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On the development of a drill-borer for sampling tropical supra-hardwoods; a review of drill- an example using the Borneo Ironwood *Eusideroxylon zwageri*.

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Abstract

One of the greatest challenges to developing time series from non-annual ring forming tropical trees arises before a sampling campaign can begin. Tropical trees can be exceptionally hard, often containing chemicals and minerals which make the wood near non-biodegradable. Such trees have considerable palaeoclimatic potential due to their longevity and landscape survival times, but are challenging to sample non-destructively. The hardest of these trees, the Ironwoods, are often the target of sampling campaigns as their properties are associated with longevity. Our objective was to develop a low-technology drill-borer capable of extracting cores from the Borneo Ironwood (*Eusideroxylon zwageri* Teijsm. and Binn) of a suitable diameter for carrying out stable isotopic analysis and radiocarbon analysis (necessary for chronology development in non-annual ring forming trees). Due to the inaccessibility of tropical sampling field sites our criteria for development included: construction to be from readily available and replaceable parts; power to be derived from batteries; the main body [drill] to be of a weight and size appropriate to sampling in remote locations; a system operable with minimal training by a non-expert. The cores produced by our drill system were of high quality, and samples could successfully be taken from extremely hard trees without charring. The biggest limitation to the operation of our system was that core segments snapped and had to be sequentially removed from the tree and stored separately. This trial is the first successful non-destructive sampling of living *E. zwageri*, a species which has considerable palaeoclimatic potential.

Keywords: tropical dendroclimatology, sampling methods, core drill

Introduction

One of the greatest challenges to developing time series from non-annual ring forming tropical trees arises before a sampling campaign is even at the design stage. Tropical trees can be exceptionally hard (Table 1), often containing chemicals and minerals which make the wood near non-biodegradable and toxic to saprophytes (Dimmitt, 2000). The hardest of these trees, the so-called Ironwoods (Table 2), are often the target of sampling campaigns as their properties are associated with exceptional longevity (Turner, 2001).

Detrimental atmospheric warming is likely to be experienced first in the tropics where small changes in climate could induce considerable biological responses due to the ecosystem's pre-industrially narrow climate bounds (Mora *et al*., 2013). For this reason, and a paucity of long instrumental climate records for the tropics, there has always been a keen drive within dendroclimatology to find ways to develop tree-derived climate time series in the tropics. Despite significant advances in tropical dendroclimatology, further methodological and technical sampling developments are needed in order to establish regional tropical climate reconstructions from tropical areas (Jacoby and D'Arrigo, 1990; Worbes, 2002), particularly the ever-wet regions where trees do not form annual rings. Options for sampling in primary ever-wet rainforest areas across the world's major relevant biomes (Amazonia, central Africa and parts of South East Asia) are now generally reduced to small conservation areas and forest reserves. For this reason, and for reasons associated with respecting conservation efforts, sampling of these supra-hard trees needs to be conservative. Whilst tropical Ironwood, even from strictly protected species, is, unfortunately, available at logging landing yards across the tropics it is the wish of the dendroclimatologist to sample with care and due diligence. Whilst planning a sampling campaign in Sabah, Malaysian Borneo, targeting the long lived Borneo Ironwood (*Eusideroxylon zwageri* Teijsm. and Binn.) we revisited the drill-borer design with the aim of developing an inexpensive, low-tech system, such that it is easy to obtain and replace parts, easy to transport and capable of sampling supra-hard trees.

Background and methodology

Whilst topical forests are known to contain woods of highly varying densities, including very light woods which give the forest ecosystem as a whole an average density distribution of between 0.56-0.62 c cm-3 (Turner, 2001), the tropical lowland rainforest is also the home to the world's densest tropical trees, found particularly in the caesalpinoid subfamily of the legumes. Hardness has many advantages for trees growing in the ever-wet tropics, primarily associated with defence against disease, and has long been associated with slow growth rates, longevity and shade tolerance.

