 May 2005	http://data.rbge.org.uk/herb/E00217414	Rembo Rabi River
<i>Pouteria altissima</i>	RBGE	E00125846	Chapman, J.D. & Chapman E.G.	7715	13 June 1986	http://data.rbge.org.uk/herb/E00125846	Malawi
<i>Pouteria altissima</i>	RBGE	E00547274	Moukassa, G.	548	12 October 2006	http://data.rbge.org.uk/herb/E00547274	Sangha
<i>Pouteria altissima</i>	RBGE	E00547273	Harris, David J. & Fay, J.M.	2002	7 March 1989	http://data.rbge.org.uk/herb/E00547273	Sangha-Mbaere
<i>Pouteria altissima</i>	RBGE	E00547272	Harris, David J. & Fay, J.M.	2014	9 March 1989	http://data.rbge.org.uk/herb/E00547272	Ndakan, gorilla study area
<i>Pouteria altissima</i>	RBGE	E00547271	Harris, David J. & Fay, J.M.	1413	13 October 1988	http://data.rbge.org.uk/herb/E00547271	Ndakan, gorilla study area
<i>Pouteria altissima</i>	RBGE	E00547253	Nzolani Silaho, F.O.	479	6 October 2006	http://data.rbge.org.uk/herb/E00547253	Ndakan, gorilla study area
<i>Pouteria altissima</i>	RBGE	E00547224	Harris, David J., Asonganyi, J.N. & Koufani, A. & Onana, J.-M.	6510	23 November 1998	http://data.rbge.org.uk/herb/E00547224	Kombolo camp
<i>Pouteria altissima</i>	RBGE	E00277617	Egging, W.J.	E. 1183		http://data.rbge.org.uk/herb/E00277617	Uganda
<i>Omphalocarpum procerum</i>	RBGE	E00547251	Nzolani Silaho, F.O.	1186	15 November 2006	http://data.rbge.org.uk/herb/E00547251	Sangha
<i>Omphalocarpum procerum</i>	RBGE	E00547252	Harris, David J.	9327	19 June 2007	http://data.rbge.org.uk/herb/E00547252	Sangha
<i>Omphalocarpum procerum</i>	RBGE	E00547217	Moukassa, G.	448	5 October 2006	http://data.rbge.org.uk/herb/E00547217	Sangha
<i>Omphalocarpum procerum</i>	RBGE	E00547216	Harris, David J.	5333	3 May 1995	http://data.rbge.org.uk/herb/E00547216	Likouala
<i>Omphalocarpum procerum</i>	RBGE	E00547206	Harris, David J. & Fay, J.M.	1399	12 October 1988	http://data.rbge.org.uk/herb/E00547206	Ndakan, gorilla study area
<i>Omphalocarpum procerum</i>	RBGE	E00547214	Harris, David J. & Ndolo Ebika, S.T.	9098	6 May 2007	http://data.rbge.org.uk/herb/E00547214	Nouabal-Ndoki National Park
<i>Omphalocarpum procerum</i>	RBGE	E00547215	Harris, David J. & Fay, J.M.	148	19 January 1988	http://data.rbge.org.uk/herb/E00547215	Ndakan, gorilla study area
<i>Omphalocarpum procerum</i>	RBGE	E00547211	Harris, David J.	5308	1 May 1995	http://data.rbge.org.uk/herb/E00547211	Likouala
<i>Omphalocarpum procerum</i>	RBGE	E00547208	Harris, David J.	4194	23 December 1993	http://data.rbge.org.uk/herb/E00547208	Sangha-Mbaere, Kongana research camp.
<i>Omphalocarpum procerum</i>	RBGE	E00325120	Irvine, Frederick Robert	950	15 April 1928	http://data.rbge.org.uk/herb/E00325120	Agogo
<i>Synsepalum longecuneatum</i>	RBGE	E00547279	Goldsmith, M.	225	9 May 1994	http://data.rbge.org.uk/herb/E00547279	Sangha-Mbaere, Bai Hoku
<i>Synsepalum longecuneatum</i>	RBGE	E00547278	Harris, David J.	4325	28 January 1994	http://data.rbge.org.uk/herb/E00547278	Sangha-Mbaere
<i>Synsepalum longecuneatum</i>	RBGE	E00547277	Harris, David J.	5532	15 May 1996	http://data.rbge.org.uk/herb/E00547277	Sangha-Mbaere, Bai Hoku
<i>Synsepalum longecuneatum</i>	RBGE	E00547254	Harris, David J.	5735	2 January 1998	http://data.rbge.org.uk/herb/E00547254	Sangha-Mbaere
<i>Synsepalum subcordatum</i>	RBGE	E00547241	Harris, David J.	8939	21 February 2007	http://data.rbge.org.uk/herb/E00547241	Sangha
<i>Synsepalum subcordatum</i>	RBGE	E00547240	Harris, David J.	3562	21 October 1993	http://data.rbge.org.uk/herb/E00547240	Sangha-Mbaere, Dzangha camp
<i>Synsepalum subcordatum</i>	RBGE	E00547239	Harris, David J.	7562	5 May 2001	http://data.rbge.org.uk/herb/E00547239	Sangha-Mbaere, Madiw
<i>Synsepalum subcordatum</i>	RBGE	E00547255	Harris, David J.	9321	19 June 2007	http://data.rbge.org.uk/herb/E00547255	Sangha
<i>Tridestomonem omphalocaroides</i>	RBGE	E00547232	Harris, David J.	4783	18 March 1994	http://data.rbge.org.uk/herb/E00547232	Sangha-Mbaere
<i>Tridestomonem omphalocaroides</i>	RBGE	E00547231	Harris, David J.	4752	9 March 1994	http://data.rbge.org.uk/herb/E00547231	Sangha-Mbaere, Bayanga
<i>Tridestomonem omphalocaroides</i>	RBGE	E00547230	Harris, David J. & Fay, J.M.	1175	22 September 1988	http://data.rbge.org.uk/herb/E00547230	Ndakan, gorilla study area
<i>Tridestomonem omphalocaroides</i>	RBGE	E00547229	Nzolani Silaho, F.O.	817	23 October 2006	http://data.rbge.org.uk/herb/E00547229	Sangha
<i>Tridestomonem omphalocaroides</i>	RBGE	E00547228	Harris, David J.	4252	6 January 1994	http://data.rbge.org.uk/herb/E00547228	Mbaere
<i>Tridestomonem omphalocaroides</i>	RBGE	E00547227	Harris, David J. & Fay, J.M.	150	19 January 1988	http://data.rbge.org.uk/herb/E00547227	Ndakan, gorilla study area
<i>Tridestomonem omphalocaroides</i>	RBGE	E00547226	Harris, David J. & Fay, J.M.	168	20 January 1988	http://data.rbge.org.uk/herb/E00547226	Ndakan, gorilla study area
<i>Tridestomonem omphalocaroides</i>	RBGE	E00547281	Harris, David J.	3307	6 June 1993	http://data.rbge.org.uk/herb/E00547281	Sangha-Mbaere

