Modeling biomass of forests in the southwest Amazon by polar ordination of Landsat TM

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Abstract Polar ordination is used to project all pixels in Landsat TM band space onto a single axis whose endpoints are the centroids of training areas in two spectrally distinct natural forest types – one with and the other without bamboo – which dominate the landscape in the southwest Amazon. Assuming the same wood density in both forests, biometric data collected in the training areas (Oliveira, 2000) indicated that biomass of forest with high bamboo density was 29% lower than forest without bamboo. Linear interpolation along the ordination axis models biomass of spectrally intermediate pixels. Thresholds based on band-space distance from the axis and ordinated distance beyond the axis endpoints are used to mask pixels unacceptable for modeling: water, beaches, pastures, roads, urban area, and deep topographic shade. The final product is a biomass image of an area covering 90x90 km, with 79% of all pixels being modeled. Because of spectral variability between bamboo forests in different recovery stages after their last monocarpic dieback, the model should only be applied to landscapes with mature, spectrally stable bamboo populations.

Keywords: spectral mixture, rainforest, bamboo, *Guadua*

1. Introduction

Above-ground biomass in the southwest Amazon was estimated in two training areas constituting spectrally distinct populations of Landsat TM pixels, corresponding to two natural forest types: “restinga” and “tabocal”. The two training areas are adjacent, on similar vertisol soil and similar topography (D. Vidalenc, 2000). Restinga is a tall rainforest without bamboo, while tabocal in the study area is a mixture of trees and the arborescent bamboo *Guadua weberbaueri*. New adult culms of this bamboo are 15-20 cm circumference at breast height (CBH) and extend 8-12 meters vertically before branching and arching over. Each arching culm with its branches is a ramet which lasts only a few years, part of a much longer-lived genet (M. Smith, 2000). As the ramet collapses, it weighs heavily on the stems of thin palms and young dicot trees in the understory and intermediate heights. By bending, breaking and smothering these trees, *G. weberbaueri* impedes their recruitment into larger size classes and maintains large canopy gaps. The main physiognomic distinction between forest with and without bamboo is a reduced number of trees in the size class >60 cm CBH in the former (Oliveira, 2000). Viewed from above this is seen to be due to gaps between the crowns of large trees. The gaps are densely occupied by arching bamboo among scattered thin trees, mostly early seral species.

2 Objective

The objective of this paper is to estimate the biomass of pixels with intermediate bamboo density by linear interpolation between two physiognomic extremes – pure tabocal and pure restinga – taken as spectral end members.

3 Methods

Biomass is modeled over a 90x90 km area, the lower left quadrant of Landsat Thematic Mapper scene 002-066, which straddles the border between the Brazilian states of Acre and Amazonas. The model is based on the spectral patterns of Landsat TM pixels in two small training sites, each covering about five km^2, located in primary forest 25 km west of the town of Sena Madureira at a sharp natural border between the two vegetation types (**Figure 1**). Like many woody bamboos, *G. weberbaueri* exhibits gregarious monocarpy, i.e., a particular population undergoes a single synchronized reproduction event followed by synchronized mortality. Each population occupies a large area (10^2 - 10^4 km^2). A population's extent can be seen during and shortly after mortality because of the distinct spectral pattern of leafless branches on Landsat TM images. According to several local informants, near Sena Madureira *G. weberbaueri* has a 30 year reproductive cycle. Inspection of a time series of digital TM images from INPE and NASA (1987, 88, 89, 90, 91, 92, 96, 99) indicated that all bamboo populations in the quarter scene were mature or nearly so in 1987, since they all reproduced and died within the period 1988-93. This evaluation was necessary since a bamboo-dominated forest in this area is spectrally variable for at least ten years as the bamboo slowly reestablishes itself after seeding and dying. Fig. 01

Each of the two training sites has ten 250m x 40m plots for estimating biomass, abundance, and basal area of trees >60 cm CBH. Nested within these are ten plots of 250m x 20m for collection of biometric data on the more abundant smaller trees (30-60 cm CBH) and ten 312.5 m^2 plots for plants of 7.8-29.9 cm CBH (Oliveira, 2000).

The model requires four input variables for each pixel and outputs two attributes. Inputs are the raw encoded radiances of the four Thematic Mapper (TM) bands 3,4,5 and 7 in the 1987 image, when the bamboo was fully mature. Outputs are above-ground dry biomass (10^3 kg ha^{-1}) and an indicator of quality of the biomass estimate.