Ironwoods are a key group of hardwood trees; a categorization which encompasses a wide range of species across varying ecological habitats. Over 100 species of trees and shrubs across the world are traded under the name 'Ironwood' (Wahyuni, 2011). Some species of this group with commercial and scientific value are indicated in Table 2. The ecological importance of Ironwoods, as trees with a significant canopy lifetime, is widely documented (Turner, 2001; Whitmore, 1984). Whilst the group is extremely diverse all Ironwood species possess the distinctive mutual characteristics of wood hardness, durability and longevity.

The Borneo Ironwood, *Eusideroxylon zwageri,* locally known as Belian, is a canopy tree found in the lowland Dipterocarp rain forests of eastern and southern Sumatra, Bangka, Belitung, Borneo and the Sulu archipelago and in Palawan in the Philippines. Belian exhibits remarkably high specific gravities of between 0.8 – 1.19 at 15% moisture in mature trees

(Kostermans *et al.,* 1994) (See Table 2).The strong structural defences of Belian, in the form of high wood density (Loehle, 1988) and lignin investment (Wainhouse *et al.,* 1990), in conjunction with decay and pathogen resistance from defensive chemicals (Coley, 1986; Zucker, 1983; Loehle, 1988), contribute significantly to the species' longevity; however, these life strategies appear to reduce the growth rate (Kurokawa *et al.,* 2003) and Belian is far from being the largest of the emergent trees in Borneo's typical lowland Dipterocarp forest.

The hardness and durability of Belian wood also makes it a highly valuable commercial commodity as a building material, however, and thus it has been extensively logged (Peluso, 1992). The species has been listed as 'vulnerable' in the Red List of threatened trees of Indonesia since 1998 (IUCN, 2014) and was once considered to be almost extinct in Sabah. The species is protected by laws restricting logging and export and thus, a non-destructive method of sampling is required for its use in time series construction.

A review of tree drill-borer development

The traditional and most widely applied method of obtaining tree cores is through the use of an incremental borer developed in Germany ca. 1855 by Pressler (Grissino-Mayer, 2003). Incremental borers are used to extract cores from living trees whilst minimising damage to the tree in order to determine age and study ring patterns for dendrochronological purposes, and more recently, to conduct isotopic analysis. The traditional incremental borer was originally designed for softwoods; however, many modifications allowed the development of hardwood borers and dry wood borers (for sampling dry archaeological timbers). Nonetheless, hand borers remain unsuitable for coring supra- hard tropical trees due to their extreme density. For this reason there is a published history of developing drill-borers for sampling tropical trees. However, upon beginning this study the authors discovered a significant hiatus over the last few decades in methodological publications related to drill-borer design for tropical hardwood sampling.

Early designs for mechanised drills were based on two power sources, the electric drill (Steenkamp *et al.,* 1999) and petrol engines (Bowers, 1960; Hall & Bloomberg, 1984); and utilized either the traditional increment borer (Bowers, 1960) attached to a drill, or a drill head of original design (e.g. Steenkamp *et al.,* 1999). Gasoline motors were often weighty and cumbersome and were usually mounted on stands or tracks for stability (e.g. Bowers, 1960). This made them difficult to transport and ineffective at quickly collecting the large sample sizes now required for isotope dendroclimatology, and additional radio carbon dating. In addition, the fast rotation of even the smallest gas engines tended to cause charring of the core which poses a problem for stable isotopic analysis (Echols, 1969). Although electric drills were lighter than their gas-based counterparts, they were often not reversible, which made removing power-driven standard increment borers from trees labour intensive. This is not an issue now, however, due to the reversible function of modern electric and petrol driven drills.