8.2 Appendix 2: Image-based Key

KEY TO GENERA



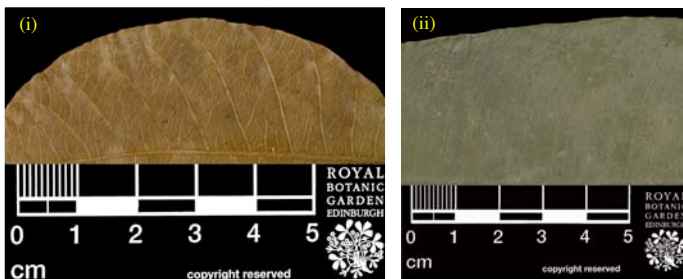
1a Stipules absent (i); tertiary leaf venation running parallel to secondary (ii), scalariform (iii) (linearly linking secondary veins) or looping backwards from the mid-rib to secondaries (iv); leaf base *not* decurrent ..... 2



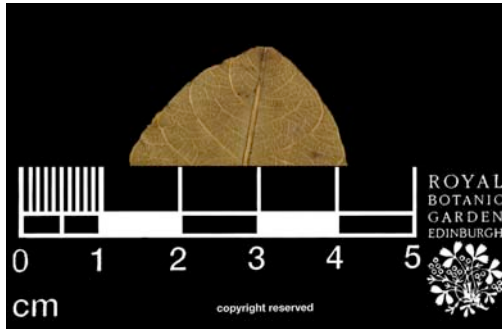
1b Stipules present (i) – or if absent, *either* tertiary leaf venation forming a randomly reticulate pattern (ii) *or* leaf base clearly decurrent (iii)..... 4



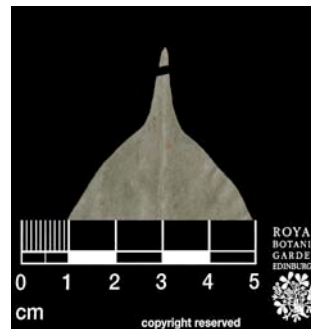
2a Tertiary leaf venation open parallel (easily distinguishable from secondary) ..... *Manilkara*



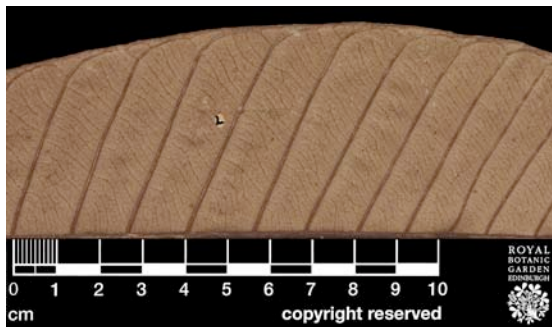
2b Tertiary venation scalariform (i), or compact parallel (ii) and *not* easily distinguishable from secondaries ..... 3



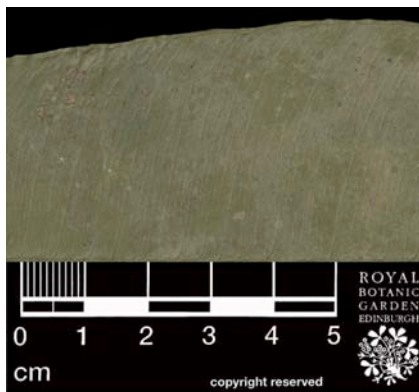
3a Acumen absent ..... *Pouteria*



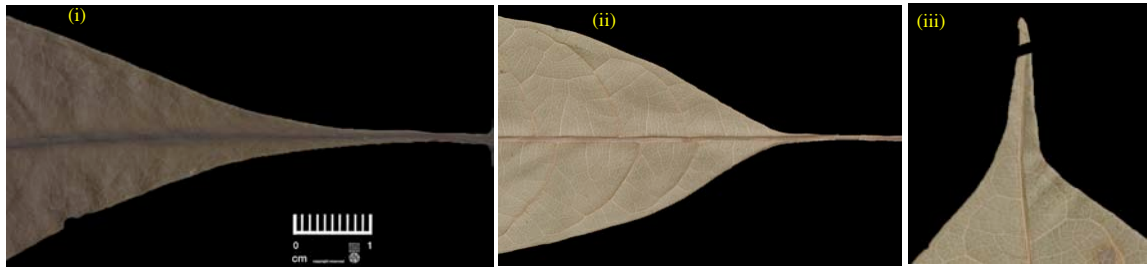
3b Leaf apex with a distinct acumen (extended leaf tip) ..... *Chrysophyllum*



