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Complete life cycle of southwest Amazon bamboos (*Guadua* spp) detected with orbital optical sensors

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Abstract. Here we infer that 28-30 years is the length of a full life cycle of semelparous woody bamboos which dominate extensive areas of *terra firme* forest canopy in the southwest Amazon. This estimate is possible because of the distinct spectral patterns associated with different stages of the bamboo life cycle, the synchrony of life stages within each bamboo population and asynchrony between spatially separate populations. The spatial configurations of all bamboo populations at the canopy-dominant life stage were mapped in an area of 34,700 km^2 for each of seven dates in a 28-year series of Landsat MSS, Landsat TM and MODIS optical bands. The first and the final thematic maps in the time series showed 97% spatial congruence, indicating completion of a full life cycle. No mature bamboo population has yet been observed to die in the same place twice; however, we have identified areas with a spectral pattern that suggested synchronous bamboo mortality just prior to a Landsat image of 1976 which have all died again in 2003 or 2004.

Keywords: remote sensing, MODIS, Landsat, bamboo, monocarpy, Amazon

1. Introduction

Forest communities on *terra firme* in the southwest Amazon are unusual in hosting a high density of spiny woody bamboos of the genus *Guadua*. These are *G. weberbaueri*, *G. scarcocarpa* and probably other species, all of which are basally erect and distally climbing. They occupy gaps and understory in the *terra firme* forest over an area of about 180,000 km^2. In the Peruvian Amazon, Griscom (2003) showed the bamboo itself creates and maintains such gaps by crushing small trees, while Oliveira (2000) demonstrated that large trees are the most rarified size class in bamboo-dominated forests of north Central Acre. This exposes a middle story of arching bamboos to orbital sensors. When bamboo dominates an open forest, it presents a dense shell of leaves at the mid-canopy level (**Figure 1**), resulting in higher reflectance in the near and middle infrared optical bands compared with typical Amazon primary forest.

Figure 1. Dense *Guadua sarcocarpa* under open tree canopy near Sena Madureira, Acre.

Within a single dense population of *Guadua* on *terra firme*, all individuals (genets) flower only once, produce massive quantities of seed and then die. Each stage occurs in synchrony. This gregarious semelparous life cycle is typical of many woody bamboo species

(Judziewicz *et al.* 1999). A synchronized population of southwest Amazon *Guadua* sp. can cover tens to thousands of square kilometers. The length of a full cycle of SW Amazon *Guadua* remains poorly documented. Interviews of rural informants in the Brazilian state of Acre suggested a 28-30 year cycle (Nelson 1994, Silveira 1999), but many people had an unreliable memory of dates or were confounded by different mortality events in geographically separate bamboo populations.

2. Temporal and spatial spectral patterns of bamboo populations

Temporal changes in the spectral pattern of *Guadua*-dominated forest canopies in the SW Amazon have been previously documented within one or more Landsat scenes (Nelson, 1994, Crósta et al. 1995, Espirito-Santo, Silva and Shimabukuro 2001). Verification of the spectral patterns of different bamboo life stages in a Landsat TM time series (1987-2002) of north central Acre was also conducted by rural interview, ground observation and overflight, plus observations from other observers. With the corrections for bidirectional and atmospheric effects implemented in MODIS product 43B4, nadir-view surface reflectance can now be easily compared for Amazon forest canopies with recently dead bamboo, dominant live bamboo, and forest without bamboo (**Figure 2A**). All these canopies have a typical green leaf spectral pattern. There are differences, however, evidenced by this graph and by the work of Espirito-Santo, Silva and Shimabukuro (2001). There is a greater fraction of healthy green leaves illuminated in the bamboo-dominated pixel and higher shade fraction in a pixel of forest without bamboo. Forest canopy with recently dead bamboo also has more shade, but includes some illuminated dead bamboo branches. This dry non-photosynthetic vegetation is evident in **Figure 2A** as lower NIR/red ratio and higher reflectance of the two longest wavelength optical infrared bands, compared with forest without bamboo.

