treecm: an introduction

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1 Examples

1.1 Plot centre of mass

We will make use of the data set bundled in the package to plot a basic view of masses of branches and logs of a stone pine sampled by the author:

```
> library(treecm)
> data(treeData)
> print(treeData)

$fieldData
```

	azimuth	dBase	dTip	length	tipD	height	tilt	toBePruned	biomass
L1	275	73	41	10.2	2.50	0.00	80	FALSE	1740.88372
L2	275	41	16	3.9	2.75	10.20	80	FALSE	183.92713
B1	190	15	0	NA	7.95	10.10	0	FALSE	119.69839
B2	200	22	0	NA	7.95	10.40	0	FALSE	246.69214
B3	230	15	0	NA	7.95	10.40	0	FALSE	119.69839
B4	200	18	0	NA	7.95	11.15	0	FALSE	168.88783
B5	180	7	0	NA	7.95	11.30	0	FALSE	28.38618
B6	150	6	0	NA	7.95	11.30	0	FALSE	21.21769
B7	340	16	0	NA	3.95	11.30	0	FALSE	135.21104
B8	220	13	0	NA	7.95	11.80	0	FALSE	91.35675
B9	165	19	0	NA	7.95	11.80	0	FALSE	187.04037
B10	280	8	0	NA	3.95	11.90	0	FALSE	36.52644
B11	170	9	0	NA	7.95	11.90	0	FALSE	45.62402
B12	265	8	0	NA	7.95	12.20	0	FALSE	36.52644
B13	75	6	0	NA	3.95	12.20	0	FALSE	21.21769
B14	180	6	0	NA	7.95	12.20	0	FALSE	21.21769
B15	170	6	0	NA	7.95	12.60	0	FALSE	21.21769
B16	120	5	0	NA	7.95	12.60	0	FALSE	15.03793
B17	10	14	0	NA	3.95	13.00	0	FALSE	105.07799
B18	180	13	0	NA	7.95	13.00	0	FALSE	91.35675
B19	260	13	0	NA	7.95	13.20	0	FALSE	91.35675
B20	75	6	0	NA	3.95	13.20	0	FALSE	21.21769

```
B21      75      10      0      NA 3.95  13.75      0      FALSE    55.66636
B22     215       7      0      NA 7.95  13.75      0      FALSE    28.38618
B23     140       7      0      NA 7.95  13.75      0      FALSE    28.38618
C       275      16      0     3.0 3.00  14.10     80      FALSE   135.21104

$density
[1] 620

$allometryFUN
function (x, diameter)
{
    a <- 0.7201
    b <- 1.8882
    powerEquation(a, b, as.real(x[diameter]))
}

$branchesCM
[1] 1
```

This data set has been collected for a 17.1 metres tall stone pine whose stem was tilted approx. 20° from the vertical plane (or 80° from the horizonatal plane). The stem has been sectioned in two logs (L1 and L2), and a final branch (C). The crown was made up of 23 branches (B1-B23), all of them horizontal (ie tilted 0°). The package recognizes rows as branches because their diameter at tip is 0.

Please notice that some rules have to be followed in order to record sound data in the field:

- the diameter of the tip of L1 is equal to the diameter of the base of L2. L2 tip diameter is, in turn, equal to C base diameter. Height figures must match as well as diameter measures

- the distance of the tip of the branch (tipD) is not the length of the branch but the distance between tree base (the origin of the cartesian plot) and branch tip

- note that only the length of C branch has been recorded as it is the only branch not being horizontal. Non horizontal branches affect tree CM z-coordinate. When non-horizontal branches are present, and if one is interested in the z-coordinate of CM, than one should record branch length and its angle from the horizonatl plane (tilt). Otherwise branch length is not needed.