In earlier investigations it was often found that the small diameter of a standard increment borer, in combination with typically high rotation speeds in a drill, resulted in the degradation of cores by high temperature and compression in harder, or dryer, woods (Nicholls & Santer, 1961; Sulc, 1967). The increment borer itself was also often at risk of snapping due to the high friction and torque created by the power-source. Standard increment borers work by essentially compressing the cut wood on either side of the core, rather than expelling it from the borer hole. The borer barrel is effectively ‘screwed’ into the tree, rather than the core being cut from the tree. In very hard trees this method simply cannot work; the forces which would be required to screw the barrel into the trees would break the barrel of the borer.

Generally, for harder woods, a different mode of operation is required whereby a cutting head removes a circle of wood on either side of the core, expelling sawdust out of the borer channel, and leaving the core remaining within the tree, to then be ‘snapped’ free. The critical operational difference in comparison to the ‘compression’ borer is that the drill-borer is repeatedly removed from the tree for sawdust clearance whilst coring. Prestemon (1965) attempted to circumvent the drawbacks of the traditional ‘compression’ method of coring by designing a mechanised increment borer that utilized a modified plug cutterhead which was mounted on a battery powered impact wrench drill. The crucial developments were capping the cutting edges with carbide to increase strength and durability; improving clearance to facilitate the removal of material from around the core and reducing friction; and a multiple reversal coring technique based on frequent withdrawal of the drill to remove sawdust build up around the core. Prestemon (1965) successfully applied their modified drill to Tan Oak (*Lithocarpus densiflorus*), Madrone (*Arbutus menziesii*), and California Live Oak (*Quercus agrifolia*), all of which are classed as dense hardwoods (Cobb *et al.*, 2011), but which bear little comparison to the density of Belian (at up to 1.20g/cm^{-3}; Maharani *et al.*, 2010).

Steenkamp *et al*. (1999; 2008) also utilized a tungsten carbide tipped holecutter to successfully core *Acacia erioloba*, which is of similar density to Belian at 1.07g/cm^{3} (Kromhout, 1975 c.f. Steenkamp, 1999). The multiple reversal technique was also applied which, in addition to cooling the borer with water, was considered to improve the quality of the cores. A significant drawback of Steenkamp’s design, however, was the combined bulk of the stand, drill and generator.

The previous attempts to construct an efficient mechanised drill borer for hardwoods provided a solid base from which to develop a similar method, adapted to the requirements of non-destructively coring supra-hard tropical trees. The wood of *E. zwageri* is too hard and dense to be sampled using traditional hand-powered increment borers, even if attached to power tools; however, the tungsten carbide tipped holecutter offered a promising solution as demonstrated by its use on *A. erioloba* (Steenkamp, 1999). The holecutter needs to be mounted on a light-weight tube long enough to reach the pith of large specimens and designed with flutes to allow trapped air and sawdust to escape for borer hole (see Prestemon, 1965).

We core-sampled Belian at two sites within, and around, the lowland rainforest conservation sites at Danum Valley and Imbak Canyon in Sabah, Malaysian Borneo. Initial borer testing and development was carried out in and around the Danum Valley Conservation Area (4°57´ N, 117°48´ E) and further sampling was carried out in and around the Imbak Canyon

Conservation Area (5°53´ N, 117°05´ E) (Figure 1). Our objective was to develop a low-technology drill-borer capable of extracting cores from Belian of a suitable diameter for carrying out stable isotopic analysis and radiocarbon analysis (necessary for chronology development in these non-annual ring forming trees). Due to the inaccessibility of many tropical sampling field sites our criteria for borer development included:

- construction to be from readily available and readily replaceable parts;
- power to be derived from batteries;
- a weight and size appropriate to sampling in remote locations and sampling under physically strenuous conditions;
- a system operable with minimal training by a non-expert.

