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Challenges
and Solutions

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Assessments, changes, challenges, and solutions

Edited by

Rasmus Revermann¹, Kristin M. Krewenka¹, Ute Schmiedel¹,
Jane M. Olwoch², Jörg Helmschrot^{2,3}, Norbert Jürgens¹

¹ Institute for Plant Science and Microbiology, University of Hamburg

² Southern African Science Service Centre for Climate Change and Adaptive Land Management

³ Department of Soil Science, Faculty of AgriSciences, Stellenbosch University

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A radar- and LiDAR-based earth observation system for monitoring savanna woody structure in southern Africa

Renaud Mathieu^{1,2*}, Konrad Wessels^{2,3}, Russell Main¹, Laven Naidoo¹, Frans van der Bergh³, Barend Erasmus⁴

1 Ecosystems Earth Observation, Natural Resources and the Environment, Council for Scientific and Industrial Research (CSIR), Pretoria, South Africa

2 Department of Geography, GeoInformatics and Meteorology, University of Pretoria, Pretoria, South Africa

3 Remote Sensing Research Unit, Meraka Institute, CSIR, Pretoria, South Africa

4 Global Change Institute (GCI), University of the Witwatersrand, Johannesburg, South Africa

* Corresponding author: rmathieu@csir.co.za

Abstract: In southern Africa, landscapes are dominated by savannas, i.e., mixed tree-grass communities. These savannas are threatened by land clearing and degradation, as well as the densification of woody plants, a process known as bush encroachment. There is, however, very limited spatial information on woody cover distribution and changes. Here, we report on the development of an operational system designed to map and monitor woody vegetation cover at a regional scale. This system is based on the combined use of freely available airborne light detection and ranging (LiDAR) data and synthetic aperture radar (SAR) satellite imagery. The integration of these two datasets provides an effective solution for assessing woody fractional cover in southern Africa beyond the level of details and accuracy previously available. Woody fractional cover was mapped at a national scale for South Africa and Namibia in 2010 and 2015 at 1 ha (100 × 100 m) pixel size.

Resumo: Na África Austral, as paisagens são dominadas por savanas, isto é, por comunidades de herbáceas e de lenhosas. Estas são ameaçadas pelo desmatamento e a degradação da terra, mas também, em muitas áreas, pela densificação de espécies lenhosas, conhecida por *bush encroachment* (invasão de lenhosas). Existe, porém, informação espacial muito limitada sobre a distribuição e as alterações da cobertura de espécies lenhosas. Neste artigo, relatamos o desenvolvimento de um sistema operacional desenhado para mapear e monitorizar a cobertura vegetal lenhosa à escala regional. Baseia-se no uso combinado de dados aéreos da tecnologia LiDAR (*Light Detection and Ranging*) disponíveis gratuitamente, e de imagens de satélite de SAR (Radar de Abertura Sintética). A integração destes dois conjuntos de dados fornece uma solução eficaz para avaliar a distribuição da savana e cobertura fracionada de lenhosas no Sul de África, para além do nível de detalhe e precisão actualmente disponíveis. A cobertura de lenhosas foi mapeada à escala nacional para a África do Sul e Namíbia em 2010 e 2015, com o tamanho de pixel de 1 ha (100 × 100 m).

Introduction

Southern African landscapes are dominated by savannas, or mixed tree-grass communities with a woody cover varying between 10% and 70%, which occupy close to half of the land mass (Scholes, 1997). Savannas provide a large number of ecosystem services and goods to millions of predominantly poor, rural people (e.g., firewood, charcoal, grass, construction timber, edible fruits) (Shackleton et al., 2007; Fig. 1), host a unique suite of floral and animal biodiversity, and are the third largest biome in terms of con-

tributions to the land carbon storage pool (Grace et al., 2006). Savannas are threatened in some regions by clearing for cultivation or degradation through timber and fuelwood extraction, but there is mounting scientific evidence of a global trend of increasing woody vegetation, or bush encroachment (Eamus & Palmer, 2007; Lehmann et al., 2009; Mitchard & Flindrop, 2013), possibly driven by an atmospheric CO₂ level increase. Bush encroachment is a significant risk for livestock production (Skowno et al., 2017). Savannas are critical to food and energy security of rural communities, but their

regional dynamics and sustainability remain largely unknown.