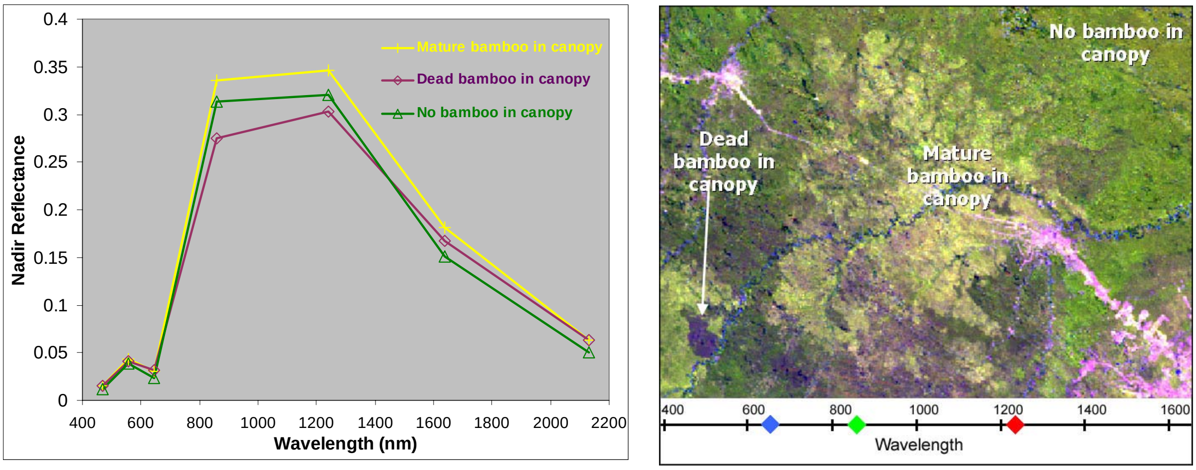

Figure 2. A) Graph of mean surface reflectance corrected to nadir view and constant solar elevation angle for pixels within three forest types. **B)** Color-composite of MODIS nadir-corrected surface reflectance, bands 5-2-1 (rgb) with the same three forest types.

To the best of our knowledge, orbital sensors have not yet been used to investigate the duration of the canopy-dominating phase, nor the length of an entire bamboo life cycle in the SW Amazon. The edges of two adjacent bamboo populations are visible to orbital optical sensors only if the two life cycles are strongly out of phase or if one population has recently died. The limits of a population are best revealed just after it dies (**Figure 2B**). In the warm humid Amazon the dead material rots and falls to the ground by 1-2 years after a mortality event. For the following 8-15 years the new bamboo cohort arising from seed is hidden in the understory or remains low in density. At this stage the forest canopy as seen by orbital optical sensors is spectrally similar to a forest without bamboo. Examination of mortality events in four years of MODIS images covering the entire range of SW Amazon bamboos revealed an imperfect falling-dominos pattern of mortality. Some (but not all) populations close in space also tend to die close in time. How this semi-synchrony evolved or is maintained is unclear.

3. Methods

At least two annual images around the beginning and several annual images around the end of a full life cycle could be used to document a repeated mortality event in the same place in a bamboo population. But this would only describe the life cycle of one or a few populations. Furthermore, there was only one image at the start of our time series and no further acquisition available until ten years later. We therefore adopted another approach. Assuming all bamboo populations in a study area have life cycles of about the same length, the borders of populations at the canopy-dominant stage should match up between two images that are one full cycle apart in time. Populations must remain in place, not invading surrounding areas during the time frame of the study. Unlike a mortality event, the canopy-dominant phase does not mark an exact point in the life cycle because it lasts several years. But this imprecision is overcome if there are many separate bamboo populations in the area, and if one or more populations die almost every year, causing frequent temporal changes in maps of the canopy-dominant phase.