Let's get going and compute the centre of mass of this pine:

```
> vectors <- treeVectors(treeData)
> CM <- centreOfMass(vectors)
> summary(CM)
```

2

```
Coordinates of the centre of mass:
Cartesian (x/m, y/m, z/m): -2.09 , -1.98 , 7.70
Polar (angle/degrees, distance/m, height/m): 226 , 2.88 , 7.70
```

The core of the package is the `summary` method for CM object. The centre of mass for this stone pine lies 2.88 metres South-West of tree base (226° from magnetic North), 7.70 metres above ground. Cartesian coordinates are provided as well, though not so usefull as polar ones.

A simple visualization of tree centre of mass and its logs and branches is achieved simply by:

```
> plot.vectors(vectors, CM = CM, main = "A stone pine centre of mass")
```

A stone pine centre of mass
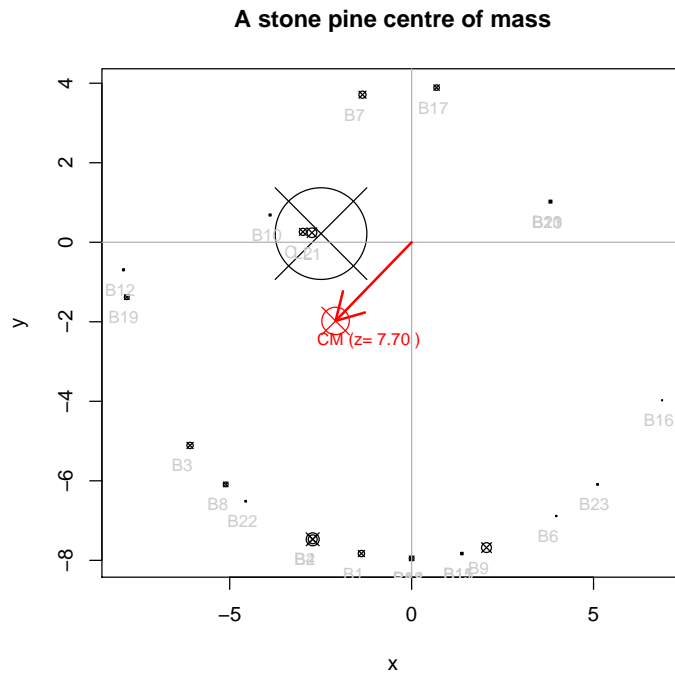
In a cartesian coordinate system whose origin lies at tree base, the masses of logs branches and branches are plotted as vectors pointing inwards, towards the ground. Each circle represent a branch or log mass. Circle radius is proportional to branch or log mass. Likewise, the centre of mass is plotted as a vector pointing inwards, in red colour. Its height component is written alongside its label as z coordinate. A red arrow exemplifies the direction the tree will follow should it break from its base.

If we measured the polar coordinates of the building(s) around the tree we would have plot them alongside the tree using the `plotPolarSegment` function:

3

```
> plot.vectors(vectors, CM = CM, main = "A stone pine centre of mass",
+     xlim = c(-8, 10), ylim = c(-12, 4))
> plotPolarSegment(210, 10.6, 140, 14.4)
```

A stone pine centre of mass
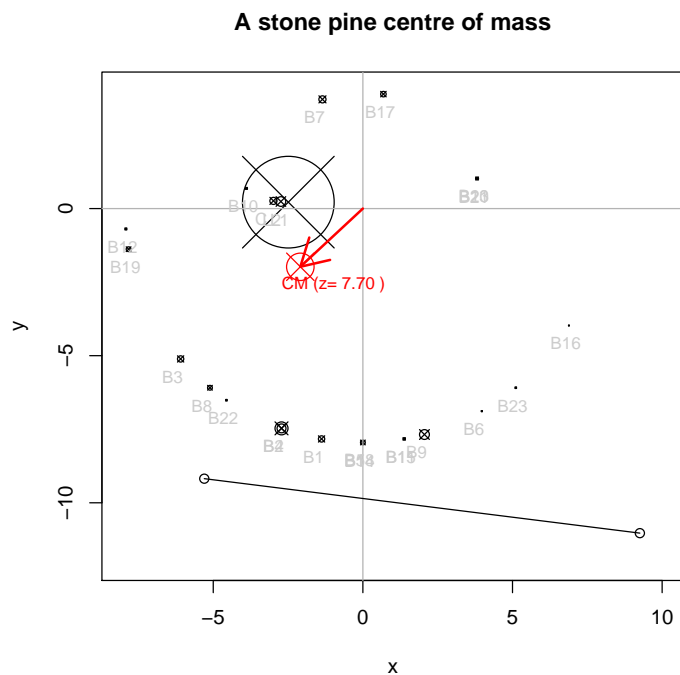
1.2   Snow load