Our initial design developments came about as a result of our involvement in an earlier project which sampled *Acacia totalis* in northern Africa (see Andersen and Krzywinski, 2007). Whilst collaborating with colleagues on the ACACIA project they introduced us to their drill borer which, whilst being used to cores trees which are considerably less hard than the Ironwoods we wished to sample, followed some important design rules. A fine balance of multiple factors was considered when choosing the most appropriate power source for our drill borer. First, power-output needed to be sufficient to keep the cuttinghead rotating in the dense wood (at high speed, low torque); on the other hand, it must not be overly powerful so as to pose significant threat of injury to the operator if the drill head became stuck in the tree, or cause charring which would affect isotope data, nor prematurely snap the core. Second, the weight-to-power ratio was evaluated as the remote rainforest location and more time consuming drilling technique necessitated a light, portable system. Finally, the power source needed to last for an entire day of sampling in the field, or to be easily replaceable. Electric drills are lighter than their gas-based counterparts, readily reversible, and have rechargeable batteries of which extras can be used to accommodate extended periods of sampling. A summary of our decision making process with regards to our drill borer design is given (Table 3).

Results

Taking into account the decisions made on the basis of previous research and our sampling requirements (Table 3) we developed a borer system combining a range of elements from the development histories discussed above. Two types of cutting head s were trialled, taking into account previous designs and the specific features of Belian: 19 mm diameter and 550 mm long hole saw with one tungsten carbide cutting tooth (Figure 2a and 2c) and a 19 mm diameter and 54 mm long bimetal hole saw was utilized (Figure 2b and 2d). The carbide hole saw was brazed on to two differing lengths of 19 mm diameter fluted, hollo EN8 steel tube (350 mm and 610 mm, Figure 2a and 2c, respectively) to provide stability and also allow coring to the centre of large diameter trees. The bimetal hole saw head was designed to be interchangeable as it was anticipated to wear down quickly on exceptionally hard woods; thus, a 6100 mm long section of solid EN8 steel pipe was threaded at on the end of the detachable cuttinghead.

When operating drill borers in living trees experience suggests that a guide is necessary. This is because a key component of the process involves the repeated removal of the barrel from the tree, in order to remove sawdust, unlike compression boring whereby the borer barrel is not removed from the trees once coring begins. We initially developed a small guide plate to be attached to the trunk of the tree, prior to sampling. The guide plate was used to ensure that minimal lateral movement of the barrel occurred whilst coring. It also allowed the barrel to be repeatedly removed from the tree (Figure 3). A number of guide modifications were also explored. A more stable guide was developed, after initial testing, which permitted easier removal of saw dust and snapped core sections; however, it has to be mounted on the drill bit first, then screwed to the trunk prior to connecting the drill head to the drill (Figure 3).

In order to ensure portability of our system a commercially available Makita BHP451RFE electric combi drill was used as the power source. The drill was successfully trialled on both dead wood slabs in the laboratory and on living Belian in the field (Figure 4). Core samples of up to ~60cm, with a core diameter of 19mm were sampled using our preferred combination of a Tungsten carbide head, with the guide modification shown in Figure 3A.

Discussion

The cores produced by the drill system were of high quality, and samples could successfully be taken from extremely hard trees without charring (Figure 4). Operating the drill, especially with the longest drill bit attached, was strenuous work and it was necessary to rotate amongst team members. The lengthy time taken to core each tree was worthwhile for the quality and anticipated old-age of the cores collected; however, it requires multiple drill batteries and/or the means to recharge batteries in the field.