The study area covers 34,700 km^2, defined by borders of Landsat scene WRS-1, orbit 3, point 67 -- a remote area at the heart of the bamboo-dominated Amazon forest (**Figure 3**). Deforestation has been insignificant and major spectral changes over time have been due to

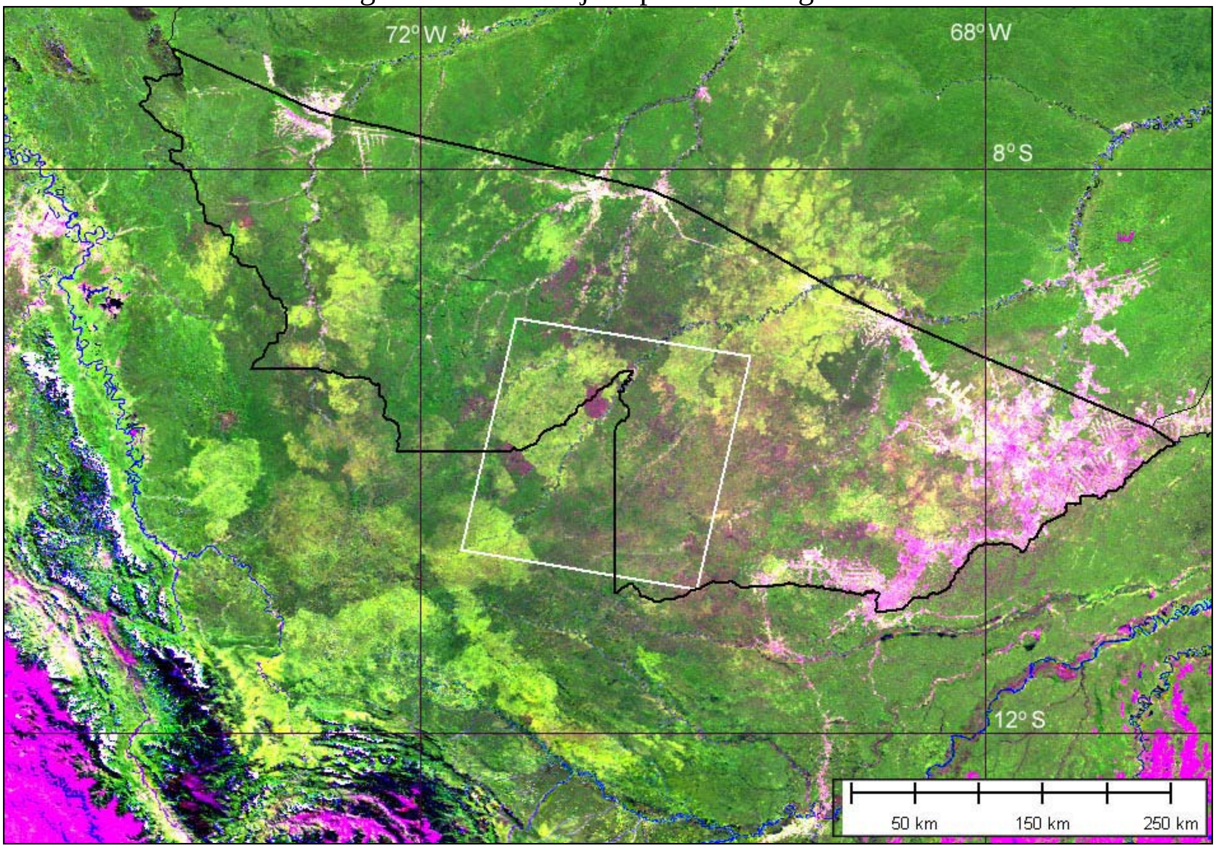

Figure 3. MODIS product 43B4, bands 621(RGB), a 16 day composite ending 28 July 2001. Study area is white outline, Acre state border is black. Recently dead bamboo populations are dark magenta, forest canopy dominated by bamboo is yellow or light green, earlier bamboo life stages and forests without bamboo are darker green. Alpine meadow, lowland savanna and lowland deforestation are light magenta to white.

natural bamboo phenology. Landsat and MODIS images covering this area at seven points in time over a 28 year period were visually classified into three categories: (1) bamboo not dominant or not present, (2) forest canopy dominated by live bamboo and (3) masked areas. Class 1 included a diversity of targets: rivers, floodplains, recently dead bamboo in the forest canopy, forest which never has bamboo, forest where bamboo was in a juvenile state hidden by the trees and forest with low density of bamboo between the trees. Masked areas were attributed a value of zero, and constituted the union of all dense clouds and cloud shadows over the seven dates, plus the no-data background outside the slanted borders of the Landsat scene. The masked area had the same spatial extent and the same number of pixels in all dates of the final thematic set of raster maps.