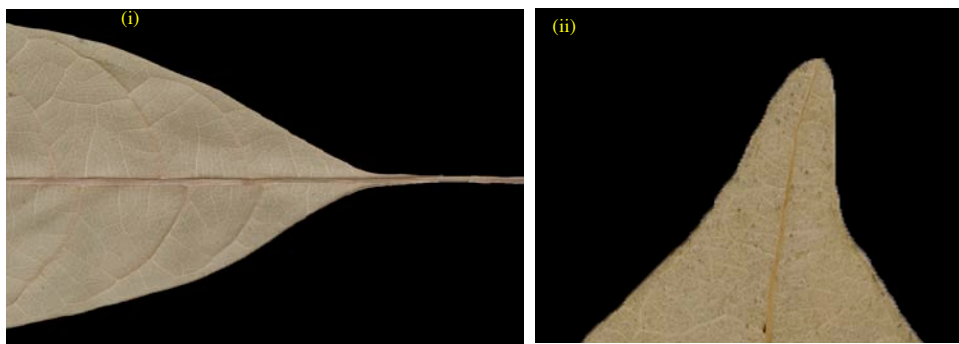
4a Secondary venation widely spaced – more than 10mm apart ..... 5



4b Secondary leaf venation closely spaced – less than 10mm apart ..... 8



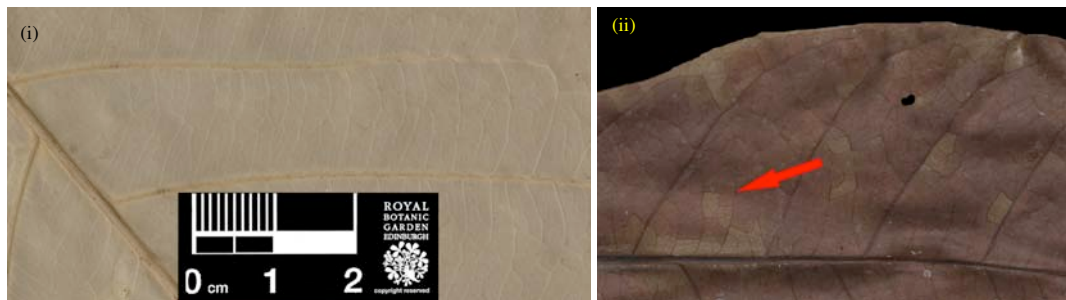
5a Leaf margin tapering from mid point in a straight line to the leaf base (i) or if sinuate (ii), acumen very elongate sub-triangular (iii) ..... Omphalocarpum



5b Leaf margin sinuously curved from mid-point to base (i), acumen never very elongate sub-triangular (ii).. 6



6a Tertiary venation forming random reticulate pattern ..... Synsepalum



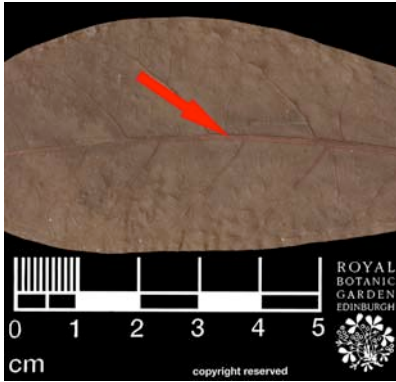
6b Tertiary venation scalariform (i) or looped backwards between mid-rib and secondary (ii) ..... 7



7a Tertiary venation looping backwards ..... *Tridesmostemon*



7b Tertiary venation scalariform ..... *Synsepalum*



8a Centre of mid-rib on abaxial (lower) surface glabrous ..... 9



8b Centre of mid-rib on abaxial (lower) surface with hairs ..... 10



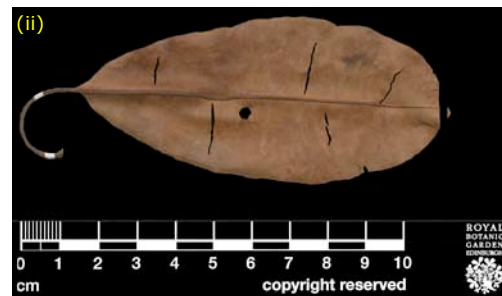
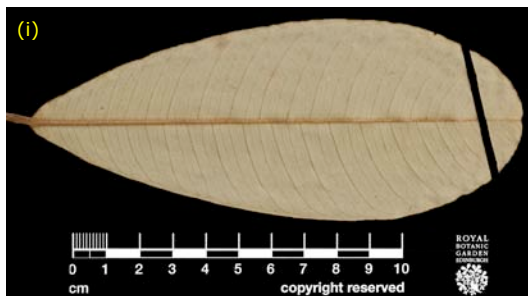
9a Leaf shape strongly elliptic (longitudinally symmetrical and widest at the mid-point) ..... *Mimusops*