The biggest limitation to the operation of our system was that core segments regularly snapped and had to be sequentially removed from the tree and stored separately. This presents an interesting problem with regards to tropical dendroclimatology. As the supra-hard trees we sampled were from the ever wet tropics they contained no rings and, as such, were not intended for dendrochronological dating. This meant that snapped core sections were really unproblematic in terms of analysis. However, extreme care had to be taken with regards to storage of the core sections as the lack of rings meant that determining direction of growth could not always be carried out by eye in the field. Our system was essentially used to take sequential, small, core sections from trees of very large diameter, much in the way that a lake, or ice, core would be removed in sections. In our view adopting methods from the suite of lower resolution proxy sampling systems could be useful in the effort to maximise the potential of non-annual ring forming trees from the ever wet tropics. Our analysis system for the samples taken in Sabah essentially treats the tree cores in the same manner in which a lake sediment or peat core would be treated. The core sections are dated via high resolution radio carbon methods and age depth models developed. This process, in ringless tropical trees, is made considerably easier by the lack of bioturbation and significant growth hiatuses; the assumed 'down-core' age profile is more uniform. Calendar chronologies of individual cores can then be constructed, using novel methods such as 'free-shape age-depth modelling', developed specifically for radio carbon dating ringless trees (Goslar *et al.*, 2009). The unique elements of this modelling approach include balancing fit-quality as a combination of; the fit of the ^{14}C dates to the calibration curve, the smoothness of the age-depth lines produced, and, crucially, the relative tree growth rates. Free-shape modelling utalises an algorithm to search for the most reasonable equilibrium between these three variables in order to give dates which satisfy the radiocarbon calibration process and the most likely tree-growth history, for example allowing for smooth, not abrupt, changes in growth rate (Goslar *et al*., 2009). Following the development of age-depth models, a sampling plan can then be developed for stable carbon and oxygen isotope analysis on the cores. The methods are very similar to the analysis of lower resolution proxies and allow for the investigation of palaeoclimatic potential in ringless tropical tress, accepting certain sampling limitations.

This is the first successful non-destructive sampling of living *E. zwageri*, a species which has considerable palaeoclimatic potential (Loader *et al*, 2011). As such we feel this is an advancement in the area of dendrochronology sampling methods. The specific features of Belian and the sampling conditions in the rainforest were addressed by the drill borer design; it is light, portable, and capable of enduring the super hard wood and produces smooth cores. The only significant problem was the frequently snapping of the core. Further testing with the new guide system to improve stability and maintain clearance between the core and the trunk is anticipated to produce longer cores in the field. The results of this design show clear potential for coring supra-hard tropical wood to advance tropical dendroclimatology.

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Table 1. Comparison of properties between temperate and tropical species (modified from Wiemann & Green, 2007). $\boldsymbol{G_g}$ = specific gravity; $\boldsymbol{H_g}$ = Janka hardness of green wood; $\boldsymbol{H_{12}}$ = Janka hardness of 12% moisture content wood.

Property	**Characteristic**	**Temperate softwood**	**Temperate hardwood**	**Tropical hardwood**
	Number of species	47	71	166
$\boldsymbol{G_g}$	Mean	0.39	0.5	0.56
	Minimum	0.29	0.31	0.15
	Maximum	0.54	0.66	0.92
$\boldsymbol{H_g}$	Mean	1720	3550	4790
	Minimum	1020	1110	530
	Maximum	2620	6960	13570
$\boldsymbol{H_{12}}$	Mean	2470	4620	6020
	Minimum	1420	1550	620
	Maximum	3860	8270	18950

Table 2. Characteristics of ironwoods from a range of locations (after Myers 2009)

Scientific Name	Common Name	Native Country	Specific Gravity	Janka Hardness (N)
Guaiacum officinale	Lignum Vitae	S.E. U.S. & Caribbean	1.37	20410
Piratinera guianensis	Snakewood	South America	1.35	16900
Krugiodendron ferreum	Leadwood	S. Florida and Keys	1.31	16600
Xylia xylocarpa	Burma Ironwood	India Burma	1.29	10210
Schinopsis balansae	Quebracho	Argentina S. America	1.28	19280
Swartzia leiocalycina	Wamara	British Guiana	1.28	16260
Combretum imberbe	Leadwood	Zimbabwe South Africa	1.23	15880
Eusideroxylon zwageri	Belian	Borneo Malaysia	1.20	13433
Tabebuia serratifolia	Pau D'arco	Brazil S. America	1.20	16387
Acacia nigrescens	Knob-thorn	South Africa	1.19	19080
Caesalpinia ferrea	Brazil Ironwood	Brazil S. America	1.15	14240
Olneya tesota	Desert Ironwood	S.W. U.S. Mexico	1.15	14500
Mesua ferrea	Ceylon Ironwood	India/Burma Ceylon	1.12	13110
Diospyros ebenum	Ceylon Ebony	India Ceylon	1.12	14610
Cercocarpus ledifolius	Mountain Mahogany	S.W. U.S. Mexico	1.12	14510
Olea laurifolia	Black Ironwood	South Africa	1.11	14150