Dates, sensors and bands employed are given in **Table 1**. The date January 1990 is a weighted average of four mosaicked Landsat TM images acquired between June1987 and August 1990. The date June 2000 is a weighted average of four images from August 1999 to July 2000.

Table 1. Orbital optical sensor images used in this study.

Date	*Sensor*	*Bands (r,g,b)*
7 July 1976	Landsat MSS	4,2,1
17 January 1990	Landsat TM	5,4,3
22 June 2000	Landsat TM	5,4,3
28 July 2001	MODIS (product 43B4)	6,2,1
28 July 2002	MODIS “	6,2,1
28 July 2003	MODIS “	6,2,1
28 July 2004	MODIS “	6,2,1

MODIS bands in sinusoidal projection were extracted from hdf files using MODIS Reprojection Tool 3.2. The study area is at the juncture of four standard tiles, so images were concatenated then windowed. Two NIR bands and one visible band underwent a standardized contrast stretch, converted to 256 bit depth, rgb composited and projected to Plate Carree. For Landsat TM, four separate WRS-2 scenes were used near to each of two target dates in order to cover the entire WRS-1 scene. Landsat rgb composites sometimes required manual cartographic correction. The cartographic reference was the free Landsat 1990 Geocover tile set, projected to Plate Carree. Landsat images were resampled to 120m resolution. The MODIS nadir reflectance product retained its original 926m resolution and required no cartographic correction. Vector polygons of canopy-dominant bamboo, of clouds, and of the study area boundary were digitized on screen and imported as shape files in Arcview, where they underwent Clean and Update operations to correct topology and guarantee a common bounding rectangle for all dates. Polygons were then converted to raster at a fixed spatial resolution to produce thematic images with the same number of columns and rows.

Finally, agreement was determined between the first thematic raster image (1976) and each of the subsequent dates. Agreement was defined as the number of congruent pixels divided by the total number of pixels in the study area, excluding the standardized no-data mask. Very high agreement between 1976 and a later date would indicate that all populations of bamboo had come full round to their life cycle stage in 1976. If forest permanently free of bamboo occupied a large fraction of the study area, class 1 configurations (bamboo absent or not dominant) would always be highly congruent and would have to be excluded from consideration. But this was not the case. Bamboo populations were visible to orbital sensors over most of the study area at some time during the 28-year history.

4. Results and Discussion

The four MODIS images with a standardized contrast stretch are shown in **Figures 4** and **5**, alongside the 1976 MSS image. Mortality events proceeded in a falling-dominoes pattern. Thematic maps of canopy-dominant bamboo phase for all seven dates are shown in **Figure 6**, with the graph of spatial agreement over time. The 1990 map has some straight internal edges, since this is actually a mosaic of straight-edged images spanning three years and bamboo was not visibly dominant in the earlier dates. The 1976 canopy-dominant bamboo populations have been overlain as a hachure onto the 2004 image (**Figure 5**) and map (**Figure 6**) to illustrate a near perfect match, i.e., completion of a full life cycle after 28 years. No mature bamboo was directly observed to die twice in the same geographic location, but areas with spectral pattern suggesting they had died just before the 1976 image would die in 2003 or 2004. Because dead bamboo material in the canopy remains visible to Landsat for no more than 2 years, the range of possible life cycle lengths for these patches is 27-30 years.