Information on woody cover variability across southern Africa savannas is available only from products developed globally, such as the 30 m global forest cover maps derived from LandsAT 7 ETM+ data (Hansen et al., 2013) or the 25 m ALOS PALSAR global forest/non-forest JAXA datasets (Shimada et al., 2014). These products were developed primarily to track tropical forest losses, and they largely underestimate the distribution of open forests (Bastin et al., 2017). As a result of the lack of



Figure 1: (a) Deciduous savannas in the South African Lowveld; (b) rural communities rely extensively on savanna goods for energy and food securities, including fuelwood; (c) subsistence cultivation; (d) grazing resources.

quantitative data on the distribution of and changes in southern Africa's woody vegetation component, regional authorities are unable to monitor, manage, and therefore use this resource sustainably. Here, we report on the development of an operational system designed to map and monitor woody vegetation cover at a national scale for South Africa and Namibia (Task205). This system is based on the combined use of airborne light detection and ranging (LiDAR) and synthetic aperture radar (SAR) satellite imagery.

LiDAR and SAR: 3D remote sensing technologies

Active remote sensing sensors such as LiDAR and SAR are highly suited for measuring woody vegetation structure because these systems penetrate the canopy foliage and interact with the vertical shrub/tree profile. LiDAR instruments use airborne lasers systems to produce detailed 3D point clouds depicting the vertical

woody vegetation profile and the underlying ground (Fig. 2). The processing of the point cloud enables the derivation of a wide range of structural woody metrics such as canopy cover, height, volume, and biomass. The spatial coverage of airborne LiDAR data is generally limited, mainly because of the high cost of acquisition. SAR sensors, on the other hand, are hosted on satellite platforms and the data cover vast areas suitable for regional mapping. Naidoo et al. (2016) demonstrated that winter (low-moisture) L-band SAR images were more effective at mapping woody cover in deciduous southern African savannas than were optical Landsat data.

Woody vegetation mapping and monitoring system

The woody cover mapping system uses large tracks of high-resolution airborne LiDAR data that are acquired for planning and monitoring of infrastructure such as roads, railway lines and power lines, as

well as conservation areas and commercial forest. The LiDAR data are processed to generate LiDAR-based woody cover maps with a 25×25 m pixel size and then use these as training and validation for predictive models (Random Forest models) to map woody cover using satellite SAR data. For national- and regional-scale mapping, the system used the JAXA 25 m L-band ALOS PALSAR backscatter annual mosaics produced for 2007–2010 and 2015–2016. Ample existing LiDAR data (Fig. 3) were collected from multiple providers at no cost (e.g., ESKOM, Peace Park Foundation, Southern Mapping Company) and processed to produce canopy height models. The mapping system architecture was designed to be flexible and integrates the following capabilities: (1) ingesting large amounts of LiDAR-based woody cover or biomass data; (2) ingesting SAR satellite and environmental data sets (e.g., rainfall or temperature, topography) as explanatory variables; (3) creating large amounts of training and validation samples from LiDAR data; (4) integrating machine