Snow may increase crown load substantially, sometimes breaking entire branches. As a side effect, snow-loaded crowns may alter tree centre of mass by moving it upwards and, in asymmetric crowns, towards the part of crown under heavier load.

Let's model a snow load that doubles the biomass of branches higher than 12 m:

```
> rows <- substr(row.names(treeData$fieldData), 1, 1)
> q1 <- subset(treeData$fieldData, subset = (height < 12 | rows ==
+     "L"))
> q2 <- subset(treeData$fieldData, subset = (height > 12 & rows !=
+     "L"))
> q2$biomass <- q2$biomass * 2
> treeData$fieldData <- rbind(q1, q2)
> rm(list = c("q1", "q2", "rows"))
```

Let's recaltulate the vectors under snow load and plot the results:
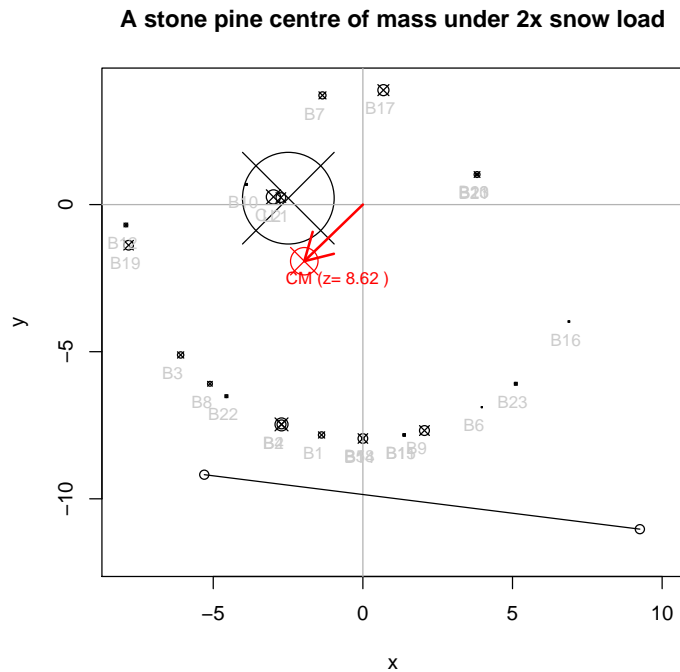
4

```
> vectors <- treeVectors(treeData)
> CM <- centreOfMass(vectors)
> summary(CM)

Coordinates of the centre of mass:
Cartesian (x/m, y/m, z/m): -1.96 , -1.92 , 8.62
Polar (angle/degrees, distance/m, height/m): 225 , 2.74 , 8.62

> plot.vectors(vectors, CM = CM, main = "A stone pine centre of mass under 2x snow load",
+      xlim = c(-8, 10), ylim = c(-12, 4))
> plotPolarSegment(210, 10.6, 140, 14.4)
```

A stone pine centre of mass under 2x snow load

Tree centre of mass has clearly shifted upwards and towards the house...