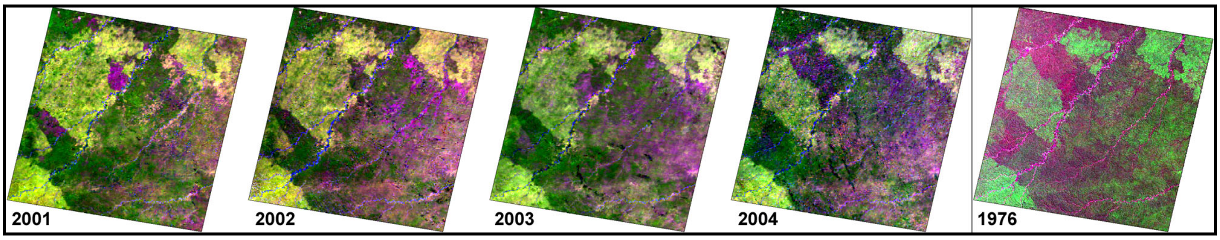

Figure 4. Four annual MODIS nadir-view surface reflectance images (bands 6-2-1, rgb) all with the same contrast stretch. Rightmost image is 1976 Landsat MSS bands 4-2-1. In all cases, light green or yellow patches indicate bamboo populations dominating the forest canopy.

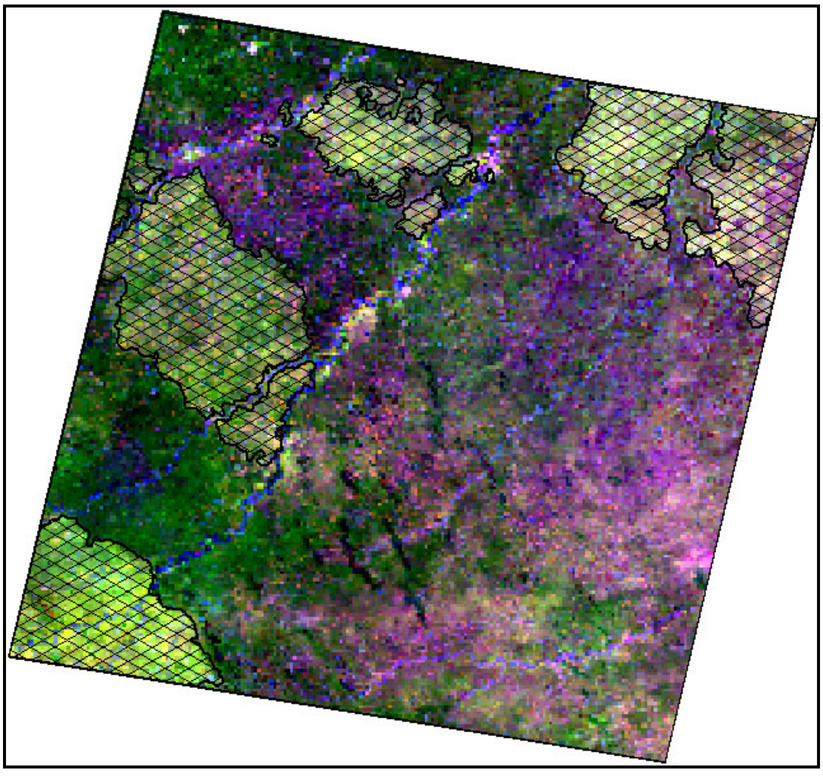

Figure 5. July 2004 MODIS image with the July 1976 distribution of canopy-dominant bamboo overlain as cross hatch pattern, showing a near perfect match. Purple tone in eastern and central portion of image probably represents semi-deciduous trees, not recently dead bamboo, because the color was maintained for four consecutive dry seasons.