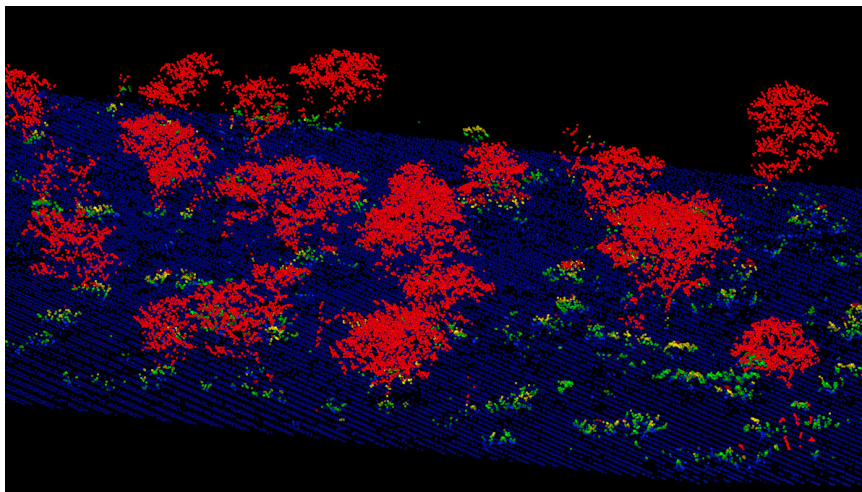


Figure 2: Example of LiDAR point cloud data for a typical savanna landscape in the South African Lowveld. Blue colours represent the ground, green and yellow colours represent shrubs, and orange and red colours represent small and tall trees, respectively.

learning models such as Random Forests, which learn from training samples in order to predict woody cover; (5) producing maps of cover and biomass at a user-defined pixel size (e.g., 25 m, 50 m, and 75 m resolution); and (6) validating the output

maps with independent LiDAR data sets. Aggregation at larger pixel sizes reduces spatial details but decreases errors by averaging noise; the system therefore allows the user to select the scale at which the map will be produced. For more details on

methods, see Main et al. (2016), Mathieu et al. (2013), Naidoo et al. (2015), Naidoo et al. (2016), and Urbazaev et al. (2015).

Outcome

Spatial patterns of woody vegetation

The regional patterns of woody vegetation cover were reliably mapped and correspond with the expected rainfall and vegetation type patterns (Fig. 4). Highest woody cover values are found in the eastern part of South Africa, where rainfall is the highest (following a north-to-south gradient from 350 to 1500 mm/year) and along the coast from Mozambique to Cape Town. Coastal forests are a mix of savannas, thickets, commercial plantations, patches of invasive alien plants (*Pinus* spp., *Eucalyptus* spp.), and remnants of dense indigenous forests. The Highveld in the South African central plateau is typically grassland and shows