1.3 Wind load

Winds may increase load on some sectors of the crown and decrease it in other sectors. We would like to model the effect of a prevailing Southbound wind that halves branches mass in the northern sector and doubles it in the southern sector.

```
> data(treeData)
> rows <- substr(row.names(treeData$fieldData), 1, 1)
> treeData$fieldData <- within(treeData$fieldData, {
```

```
+      biomass[((azimuth >= 270 | azimuth < 90) & rows != "L")] <- biomass[((azimuth >=
+          270 | azimuth < 90) & rows != "L")]/2
+      biomass[((azimuth >= 90 | azimuth < 270) & rows != "L")] <- biomass[((azimuth >=
+          90 | azimuth < 270) & rows != "L")] * 2
+ })
> rm(rows)
> vectors <- treeVectors(treeData)
> CM <- centreOfMass(vectors)
> summary(CM)

Coordinates of the centre of mass:
Cartesian (x/m, y/m, z/m): -2.08 , -3.20 , 8.69
Polar (angle/degrees, distance/m, height/m): 213 , 3.82 , 8.69
```

Under a heavy Southbound wind the CM of the tree will move considerably towards South and 1.2 metres farther away from tree base. Although too simplicistic a model the results lead to the conclusion that dynamic forces in prevailing wind conditions should be taken into account when assessing tree stability.

1.4   Effect of pruning

As far as static forces are concerned, in an effort to move centre of mass toward tree base, we could prune a few heavy branches. Let's have a look how CM would move if we cut B2 and B4. We will make use of function `switchBranchPruningStatus`:

```
> library(treecm)
> data(treeData)
> vectors <- treeVectors(treeData)
> CM <- centreOfMass(vectors)
> op <- par(mfrow = c(2, 1), mai = c(0.5, 0.5, 0.5, 0.2))
> plot.vectors(vectors, CM = CM, main = "Centre of mass of a stone pine")
> treeData <- switchBranchPruningStatus(treeData, c(4, 6))
> vectors <- treeVectors(treeData)
> CM <- centreOfMass(vectors)
> plot.vectors(vectors, CM = CM, main = "Centre of mass of a stone pine, B2 and B4 removed")
> par(op)
> rm(op)
```

Centre of mass of a stone pine

Centre of mass of a stone pine, B2 and B4 removed
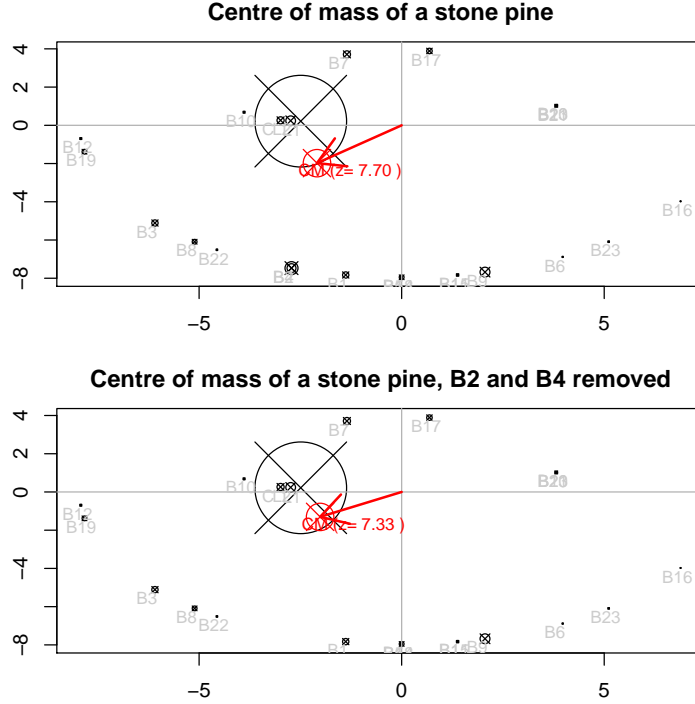
CM has actually moved 0.5 metres towards tree base, and farther away from the house. As a matter of facts, branch pruning has not been a reasonable action towards a safer tree.