The two output attributes of each pixel are obtained via polar ordination, where endpoints of the ordination axis are the center points of the two training areas in four-dimensional spectral band space. Biomass is interpolated for each pixel after it is projected onto the ordination axis. Estimate quality is the Euclidean distance of a pixel from the ordination axis prior to projection or it's distance beyond an endpoint of the axis after projection. In other words, a pixel will model poorly if it is far from the ordination axis or falls well beyond the endpoints after projection. A small distance beyond the endpoints is acceptable, the threshold being determined by variance of pixels inside the training site. Forest biomass is assumed *a priori* to vary in a linear fashion between the centroids of the training areas. The modeled gradient could as easily be some other continuous structural variable which was measured in the field, such as total basal area per hectare.

Euclidean distance between the center points of the training areas is calculated by equation 1.

Eq. 1

$$ED_{1,2} = [\sum_{i=1}^{I} (DN_{i1} - DN_{i2})^2]^{1/2}$$

where:

$ED_{1,2}$ = Distance in encoded radiance units between centroids of training areas 1 and 2;

I = number of bands;

DN_{i1} = encoded radiance value of band i at the centroid of training site 1; and

DN_{i2} = encoded radiance value of band i at the centroid of training site 2.

An ordination endpoint, or centroid, is defined in 4-band space by the average DN value in each band for pixels in the respective training area. The same point can be found on the ordination axis as the average of the projected values of training area pixels. The projection of a pixel onto the ordination axis is expressed as its along-axis distance from the center point of training area 1 (the bamboo dominated forest) and is given by equation 2.

Eq. 2

$$X = \frac{L^2 + (D_1)^2 - (D_2)^2}{2L}$$

where:

X = projected distance along the ordination axis, with endpoint 1 being the origin of the axis at the centroid of training area 1;

L = length of the ordination axis, from equation 1;

D_1 = Euclidean distance from the pixel to the center point of training area 1; and

D_2 = Euclidean distance from the pixel to the center point of training area 2.

It can be shown that equation 2 is valid for situations where the projection of the pixel falls beyond the endpoints. The projected distance X will take on a negative value when the projection falls short of endpoint 1, a positive value in all other cases.

Assessment of the quality value (Q) of the biomass estimate by original distance of the pixel from the ordination axis is given by equation 3, also valid for cases where the projection falls beyond the endpoints.

Eq. 3

$$Q = [(D_1)^2 - X^2]^{1/2}$$

Pixels in the biomass output image are rejected and masked out when Q is too large or when the projection falls too far beyond an endpoint of the axis. Setting thresholds is a subjective decision. Pixels are accepted when the conditions in the expression below are met. Endpoint 1, the bamboo-dominated forest, is arbitrarily set to zero in this expression. The first term in curly brackets identifies all pixels acceptably close to the ordination axis prior to projection; the second term in curly brackets identifies all pixels which do not project too far short of endpoint 1; the third term in curly brackets identifies all pixels which do not project too far beyond endpoint 2.

$$\left\{\frac{Q}{L} < 0.6\right\} \cap \{[(X < 0) \cap (|X| < 2s_t)] \cup (X \geq 0)\} \cap \{[(X > L) \cap [(X - L) < 2s_r]] \cup (X \leq L)\}$$

where

S_t = standard deviation of the projected values of all pixels in the tabocal training area; and

S_r = standard deviation of the projected values of all pixels in the restinga training area.

All *X* values (Eq. 2) were scaled to biomass using the values in **Table 1**, based on inventories by Oliveira (2000). The variance is based on ten replicates and is not incorporated into the model.

Table 1. Above-ground biomass of the two forest types for stems over 7.8 cm CBH. Biometric data from Oliveira (2000); allometric equations from Nelson et al. (1999) for stems <78 cm CBH; modified equations from Brown et al. (1989) and Overmann et al. (1994) for larger trees.