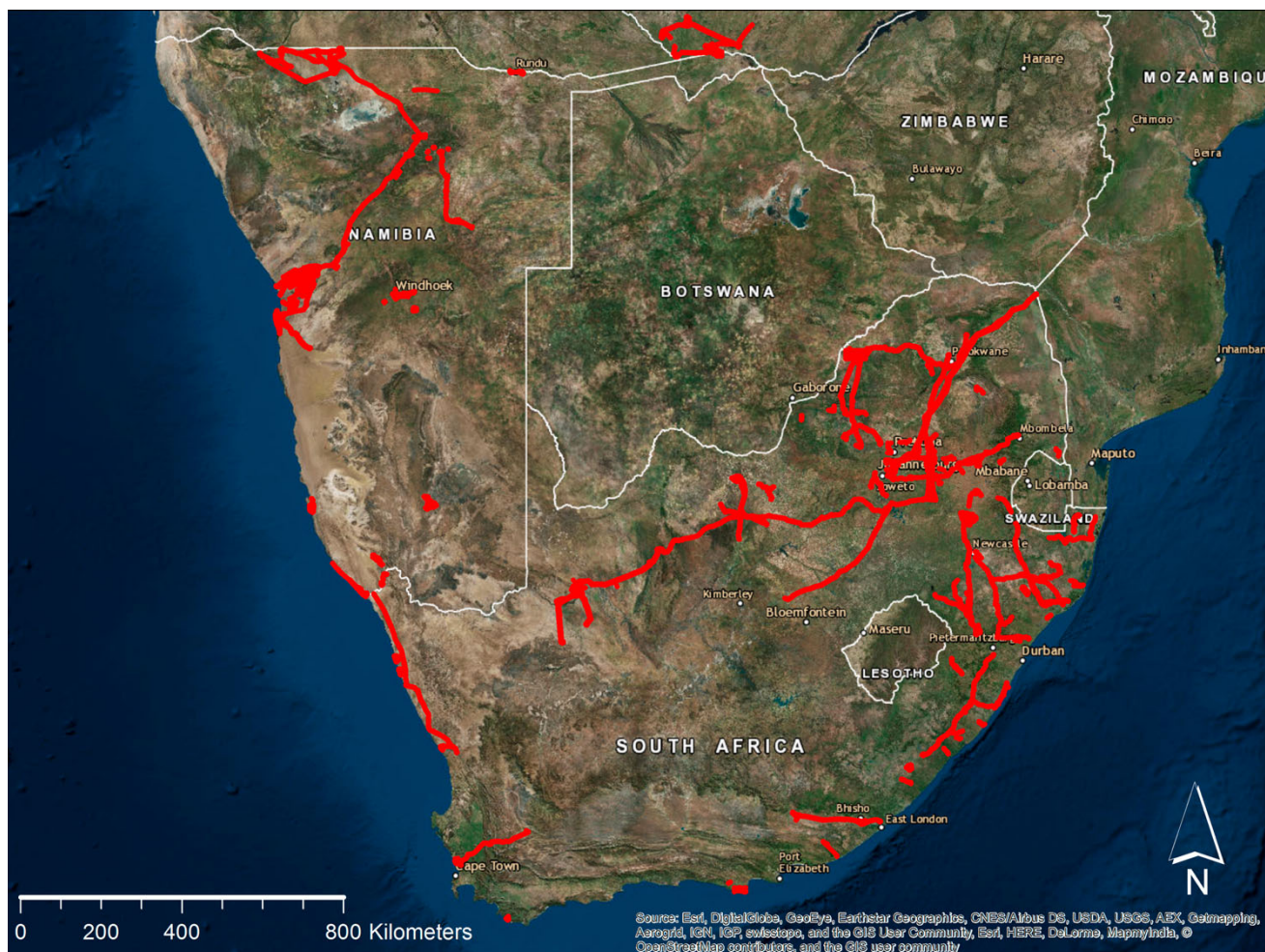


Figure 3: LiDAR coverage (red) amassed in southern Africa, including South Africa, Namibia, and Zambia. LiDAR data sets are sourced at no cost from a variety of providers including power utilities, conservation bodies, municipalities, and private plantations.