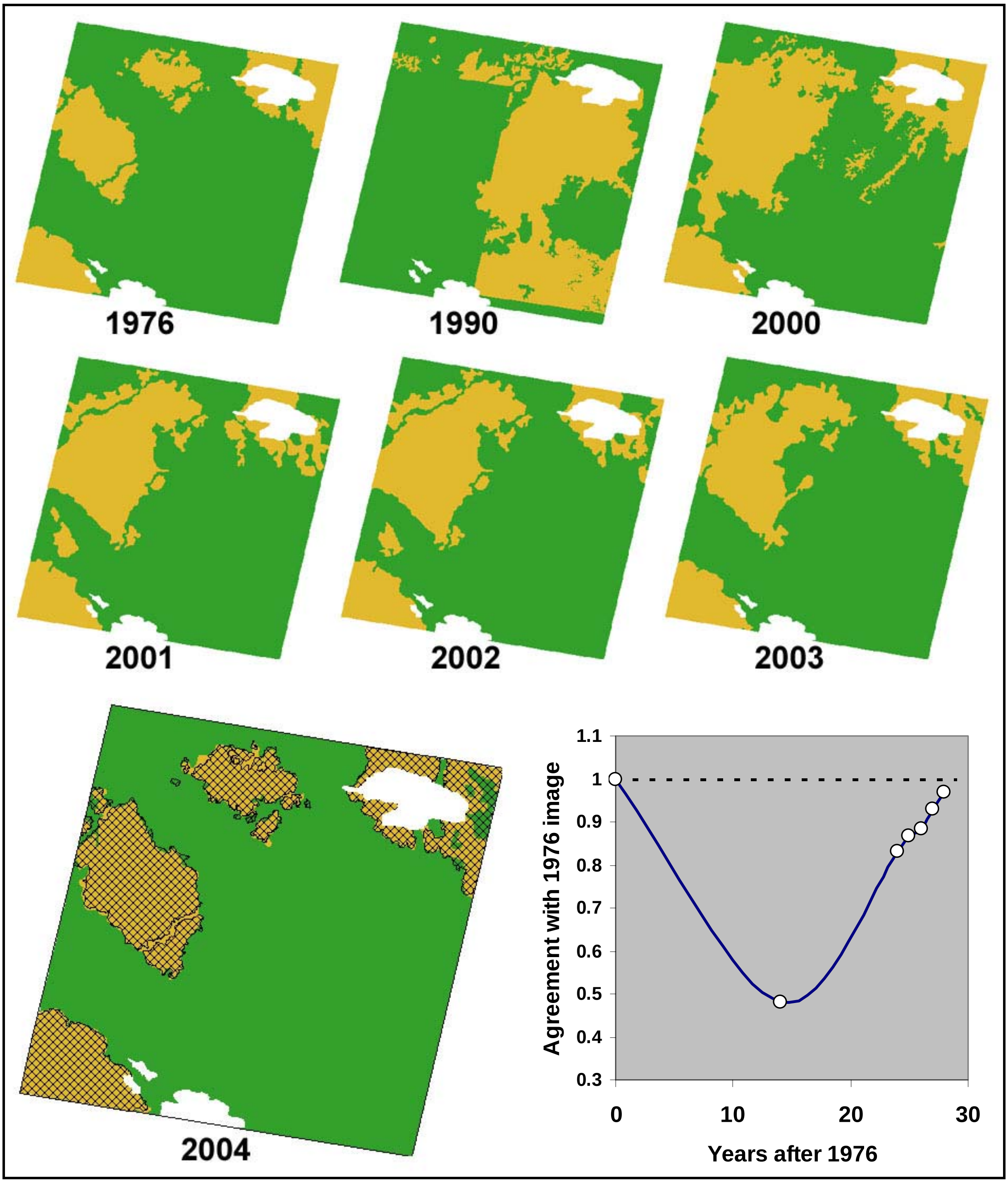

Figure 6. Complete time series of thematic maps of canopy-dominant bamboo. White is cloud mask, green is immature bamboo or bamboo absent. The 1976 configuration is overlain as a hachure on the 2004 map. Graph indicates spatial agreement between 1976 and each subsequent date, where the maximum possible is 1.0.

In July 2003 there were some mature bamboo patches that could still die to increase congruence with the July 1976 map of canopy-dominant bamboo. All these died by July 2004, exactly 28 years after the starting date. Agreement with the 1976 map of canopy-dominant bamboo was only 48% at 14 years after the starting date, but climbed to 97% at 28 years (**Figure 6**), strongly suggesting that life cycles of all populations had come full round.

Inspection of those small areas of disagreement between the 1976 and 2004 canopy-dominant bamboo maps showed these were attributable to (1) smoother digitizing of polygons when interpreting the low spatial resolution MODIS image and (2) an area below the NE corner of the study area, which was not easily classified. This particular area showed a spectral pattern of canopy-dominant bamboo in 1976 and 1986 and a pattern of recently dead bamboo in 1992, so reproductively synchronized bamboo is present there. Between 2000 and 2004 this area's spectral pattern was ambiguous, sometimes classified as canopy-dominant bamboo and sometimes as immature bamboo. One can expect this area to stabilize with a canopy-dominant bamboo spectral pattern by about 2007, 15 years after the last mortality event.