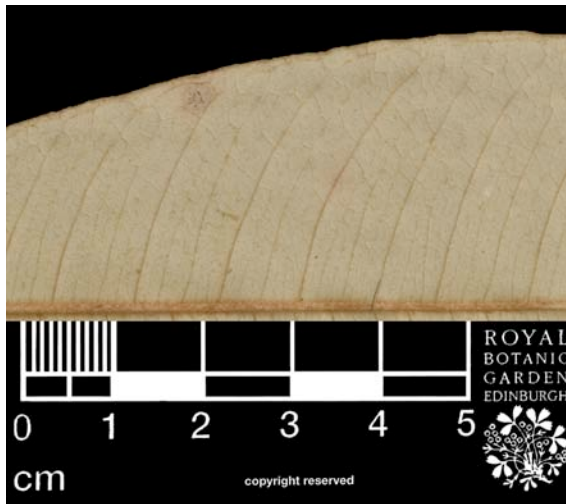
9b Leaf shape either or oblanceolate (i) or obovate (ii) (widest in the apical third and clearly narrowed towards the leaf base) ..... *Manilkara*



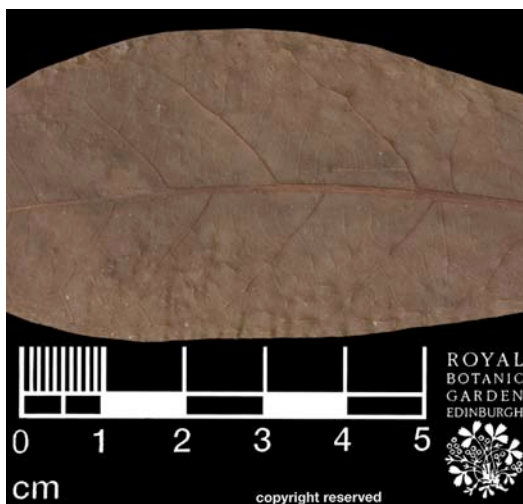
10a Leaf elongate with sub-parallel sides (i) and clearly rounded & cordate base (ii) ..... *Breviaea*



10b Leaf shape either or obovate (i) or oblanceolate (ii) (widest in the apical third and clearly narrowed towards the leaf base) ..... 11



**11a** Abaxial (lower) leaf lamina with red pubescence ..... *Englerophytum*



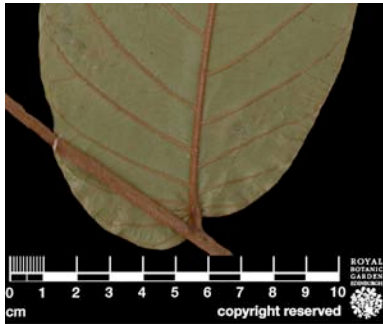
**11b** Abaxial (lower) leaf lamina glabrous ..... *Autranella*

## Taxa list:

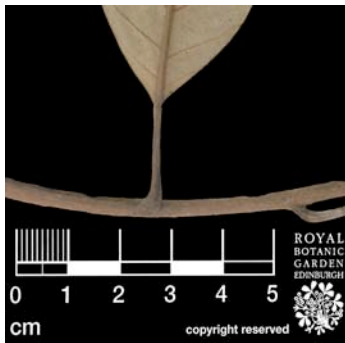
1. <i>Autranella</i>	<i>A. congolensis</i>
2. <i>Breviea</i>	<i>B. sericea</i>
3. <i>Chrysophyllum</i>	<i>C. beguei</i>
	<i>C. boukokoense</i>
	<i>C. lacourtianum</i>
	<i>C. perpulchrum</i>
	<i>C. pruniforme</i>
	<i>C. ubangiense</i>
4. <i>Englerophytum</i>	<i>E. oubanguiense</i>
5. <i>Manilkara</i>	<i>M. dawei</i>
	<i>M. mabokeensis</i>
	<i>M. pellegriniana</i>
6. <i>Mimusops</i>	<i>M. andongensis</i>
7. <i>Omphalocarpum</i>	<i>O. elatum</i>
	<i>O. pachysteloides</i>
	<i>O. procerum</i>
8. <i>Pouteria</i>	<i>P. altissima</i>
9. <i>Synsepalum</i>	<i>S. brevipes</i>
	<i>S. laurentii</i>
	<i>S. longecuneatum</i>
	<i>S. revolutum</i>
	<i>S. subcordatum</i>
10. <i>Tridesmostenom</i>	<i>T. omphalocarpoides</i>