Forest type	*Above-ground dry biomass (10^3kg ha^{-1}) +/- 2 std dev*	*Scaled values*
Restinga(no bamboo)	207.2 +/- 29.5; n = 10	100.0%
Tabocal (bamboo)	146.5 +/- 52.0; n = 10	70.7%

3. Results

A screen capture of the biomass image is shown as **Figure 2**. Of all pixels in the quarter scene 78.7% were accepted by the Boolean threshold expression. Unacceptable pixels are masked in Figure 2 and include deep topographic shade, urban areas, pastures, young regrowth forests, river sand banks, muddy water of the Purus and Iaco Rivers and sediment-free oxbow lakes. Masked pixels are more abundant in three darker forest types –*castanhal, campinarana alta* and *baixio* - different from the two training areas, located on an extensive low plateau in the northeast part of the image. The Boolean thresholds also rejected isolated dark and light pixels throughout the image, giving it a highly speckled aspect. This is to be expected since the threshold criteria of two standard deviations will reject 5% of the pixels even inside each training area. A 3x3 pixel median filter was applied to the illustration in Figure 2 to reduce this general speckling with black pixels, but all reported pixel counts are based on the unfiltered image. Fig. 02

A histogram of the unfiltered and mask-free portion of the image is shown in **Figure 3** with increments of 1% biomass reduction, where the restinga training area is 100%. Pixels below 48% or above 114% were automatically masked out. The histogram is skewed to the left, meaning that few pixels model as having more biomass than the standard restinga forest. Left skew is largely attributable to the higher variance of bands 4 and 5 in the bamboo-dominated forest compared with more homogeneous values in forest without bamboo. This is a result of the greater contrast between shaded and illuminated slopes in the bamboo-dominated forest. Fig. 03

4. Discussion and conclusions

The model makes the following assumptions:

1. *Accuracy of biomass estimate: variance*. No uncertainty terms are included in the model for accuracy of estimate of biomass. Ten estimates were made of biomass for each vegetation type so that confidence intervals were obtained. These are reported, but are not incorporated into the model because the variance in biomass estimation is highly influenced by the small size of

the individual replicates. The overall size of ten hectares per vegetation type for large trees is assumed to give a reliable value, i.e., the arithmetic center of each training site pixel cloud in band space corresponds to the average biomass of the training area. An individual pixel is much smaller that the area required to accurately estimate biomass of the forest. This fact plus topography account for the variance in the training areas.

2. *Accuracy of biomass estimate: temporal variability.* It is assumed that biomass of the bamboo-dominated forest does not change over time. Biomass was measured ten years after a bamboo mortality event and there is evidence to show that trees in the 10-40 cm CBH size class increased in density over these ten years in the gaps made available by the disappearance of the bamboo (Oliveira, 2000). There is also evidence that this same size class will suffer reduction in tree stem density over the following 20 years as bamboo density increases (Miranda & Diógenes, 1998). Over the 30 year life cycle of bamboo we assume that (1) opposing changes in the biomass of bamboo and of small trees compensate one another and (2) there is little or no change in the biomass of larger trees.

3. *Accuracy of biomass estimate: wood density.* Published allometric regressions are accurate if used in the same range of diameters found in the trees used to derive the regression and if wood density is known. Wood density was not obtained for trees in the study area. Due to an abundance of large fast growing genera with light wood (e.g. *Ceiba, Ficus, Inga, Croton, Cavanillesia, Jacaratia*) it was assumed that specific density (gm cm^{-3}: dry weight / fresh volume including bark). is similar to a suite of pioneer tree genera studied in central Amazonia (Nelson et al., 1999). These are *Bellucia*, *Vismia*, *Laetia*, *Goupia* and *Croton* (n = 132, CBH = 3-88 cm) with specific density of 0.501 +/- 0.082 (average +/- 1 std dev). For trees >78 cm CBH (25 cm DBH), equations from Overmann (1994) and Brown et al. (1989) were used, corrected by a constant that forced agreement with the secondary forest equation of Nelson et al. (1999) at 78 cm CBH. The assumption about wood density of Acre forests is clearly unsatisfactory and Z-values of pixels in the biomass image should be considered rough estimates. Since wood specific density has a linear relationship with biomass, the pattern in the "percent biomass" image (**Figure 2**) is unaffected by any error if density is the same in both forest types. There are, however, more trees typical of secondary forest in the bamboo-dominated vegetation. Average specific density of trees here is probably lower than in the restinga, so that biomass of bamboo-dominated forest is even less than 71% that of the non-bamboo forest. Fig. 02

4. *Allometric equation for bamboo biomass*. Torezon & Silveira (unpublished) developed an equation for *Guadua weberbaueri* biomass using eight individuals ranging 13.2-17.3 cm CBH. Because of many bamboos under 13 cm CBH in this study and because of strong upward leveraging of the bamboo regression by a single large individual, an alternative equation derived from 132 secondary forest trees 1-25 cm CBH (Nelson et al., 1999) was used for bamboo. The dicot regression fits the Torezon & Silveira data points well if their largest individual is excluded, but the dicot regression may have underestimated biomass of large bamboos.