1.5   Slenderness coefficient

The slenderness coefficient of a tree is defined as $SC = \frac{h}{d}$ where h is the height of the tree trunk, and d is the diameter of the tree Mattheck et al. (1995). The SC is a measure of tree stability and is extensively used in tree stability measures carried out by Visual Tree Assessment (VTA). SC in the range [30..50] are considered optimal, whereas SC greater than 50 lead to consider the tree at risk of breaking due to its excessive slenderness. The author has applied the same concept to tree branches as well. As the branch starts to deviate from the verticality (as most of the branches do) the arm of the moment gets longer, reaching a maximum limit in horizontal branches. The longer the arm, the higher the stress on the branch. In order to estimate the added stress imposed by branch angle we improved Mattheck's formula by adding a component proportional to branch tilt angle: $SC_c = \frac{h}{d} \cdot (1 + cos\alpha)$

where α is branch tilt angle (i.e. 90° for a vertical branch, 0° for an horizontal branch). When `treeData` object is filled with branches length (not the length of thei projection on the ground, from the tree base to their tip) than SC_c can be computed and plotted:

```
> data(treeData)
> treeData$fieldData$length <- c(10.2, 3.9, 7, 7, 7, 7, 7, 7, 3.95,
+     7, 7, 3.95, 7, 7, 3.95, 7, 7, 7, 3.95, 7, 7, 3.95, 3.95,
+     7, 7, 3)
> vectors <- treeVectors(treeData)
> SC <- treeSC(treeData, vectors)
> plot.SC(SC, main = "Branches coefficient of slenderness", xaxt = "n",
+     yaxt = "n", xlab = "", ylab = "")
```

Branches coefficient of slenderness
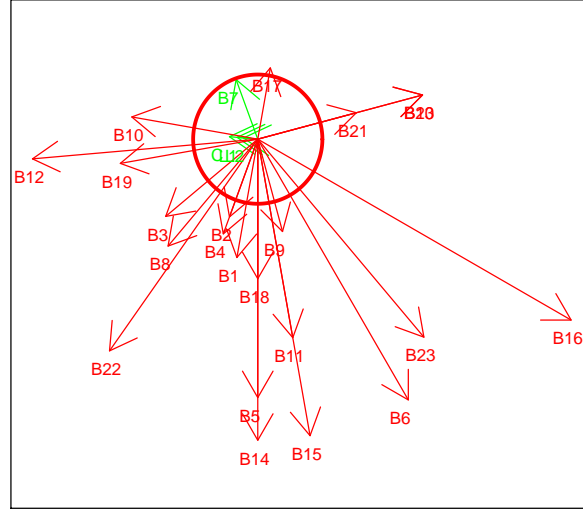
The 2D plot charts branches azimuth as arrows whose length is SC_c. The longer the arrows the more slender the branch. Arrows pointing inside the red circle are considered to be stable, whereas longer arrows are considered as risky ($SC_c > 50$). The plot may be a visual clue on the process of branch pruning selection.

2   The problem

Estimating the coordinates of the centre of mass (barycentre) of a tree is crucial to judge its static stability. The centre of mass of a perfectly static tree lies inside its circumference at its base, that is the x and y coordinates of the barycentre lie inside the $\pi \cdot r^2$ surface where r is the radius of tree base.

The more distant the centre of mass from tree base the higher the constrains

the tree poses on the soil through its roots. When concerns about tree stability are raised and the tree needs to be consolidated a proper cabling system has to be put in place. Knowing in advance the direction the tree would fall in case of breakage at its base is necessary to properly engineer the cabling system.

Nevertheless, the estimate of barycentre position is useful to assess the effects of different pruning schemes as far as tree balance is concerned.