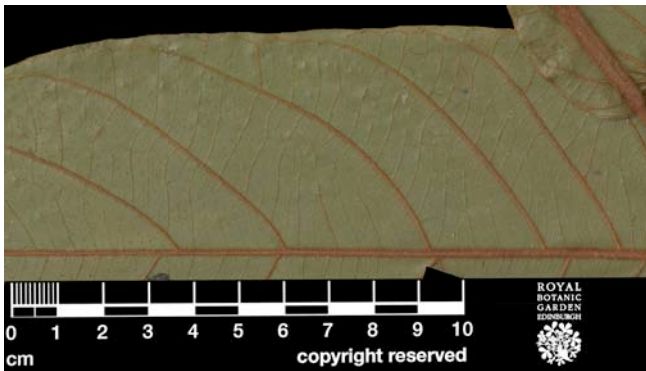
3. *Chrysophyllum*



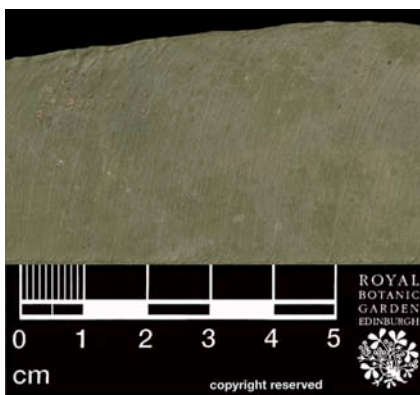
1a Leaf base asymmetric ..... 2



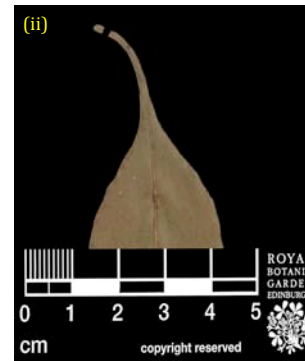
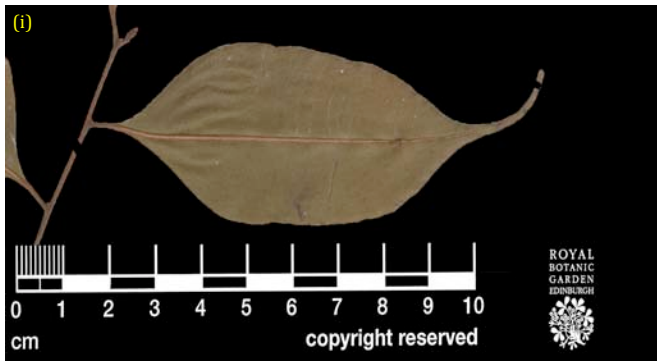
1b Leaf base symmetric ..... 4



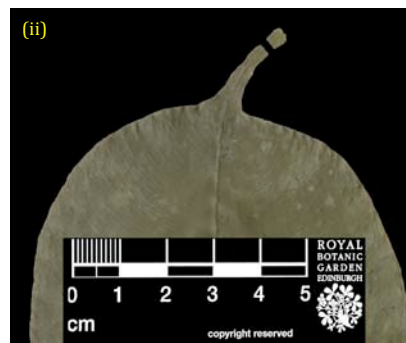
2a Secondary venation widely spaced (>10mm) ..... *C. beguei*



2b Secondary venation closely spaced (<10mm) ..... 3



**3a** Leaf asymmetrically ovate (i), broadest before the mid-point, acumen tapering sub-triangular with pointed tip (ii)..... *C. pruniforme*



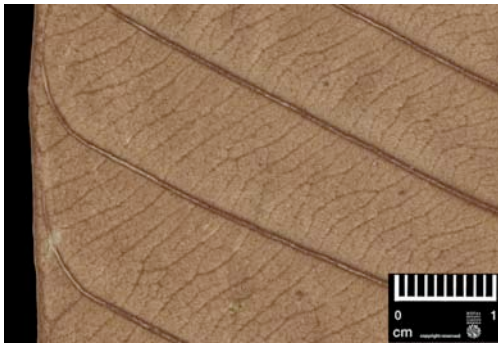
**3b** Leaf obovate, broadest in apical third (i), apical margin broadly rounded, acumen elongate, parallel-sided with blunt emarginated tip (ii) ..... *C. ubangiense*



**4a** Abaxial (lower) leaf lamina glabrous ..... *C. lacourtianum*



**4b** Abaxial (lower) leaf surface with dense pubescence ..... 5



5a Abaxial (lower) pubescence red .....*C. perpulchrum*



5b Abaxial (lower) pubescence white .....*C. boukokoense*

5. *Manilkara*



1a Stipules absent .....*M. dawei*



1b Stipules present ..... 2



**2a** Abaxial leaf surface (lower) with dense white, felt-like pubescences ..... *M. mabokeensis*



**2b** Abaxial leaf surface (lower) glabrous ..... *M. pellegriniana*

*7. Omphalocarpum*



**1a** Acumen very elongate sub-triangular, length  $\geq 4$  times basal width..... *O. pachysteloides*



**1b** Acumen relatively shorter, length only 2-3 times basal width..... 2

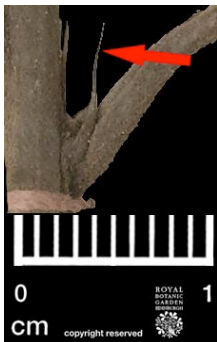


**2a** Leaf-shape oblanceolate (i); in the basal half of the leaf tertiary leaf venation loops backwards from the mid-rib to meet with secondary veins (ii) ..... *O. elatum*

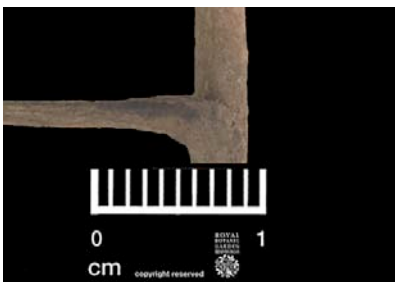


**2b** Leaf-shape obovate (i); in the basal half of the leaf tertiary venation forming a randomly reticulate pattern with quaternary (ii) ..... *O. procerum*