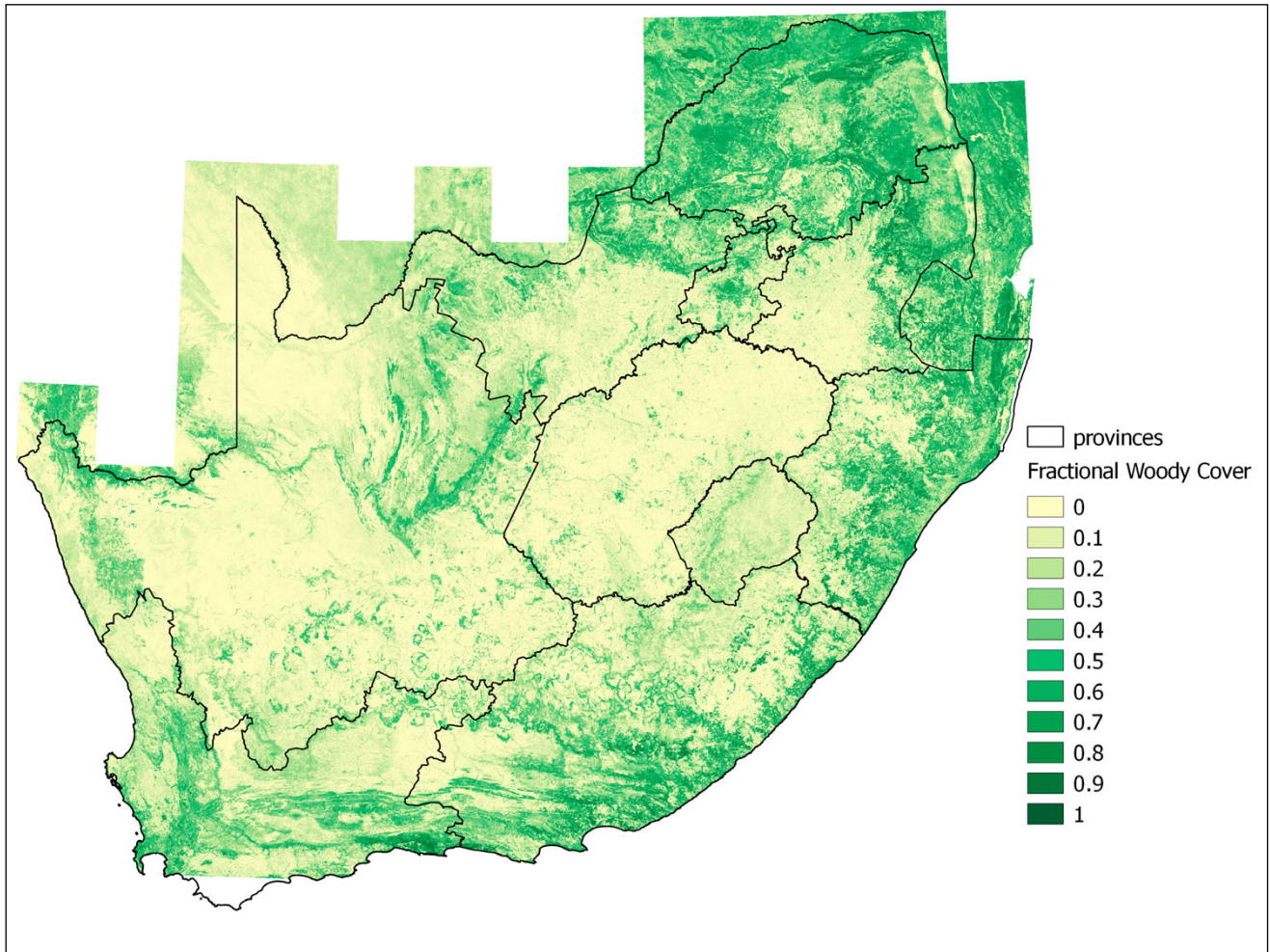


Figure 4: South African woody cover map produced from the predictive modelling exercise using airborne LiDAR and L-band ALOS PALSAR-2 mosaics acquired in 2010.

very low woody cover. The overall accuracy of the woody cover maps, expressed as coefficient of determination R^2 , ranged from 0.64 to 0.76 for the 25 m to 75 m resolution. The corresponding root mean square error (RMSE) was 0.16 to 0.13, indicating an absolute fractional cover error of 16%–13%. Beyond the independent map validation with LiDAR data, field visits were conducted in South Africa and Namibia to investigate local scale patterns. Visual assessments found that significant details were captured (for example, natural variations across the landscape) in addition to management impacts such as fence-line contrasts. Although the backscatter of the ALOS PALSAR global mosaics were pre-processed to correct for terrain variation, the woody cover on steep slopes (steeper than 25%) was overestimated and will require additional processing or correction of topographic effects on backscatter. Aboveground biomass (AGB) maps

were also produced in South Africa, but only for the savanna biome. The LiDAR-based AGB maps need to be calibrated with field AGB data acquired at the same time as the LiDAR imagery. Concurrent field data were available only for savanna vegetation, and thus could not yet be extended to the other regional vegetation types such as thicket or dense indigenous forests. This limitation is currently being addressed by CSIR, which is embarking on a large-scale field and airborne LiDAR campaign for a variety of vegetation types in South Africa, an undertaking that should lead to the development of national AGB maps in the near future.

Change detection

Woody cover change maps were calculated by subtracting an earlier woody cover map from a later map. Changes in commercial forestry (growth and clearing) areas were captured very effectively. In Namibia, large-scale debushing of bush

encroached areas was easily detected (Fig. 5). Extensive burned areas as a result of severe wildfires also caused detectable reductions in woody cover. An increase in woody cover was most prevalent in historically debushed areas. Banding effects were present in the woody cover products retrieved from the global 2015 ALOS PALSAR mosaics. These stripes result from having constructed the mosaic with single ALOS PALSAR scenes acquired at different seasons and with variable scene moisture or leaf conditions. They complicate the detection of gradual changes linked to long-term bush encroachment. Overall, the project successfully demonstrated that the system can map and monitor woody vegetation in dryland savannas in order to inform policy and management initiatives, such as Namibia's Debushing Advisory Service and National Rangeland Management Policy and Strategy, or South Africa's Working for Ecosystems programme and State of Forests report.