3   Data collection

Data collection to estimation of the centre of mass is carried out in three steps:

1. Field measurements

2. Visual check for correctness of assumptions

3. Collection of correct allometric equation in order to estimate branch and foliage biomass

3.1   Field measurements

A few field measurements are needed to estimate centre of mass position at the stem level and at the branch level. Field data are easily taken climbing the tree using tree climbing techniques or by hydraulic platforms. A few instruments are needed including:

- A forestry caliper to measure diameter of logs and branches

- A clinometer, or ipsometer or any other instrument to measure height of branches or logs

- A measuring tape to measure length of branch or log projections on the ground

The stem is ideally sectioned in logs in order to compute their volume and biomass. The measurements to be taken on each log include:

- Diameter at the base of the log, in cm

- Diameter at the top of the log, in cm

- Length of the log, in m

- Azimuth of the log, in case it is not vertical, in degrees from North (O° North, 180° South)

- Length of log projection on the ground, from the tree base to the log tip (0 for a vertical stem), in m

- Height above ground of the base of the log, in m

- Log tilt from the horizontal plane (eg a vertical log is tilted by 90°, an horizontal log is tilted by 0°), in degrees (optional)

Each branch contributes to the position of the centre of mass by means of their wooden component and their foliage component. Every part of a tree carrying foliage is considered to as a branch. This definition applies to tree tip as well, although some trees may have lost their tip or have it removed during topping operations. The measurements to be taken on each branch include:

- Diameter at the base of the branch, in cm

- Azimuth of the branch, in degrees, usually measured with a compass (O° North, 180° South)

- Length of branch projection on the ground, from the tree base to the branch tip, in m

- Height above ground of the branch insertion into the stem

- Branch tilt from the horizontal plane (eg a vertical branch is tilted by 90°, an horizontal branch is tilted by 0°), in degrees (optional)

3.2 Visual check for correctness of assumptions

3.2.1 Relative position of centre of masses of branches and logs

The position of the centre of mass of a tree is computed taking into account the centre of mass of each branch and log. Pinpointing the centre of mass along a branch, taking into account branch form factor and the pattern of distribution of leaves biomass along it, would require many more field measures raising the time spent on it and the costs of the sampling.

Since the package aims to help engineering a consolidation system, the centre of mass is by default located at branches or logs tip. This leads to an estimate of the coordinated of tree centre of mass that is further away from the base than the real one. This difference can be regarded as an inherent safety factor.

The package behaviour can be modified in order to let the position branches and logs centre of mass to get nearer to their base. The relative position of the centre of mass of branches and logs can be set as a real number ranging from 0.01 (base) to 1 (tip, the default behaviour). Setting can be done during import of field data using function `importField` and its parameter `bCM` or by using the setter function `setBranchesCM`.

3.2.2 The density

Log mass is estimated by converting its volume (as measured in the field) to fresh weight. The conversion factor is usually referred to as density. Wood density is usually quite conservative among individual of the same tree species. Density values are commonly found in published literature. The following table (Nardi Berti (1979)) can be a useful resource (density in $\frac{kg}{m^3}$):

```
> library(treecm)
> data(Dst)
> print(Dst)

                    density
Austrian black pine     550
Black alder             540
Cedars                  520
Cembran pine            450
Common cypress          610
Corsican black pine     560
Douglas fir             500
Elm                     650
European ash            750
European beech          730
European Larch          620
Evergreen oak           960
Hophornbeam             800
Hornbeam                800
Horse chestnut          550
Italian alder           540
Locust                  750
Maritime pine           630
Nettle tree             720
Norway maple            660
Oriental plane          570
Peduncolate oak         820
Poplar                  380
Scots pine              550
Sessile oak             820
Silver birch            650
Silver fir              460
Spruce                  420
Stone pine              620
Sweet chestnut          570
Sycamore                660
Tree of Heaven          660
Turkey oak              830
Walnut                  690
White poplar            480
White willow            450
Wild cherry             620
Yellow pine             380
Yew                     760
```

3.3 Finding a correct allometric equation in order to estimate branch and foliage biomass

It is not feasible to weight the branches of a living tree. As a result branch and foliage biomass is estimated using branch diameter at base. Models relating size or biomass to diameter of trees or branches are known as allometric equations. They usually take the form of $Y = a \cdot X^b$ where Y is branch biomass, X is branch diameter, a and b are parameters estimated on a subsample of branches.