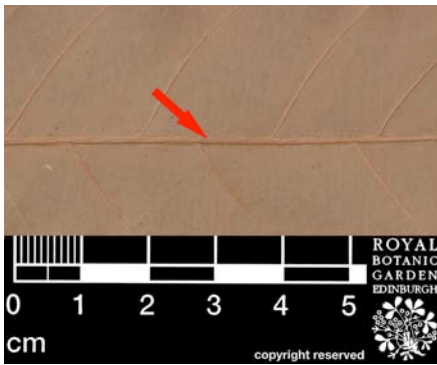
**9. *Synsepalum***



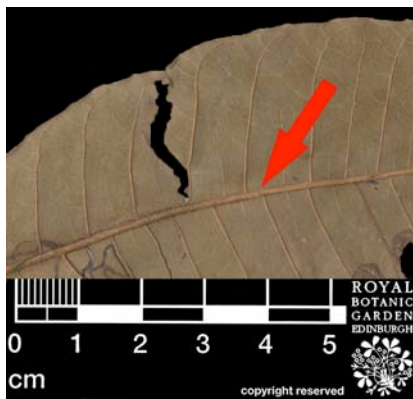
**1a** Stipules present ..... 2



**1b** Stipules absent ..... 4



2a Abaxial mid-rib glabrous ..... *S. brevipes*



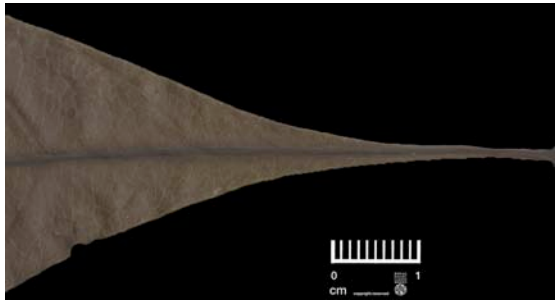
2b Abaxial mid-rib pubescent ..... 3



3a Petiole with felt-like pubescence ..... *S. laurentii*



3b Petiole with hair-like pubescence ..... *S. revolutum*



**4a** Leaf base long-decurrent, distinctly sinuous and narrow ..... *S. longecuneatum*



**4b** Leaf base (sub)cordate (i) or rounded (ii) ..... *S. subcordatum*

## Appendix 3: Key Cards



## Sapotaceae of the Sangha Trinational

## KEY TO GENERA

David A. Purvis (RBGE 2012)

- 1a** Stipules absent; tertiary leaf venation running parallel to secondary, scalariform (linearly linking secondary veins) or looping backwards from the mid-rib to secondaries; leaf base *not* decurrent ..... 2
- 1b** Stipules present – or if absent, *either* tertiary leaf venation forming a randomly reticulate pattern *or* leaf base clearly decurrent ..... 4
- 2a** Tertiary leaf venation open parallel (easily distinguishable from secondary) ..... *Manilkara*
- 2b** Tertiary venation scalariform, or compact parallel and *not* easily distinguishable from secondaries ..... 3
- 3a** Acumen absent ..... *Pouteria*
- 3b** Leaf apex with a distinct acumen (extended leaf tip) ..... *Chrysophyllum*
- 4a** Secondary venation widely spaced – more than 10mm apart ..... 5
- 4b** Secondary leaf venation closely spaced – less than 10mm apart ..... 8
- 5a** Leaf margin tapering from mid point in a straight line to the leaf base or if sinuate, acumen very elongate sub-triangular ..... *Omphalocarpum*
- 5b** Leaf margin sinuously curved from mid-point to base, acumen never very elongate sub-triangular ..... 6
- 6a** Tertiary venation forming random reticulate pattern ..... *Synsepalum*
- 6b** Tertiary venation scalariform or looped backwards between mid-rib and secondary ..... 7
- 7a** Tertiary venation looping backwards ..... *Tridesmostemon*
- 7b** Tertiary venation scalariform ..... *Synsepalum*
- 8a** Centre of mid-rib on abaxial (lower) surface glabrous ..... 9
- 8b** Centre of mid-rib on abaxial (lower) surface with hairs ..... 10
- 9a** Leaf shape strongly elliptic, longitudinally symmetrical and widest at the mid-point ..... *Mimusops*
- 9b** Leaf shape either or obovate or oblanceolate, widest in the apical third and clearly narrowed towards the leaf base ..... *Manilkara*
- 10a** Leaf elongate with sub-parallel sides and clearly rounded & cordate base ..... *Breviea*
- 10b** Leaf obovate/oblanceolate with continuously curved leaf margins and acutely angled base ..... 11
- 11a** Abaxial (lower) leaf lamina with dense red pubescence ..... *Englerophytum*
- 11b** Abaxial (lower) leaf lamina glabrous ..... *Austranella*







## Sapotaceae of the Sangha Trinational

### KEYS FOR GENERA

David A. Purvis (RBGE 2012)

#### *Chrysophyllum*

- 1a** Leaf base asymmetric ..... 2  
**1b** Leaf base symmetric ..... 4
- 2a** Secondary venation widely spaced (>10mm) ..... *C. beguei*  
**2b** Secondary venation closely spaced (<10mm) ..... 3
- 3a** Leaf asymmetrically ovate, broadest below mid-point; leaf mid-rib and petiole pubescent ... *C. pruniforme*  
**3b** Leaf obovate, broadest in apical third; leaf mid-rib and petiole not pubescent ..... *C. ubangiense*
- 4a** Abaxial leaf lamina glabrous ..... *C. lacourtianum*  
**4b** Abaxial leaf surface with dense pubescence ..... 5
- 5a** Abaxial pubescence red ..... *C. perpulchrum*  
**5b** Abaxial pubescence white ..... *C. boukokoense*

#### *Manilkara*

- 1a** Stipules absent ..... *M. dawei*  
**1b** Stipules present ..... 2
- 2a** Abaxial leaf surface with dense white, felt-like pubescens ..... *M. mabokeensis*  
**2b** Abaxial leaf surface glabrous ..... *M. pellegriniana*