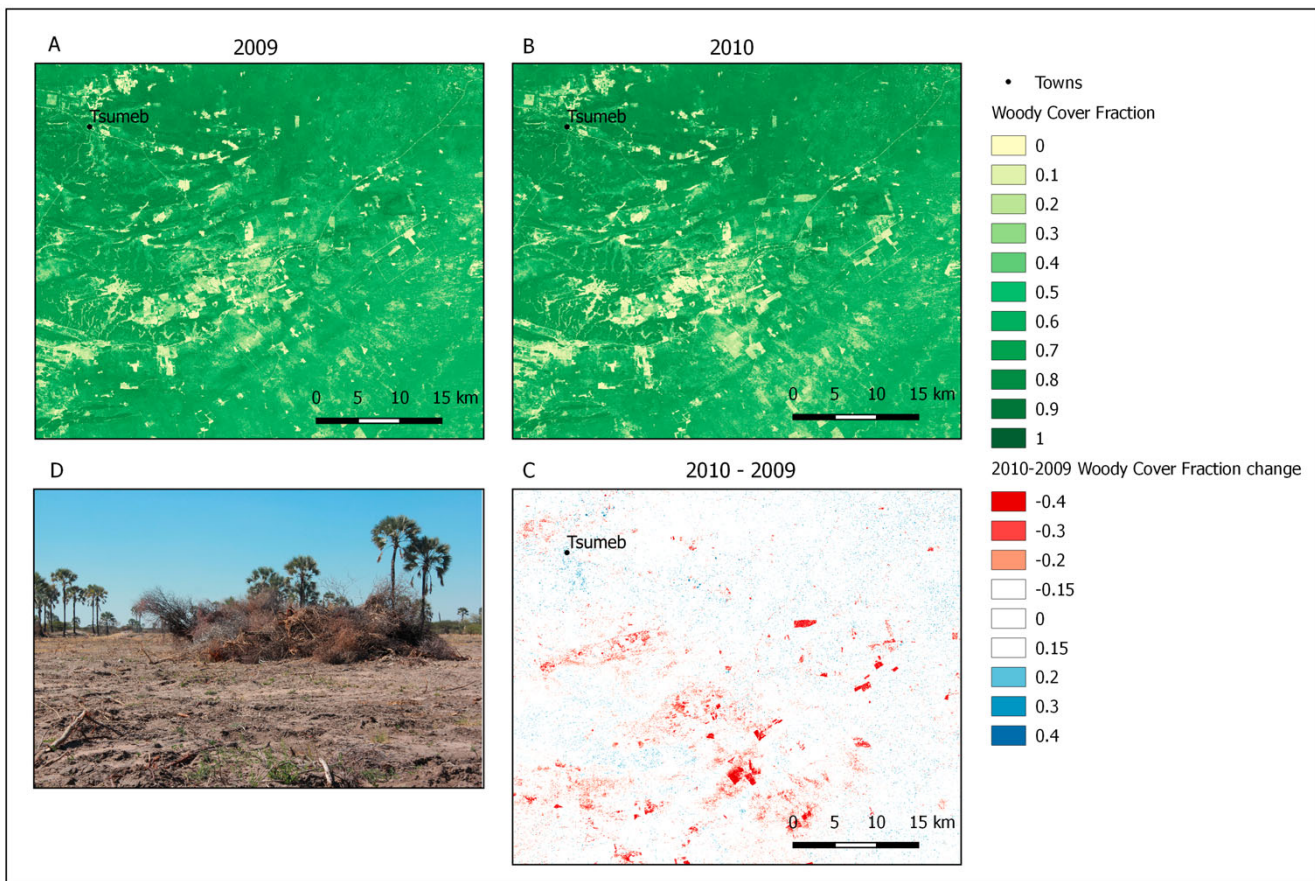


Figure 5: Woody cover fraction mapped with ALOS PALSAR data for (a) 2009, (b) 2010 and (c) the change between 2010 and 2009 in woody cover fraction near the town of Tsumeb in Namibia; (d) example of extensive debushing in north-eastern Namibia.

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