5. *Linear relationship between spectral and biomass attributes*. The model applies a simple linear interpolation for estimating biomass of unknown pixels. It is possible, however, that as forest plots approach very high bamboo density they asymptote spectrally while continuing to decrease their tree biomass in more a linear fashion.

6. *Spectral ambiguity.* The model assumes no ambiguity. Since only two vegetation types are compared there is no data for evaluating this assumption, but prior experience has shown young secondary forests to be spectrally similar to mature bamboo-dominated forest. Bamboo-

dominated forests on *terra firme* in Acre are also spectrally variable over the bamboo life cycle of ~30 years. Examination of a time series of images (1987 to 1999) has shown that by two years after a mortality event most bamboo dominated forests become spectrally indistinguishable from "restinga", but have recovered a mature bamboo spectral pattern by year 11. The spectral ambiguity attributable to bamboo-life cycle is largely eliminated in this study by choosing an image date when all bamboo populations were at or close to their maximum age, as determined from the time series.

The procedures elaborated here are a first approximation. Future versions of the model would benefit by including the following.

1. *Improved estimates of forest biomass using wood density.* Wood density data by species or average density by community are required.

2. *Removal of topographic variance prior to modeling*. Pixels with topographic shade presently model as having high biomass while brightly illuminated slopes model as low biomass. Some attenuation of topographic variance can be achieve by running a median filter over the original four TM bands as a preprocessing step.

3. *Inclusion of additional forest types*. The model presumes there are only two vegetation types, but in fact other forest types are found in the 90x90 km area. For example, a tall dense forest on well drained loam is found on a low plateau in the NE part of the quarter scene. This probably has an even higher biomass than the restinga (non-bamboo) forest. It is, however, spectrally similar to the restinga.

4. *Corrections for bidirectional reflectance distribution function (BRDF).* The two training areas are at the extreme western edge of the image, where lighting geometry reduces sub-pixel shade. This causes the biomass of most of the image to be overestimated, since increased shade models as higher biomass. An empirical BRDF correction factor image might be devised using a nearby quarter scene with homogeneous forest cover from the same time of year.

5. *Removal of band 3 from analysis*. The two training areas are almost identical in TM band 3 radiance, but aerosols cause this band to vary over the image.

6. *Validation*. A necessary follow-up for any model, validation does not necessarily require intensive field work. Proxies for checking predicted biomass reduction factor include (1) laser altimeter profiles of canopy openness and (2) videography to measure tree crowns per hectare in different diameter classes, both from airborne coverage obtained by an LBA project using the INPE plane in June of 1999.