#### *Omphalocarpum*

- 1a** Acumen very elongate sub-triangular, length  $\geq 4$  times basal width ..... *O. pachysteloides*  
**1b** Acumen relatively shorter, length only 2-3 times basal width ..... 2
- 2a** Leaf-shape oblanceolate; in the basal half of the leaf tertiary leaf venation loops backwards from the mid-rib to meet with secondary veins ..... *O. elatum*  
**2b** Leaf-shape obovate; in the basal half of the leaf tertiary venation forming randomly reticulate pattern with quaternary ..... *O. procerum*

#### *Synsepalum*

- 1a** Stipules present ..... 2  
**1b** Stipules absent ..... 4
- 2a** Abaxial mid-rib glabrous ..... *S. brevipes*  
**2b** Abaxial mid-rib pubescent ..... 3
- 3a** Petiole with felt-like pubescence ..... *S. laurentii*  
**3b** Petiole with hair-like pubescence ..... *S. revolutum*
- 4a** Leaf base long-decurrent, distinctly sinuous and narrow ..... *S. longecuneatum*  
**4b** Leaf base rounded or sub-cordate ..... *S. subcordatum*





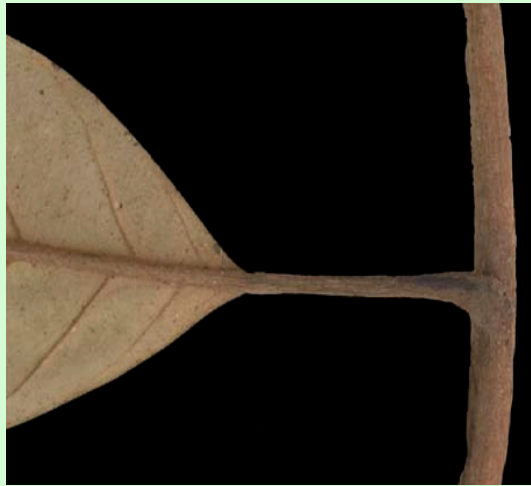
# Sapotaceae of the Sangha Trinational

David A. Purvis (RBGE 2012)

## KEY CHARACTERS

### Stipules

Absent



Present



Images not to same scale

Lines across images are tape holding herbarium specimens, also key features are indicated by red arrows.



# Sapotaceae of the Sangha Trinational

David A. Purvis (RBGE 2012)

## Leaf Shape

Elliptic



Ovate



Obovate



Elongate sides parallel (Oblong)



Oblanceolate



Tapering



Asymmetric



Images not to same scale

Lines across images are tape holding herbarium specimens, also key features are indicated by red arrows.



# Sapotaceae of the Sangha Trinational

## KEY CHARACTERS

David A. Purvis (RBGE 2012)

### Leaf Base

Acute



Rounded



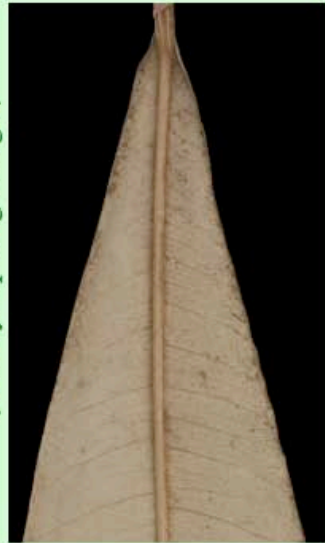
Cordate/Sub-cordate



Asymmetric



Cuneate  
(Acutely tapering straight)



Decurrent



Long-decurrent



Images not to same scale



# Sapotaceae of the Sangha Trinational

David A. Purvis (RBGE 2012)

## KEY CHARACTERS

### Leaf Apex

Acute



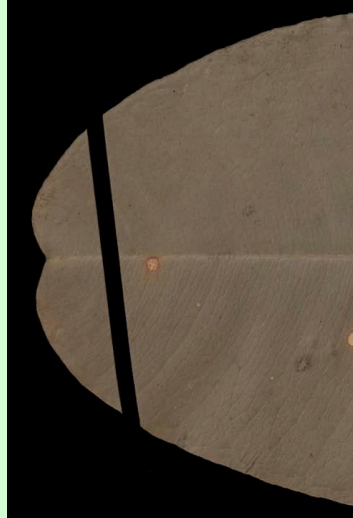
Obtuse



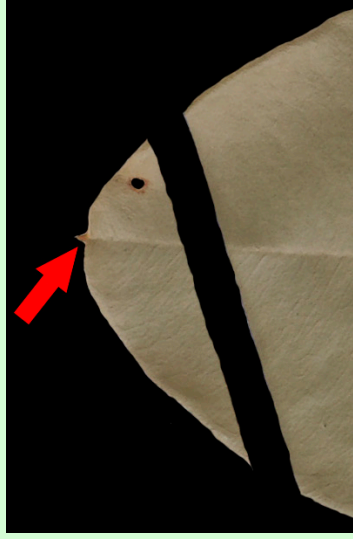
Blunt with shoulders



Emarginate



Mucronate



Broadly rounded



Images not to same scale

Lines across images are tape holding herbarium specimens, also key features are indicated by red arrows.