Table 3: Decision making with regards to drill borer design

Feature	Requirement	Examples	Decision
Cutting or compression	'Compression' versus 'removal'. In supra hard trees a coring method whereby material is compressed around the core as the borer barrel penetrates the tree can result in levels of friction which break the borer barrel.	Steenkamp *et al.* (1999; 2008)	Cutting head technique used (rather than compression technique)
Drill system	Power output is required to be sufficient to keep the cuttinghead rotating in the dense wood		Low torque high speed (not vice versa)
Diameter of cutter	The small diameter of a standard increment borer can result in the degradation of cores by high temperature and compression in harder. A larger diameter	Nicholls & Santer (1961); Sulc (1967)	Employ a larger 19mm diameter cutter
Cutter head material	The standard steel material of cutter heads was either not capable of penetrating the supra-hard wood or degraded quickly.	Prestemon (1965); Steenkamp *et al.* (1999; 2008)	Cap the cutting edges with Tungsten carbide

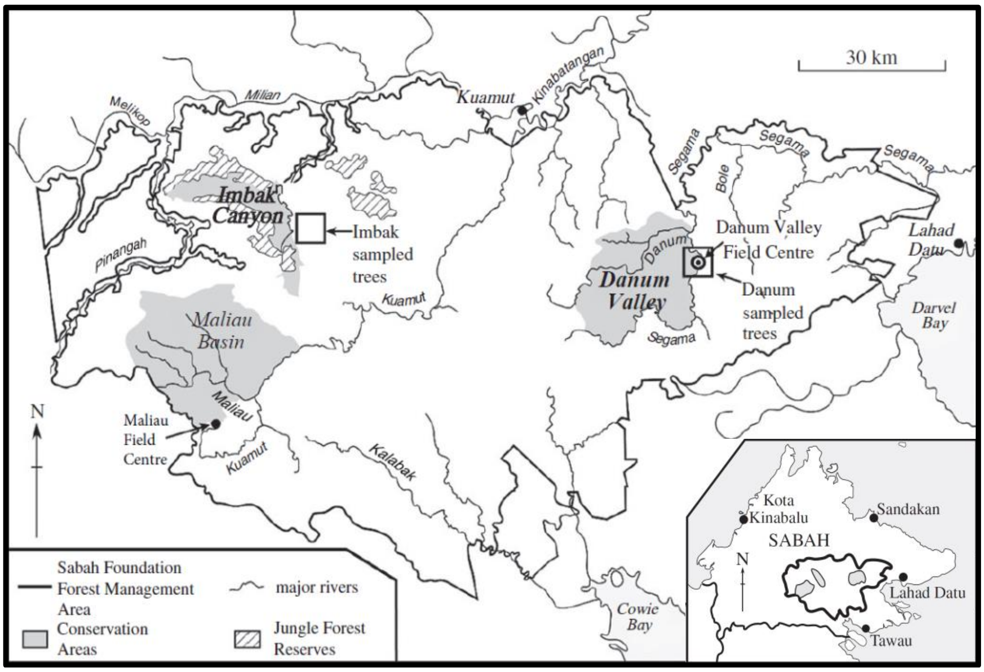
Figure Captions

Figure 1. Area map (Loader *et al*., 2011). The sampling areas within Sabah, north-eastern Borneo are indicated.