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Figures

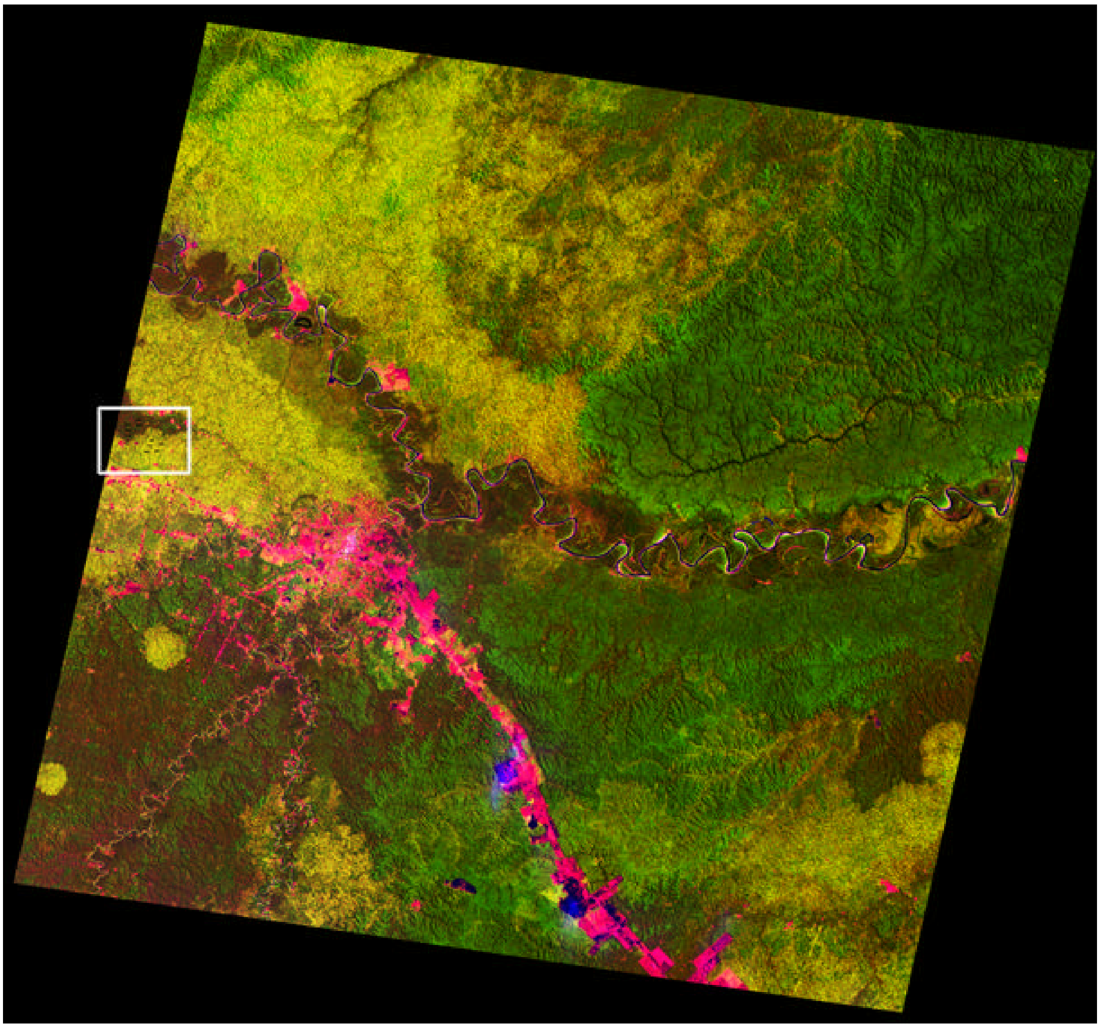

Figure 1. Landsat TM false-color composite of bands 3-4-5 (b-g-r), on the border between Acre and Amazonas, scene 002-066, lower left quadrant. Training areas where biomass was measured are in the white box. Bamboo-dominated forests are yellow. Semi-deciduous forests on low slopes without bamboo are dark with a reddish tinge. Forests on topographically higher ground, mostly without bamboo, are dark green. Recently burned pastures are black, other pastures, roads and urban areas are bright magenta. Image acquired 25-Aug-1987, prior to natural bamboo dieback. Image from INPE.