# Sapotaceae of the Sangha Trinational

## KEY CHARACTERS

David A. Purvis (RBGE 2012)

Leaf Acumen  
Very small

Absent



Elongate (x 2-3)  
sub-triangular

V. elongate (x  $\geq 4$ )  
sub-triangular

Elongate parallel-sided  
tip emarginate



Images not to same scale





# Sapotaceae of the Sangha Trinational

## KEY CHARACTERS

David A. Purvis (RBGE 2012)

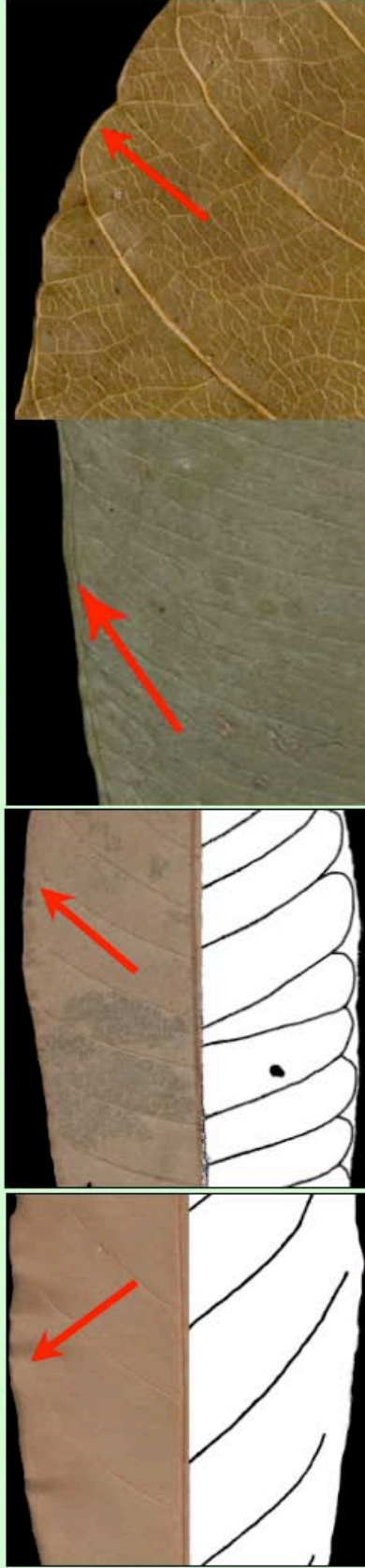
### Secondary Leaf Venation – lower (abaxial) leaf surface

Looped to form marginal vein

Straight/continuous sub-marginal vein

Continuous sub-marginal loops

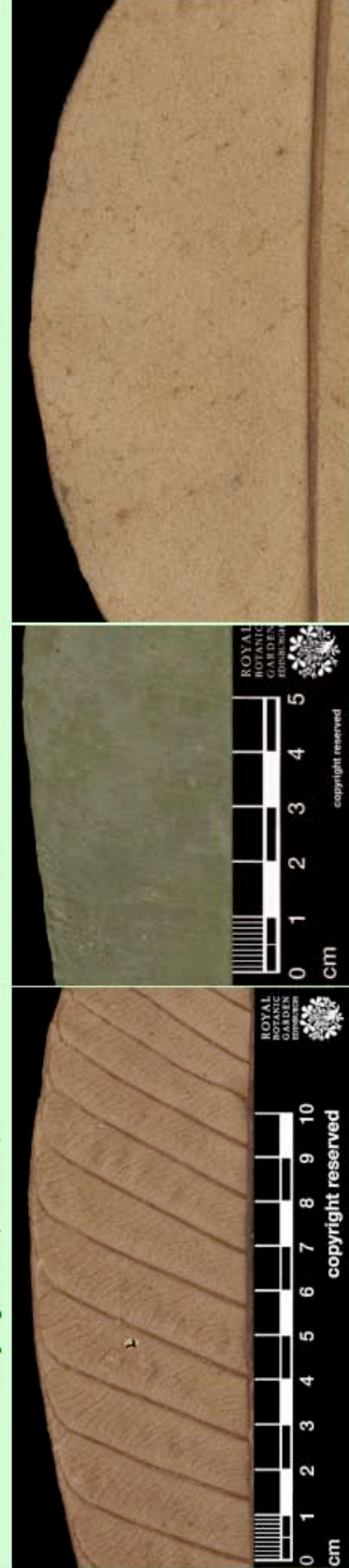
Curved near margin



Widely-spaced (>10mm)

Closely-spaced (<10mm)

Barely visible



Images not to same scale



# Sapotaceae of the Sangha Trinational

## KEY CHARACTERS

David A. Purvis (RBGE 2012)

Images not to same scale

Reticulate



Tertiary Leaf Venation (abaxial, basal leaf half)

Looped backwards from mid-rib to secondary



Scalariform (ladder-like rungs)



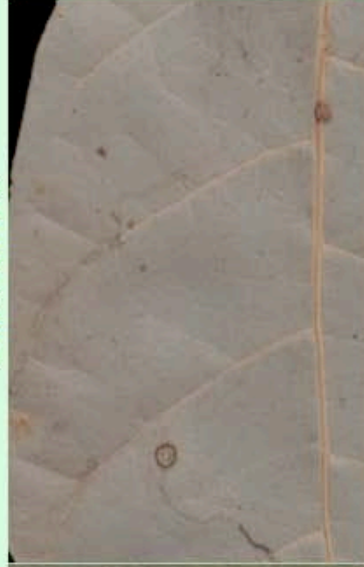
Open parallel



Compact parallel



Impressed on adaxial surface



Indistinct on abaxial surface





# Sapotaceae of the Sangha Trinational

## KEY CHARACTERS

David A. Purvis (RBGE 2012)

### Pubescence (abaxial)

- Lamina glabrous
- Lamina with silvery hairs
- Lamina with white felt-like pubescence
- Lamina with curly dense red hairs
- Lamina with sparse long red hairs



Centre of mid-rib glabrous



Mid-rib pubescent



Petiole with felt-like pubescence



Petiole with long hairs



Images not to same scale