When subsampling is not possible one should rely on published allometric equations and feed them to `treecm`. Currently `treecm` ships with three allometric equations:

- `branchBiomassPine`, tested on stone pine trees (not on branches), 40+ cm diameter, returns biomass (dry weight), Cutini et al. (2009)

- `branchBiomassPinePorte`, tested on maritime pine branches, 10- cm diameter, returns biomass (dry weight), Porté et al. (2002)

- `branchBiomassPineAsca`, tested on stone pine branches, 8-16 cm diameter, predominantly from the lower layers of the crown, returns fresh weight

The proper allometric equation to be used must be fed to `treecm` when importing field data using function `importFieldData`, parameter `branchesAllometryFUN`.

We welcome contributions to increase the available list of allometric equations.

Note that one should pick an allometric equation that yields fresh mass of branches in order to get results as closer as possible to the real tree centre of mass. Function `branchBiomassPineAsca` returns fresh weight values for stone pine branches.

4 Correct layout of CSV file

A sample CSV data file is provided in the `data` directory. Function `importFieldData` loads and stores CSV files and along with needed data. CSV files are made up of 9 columns. The first row has to hold column headers. Headers are case sensitive. Each row holds individual log or branch data. Headers include:

1. **code** a simple code assigned to each log or branch (usually Lx for logs, Bx for branches)

2. **azimuth** orientation, ie: compass bearing in degrees

3. **dBase** diameter of log or branch basal section, in cm

4. **dTip** diameter of log or branch tip (always 0 for branches), in cm

5. **length** log length (leave it empty in case of branches), in m

6. **tipD** distance of the tip of the log or branch to tree base (different from branch length when tree stem is not vertical)

7. **height** height of log basal section of height of branch insertion on stem

8. **tilt** log or branch tilt from the horizontal plane (eg a vertical branch is tilted by $90°$, an horizontal branch is tilted by $0°$), in degrees (optional, only useful to estimate z coordinate of centre of mass)

9. **toBePruned** boolean to simulate branch pruning

There are a few simple rules to be followed in order to layout a correct CSV file, please refer to page 2

5   Contribute!

`treecm` is an ongoing project hosted on GitHub (`https://github.com/mbask/treecm`). Many areas need to be expanded including:

- branch biomass estimation; allometric equations are used to estimate fresh branch and foliage biomass. So far only branch biomass for stone pine and maritime pine have been developed or integrated into the software from published data. We need to expand further the number of species represented, particularly for those species common in urban area such as cedars, magnolias, oaks

- The package does not estimate the position of the centre of mass of tree branches. This position may vary according to foliage mass and its distribution along the branchs, branch tapering, quantity of water in leaves (ie: shaded or lit leaves) *etc*. The position must be fed to the package during data loading, as the variable `branchesCM`. Although going for the safe road, setting a branch centre of mass position on its tip may not be sufficiently precise should one assess wood quality as a function of load balance. Work is under way in order to to model branch load balance

- As far as postion of centre of mass il logs, the package does not tell branches and logs apart. The position of CM in logs follows branches CM position settings, though not realistic.

References

Cutini, A. and Hajny, M. and Gugliotta, O. and Manetti, M. and Amorini, E. 2009, Effetti della struttura del popolamento sui modelli di stima del volume e della biomassa epigea (Pineta di Castelfusano - Roma) *Forest@@*, **6**, 75–84

Nardi Berti, R. 1979 *La struttura anatomica del legno ed il riconoscimento dei legnami italiani di più corrente impiego.* CNR (Firenze), 155p.

Porté, A. and Trichet, P. and Bert, D. and Loustau, D. 2002, Allometric relationships for branch and tree woody biomass of Maritime pine (*Pinus pinaster* Ait.) *Forest Ecology and Management*, **158**, 71–83

Mattheck, C. and Breloer, H., 1995, *The Body Language of Trees: A Handbook for Failure Analysis (Research for Amenity Trees)*. HMSO (London).