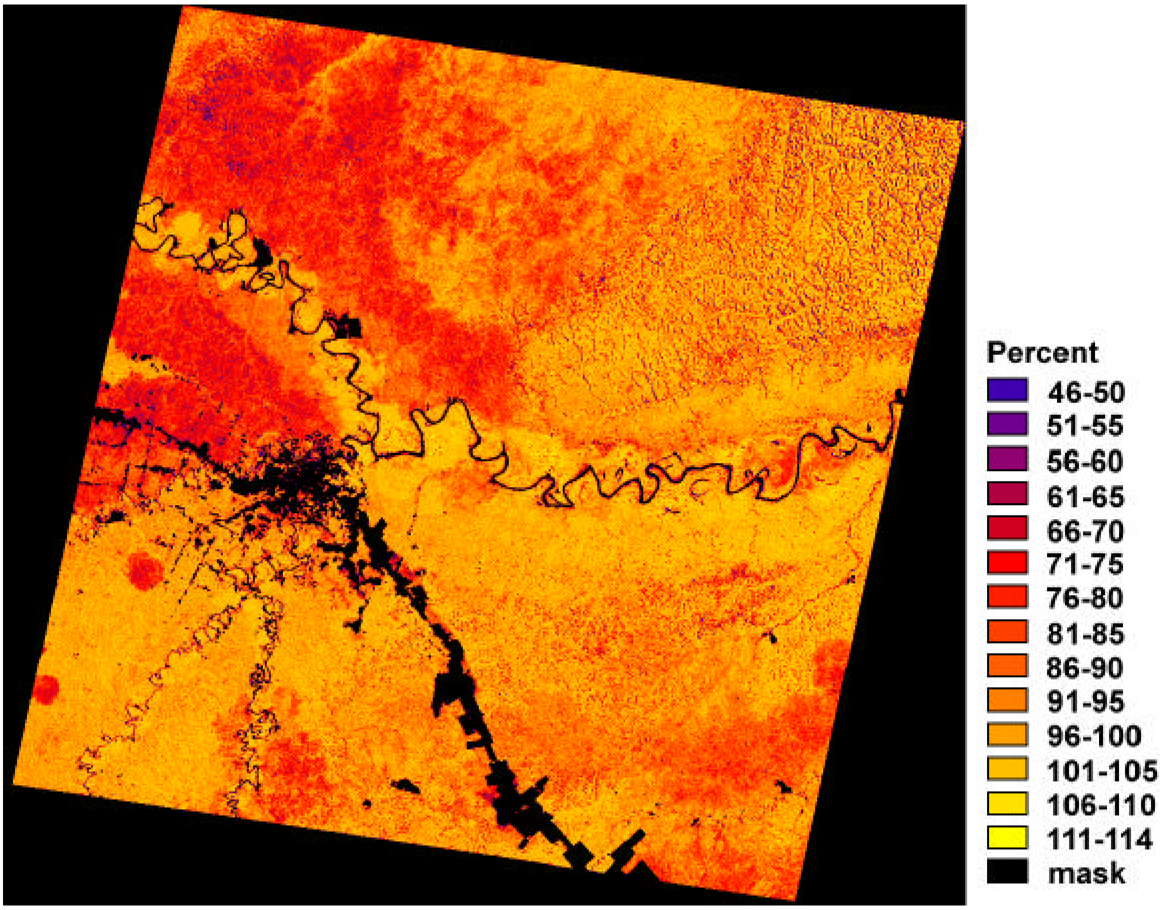

Figure 2. Screen capture of biomass image derived from four bands of Landsat quarter scene 002-006c. Pixel values are percent of the biomass of the non-bamboo forest in the training area of Figure 1. The pixel with lowest biomass reduction factor is 48%, highest is 114%. Unmodeled pixels are black. This image was median filtered to absorb isolated Boolean mask pixels.

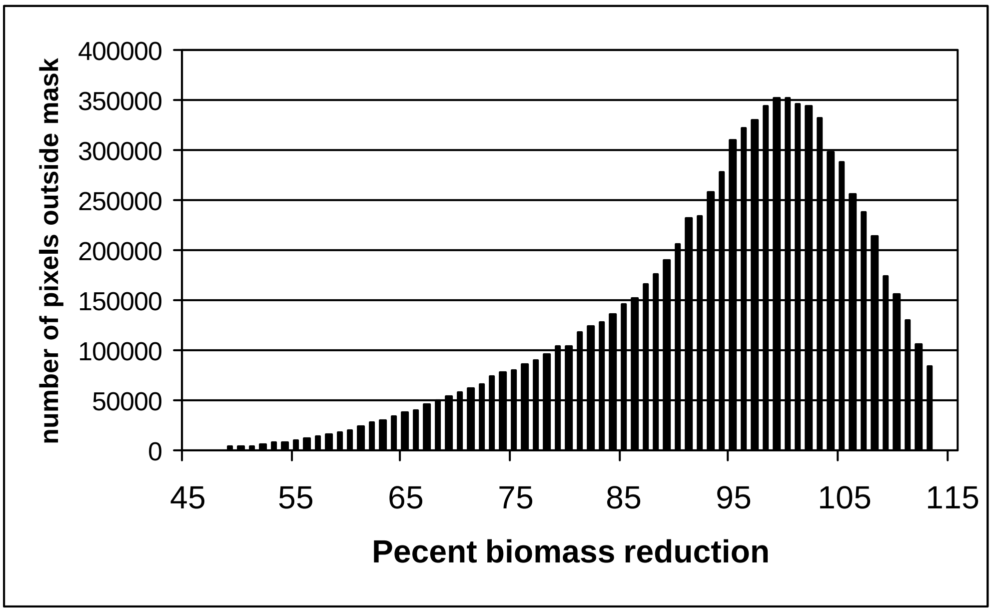

Figure 03. Histogram of unfiltered biomass image, thresholded at 48% and 114%.