Figure 2. Drill bit prototypes. (A) 610 mm long hollowed EN8 steel pipe drill bit with brazed-on 19mm diameter 55mm long hole saw with one tungsten carbide cutting tooth; (B) 280mm long hollowed EN8 steel pipe drill bit with a brazed-on 19mm diameter 55mm long hole saw with one tungsten carbide cutting tooth; (C) 19 mm diameter and 54 mm long bimetal hole saw drill bit brazed onto a 280mm long solid EN8 steel pipe.

Figure 3. Progressive design of the drill bit guide. Two guides are shown. (A) smaller guide plate which can be attached to the trunk of the tree, prior to sampling. Limited lateral movement still occurs. (B) A more stable guide was developed which must be mounted on the drill bit first, then screwed to the trunk prior to connecting the drill head to the drill. There is no lateral movement of the drill-borer using this guide.

Figure 4. Drill-borer sampled cores. Core samples removed from *Eusideroxylon zwageri* (Borneo Ironwood, local name Belian) sampled at Imbak Canyon, Sabah, Borneo. The samples shown were taken using the 19mm diameter tungsten carbide cutting head shown in Figure 3A. Typical breaks in the core samples can be seen.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Danum Valley Field Centre
Danum
Danum Valley
Danum sampled trees
Segama
Lahad Datu
Darvel Bay
Maliau Basin
Maliau
N
Maliau Field Centre
Kuamut
Kalabak
Kota Kinabalu
Sandakan
SABAH
N
Lahad Datu
Tawau
Cowie Bay
Sabah Foundation Forest Management Area
major rivers
Conservation Areas
Jungle Forest Reserves
Figure 1

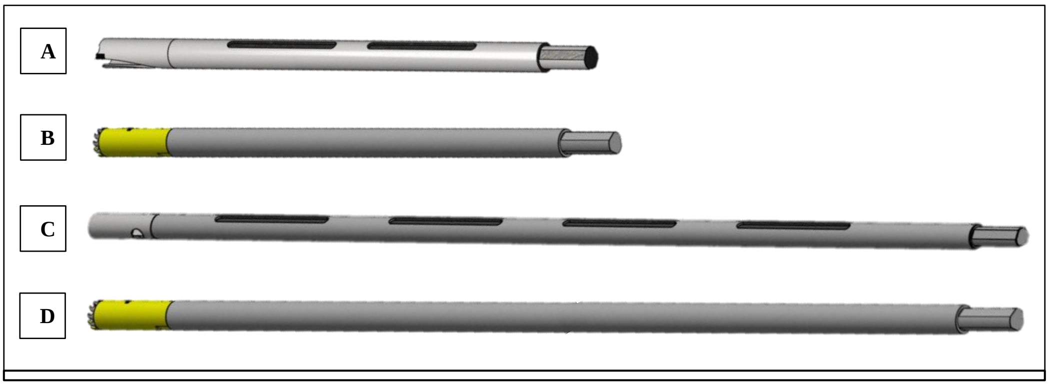

Figure 2.

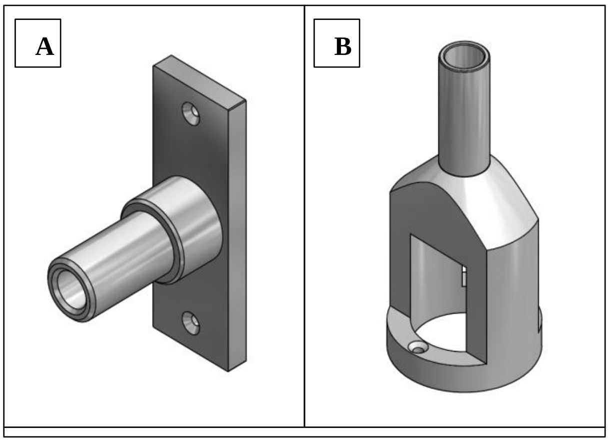

Figure 3.

Figure 4.