The study area includes one bamboo population restricted to small valleys (as inferred by borders of dead bamboo population in a 1992 image) surrounded by another population not restricted to valleys, which died later. This partitioning of the landscape suggests at least two ecotypes of bamboo, and at least two different *Guadua* taxa. The near perfect match of 1976 and 2004 maps suggests that all populations and taxa in the study area have a fixed and predictable life cycle length. It would be useful to examine MSS data of the study area from 1977 onward and compare them with future MODIS acquisitions to reinforce this observation. Recent efforts by INPE to recover its unique repository of MSS data from old magnetic tapes may make this possible. According to Keely and Bond (1999), there is as yet no firm evidence for precisely repeated flowering intervals in any bamboo species.

It is also interesting to note that -- independent of whether the bamboo is dense and mature, or immature and rarified -- the central and eastern portions of all the bamboo-dominated forests in the southwest Amazon had a lower NDVI vegetation index than surrounding permanently bamboo-free Amazon forest canopies, in all four annual dry season MODIS images. *Guadua* does not lose its leaves in the dry season, but many trees associated with bamboo become fully deciduous. There thus appears to be some dry season water stress associated with the cambisols and vertisols favored by *Guadua* (Vidalenc 2000).

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References

Crósta, A.P., Roig, H.L., Elvidge, C.D. Multitemporal image analysis applied to environmental monitoring in the Brazilian Amazon In: VII Simpósio Latinoamericano de Percepcion Remota **Proceedings**... Puerto Vallarta, México, 1995. v.1. p.25 – 30

Espirito Santo, F.B.; Silva, B.S.G.; Shimabukuro, Y.E. Detecção da dinâmica da floresta de bambu no sudeste do Acre com o uso de técnicas de processamento de imagens de satélite. In: Simpósio Brasileiro de Sensoriamento Remoto, 11., 2001, Belo Horizonte. **Proceedings**... São José dos Campos: INPE, 2001. p. 649-656. Available at <http://iris.sid.inpe.br:1908/col/ltid.inpe.br/sbsr/2002/11.11.09.59/doc/06_059.pdf> Accessed: 05 Nov. 2004.

Griscom, B.W. **The influence of bamboo (G*uadua sarcocarpa* and *Guadua weberbaueri*) on stand dynamics in lowland terra firme forests of southeastern Peru.** 2003. 294 p. Thesis (Ph.D. in Forestry). Yale School of Forestry. New Haven.

Judziewicz, E.J.; Clark, L.G.; Londoño, X.; Stern, M.J. **American bamboos**. Washington: Smithsonian Institution Press, 1999. 392 p.

Keely, J.E.; Bond, W.J. Mast flowering and semelparity in bamboos: the bamboo fire cycle hypothesis. **The American Naturalist**. v. 154, n. 3, p 383-391, 1999.

Nelson, B.W. Natural disturbance and change in the Brazilian Amazon. **Remote Sensing Reviews**. v. 10, n. 1-3, p 105-125, 1994.

Oliveira, A.C.A. **Efeitos do bambu *Guadua weberbaueri* Pilger sobre a fisionomia e estrutura de uma floresta no sudoeste da Amazônia**. 2000. 71 p. Thesis (M.Sc. in Ecology). Instituto Nacional de Pesquisas da Amazônia / Universidade do Amazonas. Manaus.

Silveira, M. Ecological aspects of bamboo-dominated forest in the southwestern Amazon: an ethnoscience perspective. **Ecotropica** v.5 n.2, p 213-216. 1999.

Vidalenc, D. **Distribuição das florestas dominadas pelo bambu *Guadua weberbaueri* em escala de paisagem no sudoeste da Amazônia e fatores edáficos que afetam sua densidade**. 2000. 92 p. Thesis (M.Sc. in Ecology). Instituto Nacional de Pesquisas da Amazônia / Universidade do Amazonas. Manaus.