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Airborne laser scanning as a method for exploring long-term socio-ecological dynamics in Cambodia

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A R T I C L E I N F O

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A B S T R A C T

Early Khmer societies developed extensive settlement complexes that were largely made of non-durable materials. These fragile urban areas perished many centuries ago, and thus a century and a half of scholarly research has focussed on the more durable components of Khmer culture, in particular the famous temples and the texts and works of art that are normally found within them. In recent years however there has been a considerable effort to broaden the perspective beyond conventional approaches to Khmer history and archaeology. Remarkable advances have been made in the domain of remote sensing and archaeological mapping, including the application of advanced geospatial techniques such as airborne laser scanning within studies of heritage landscapes at Angkor and beyond. This article describes the most recent applications of the technology in Cambodia, including the results of a newly-completed campaign of airborne laser scanning in 2015—the most extensive acquisition ever undertaken by an archaeological project—and underscores the importance of using these methods as part of a problem-oriented research program that speaks to broader issues within history and archaeology.

1. Introduction

Archaeologists working in many parts of the world have already begun to address many of the "grand challenges" facing contemporary archaeology (Kintigh et al., 2014) by using landscape-scale investigations to elucidate complex relationships between climate, subsistence, and urban morphology over multiple scales of time and space. The work has offered new insights into the sustainability of the great low-density cities of the Maya, for example, with findings that clearly resonate into the contemporary world (Dunning et al., 2012; Fisher et al., 2009; Isendahl and Smith, 2013). At the present time, however, very little comparative research at such a spatio-temporal scale has been pursued in monsoon Asia, in spite of the fact that the region—home to several great 'tropical forest civilisations'—offers some of the greatest archaeological potential in this domain of inquiry (Fletcher, 2012). The Cambodian Archaeological Lidar Initiative (CALI) aims to address this shortcoming by extending a previous landscape-scale airborne laser scanning (hereafter 'ALS') survey completed in 2012 (Evans et al., 2013) to produce a highly consistent, comparable suite of data for archaeological landscapes across Cambodia in order to facilitate comparative, quantitative spatio-temporal analyses.

Since the 1990s, evidence has gradually emerged that vast, previously undocumented urban landscapes may lie beneath the forests that surround the well-known temple sites of Southeast Asia. Using the unique ability of new laser imaging technologies to 'see through' vegetation and uncover remnant traces of past societies, CALI completed a new ALS campaign in March–April 2015 that has dramatically expanded coverage beyond the test areas covered in the 2012 campaign (Evans et al., 2013). At the time of writing much of the data are still being analysed and ground verified, while in other areas excavations based on the results are nearing completion. It is already clear, however, that the programme has successfully uncovered and mapped previously concealed urban networks by comprehensively imaging the areas surrounding all of the major temple complexes in Cambodia, the heartland of the Khmer. The new data provide a foundation for conducting the first highly-detailed landscape studies of those urban areas, in order to arrive at a more sophisticated understanding of chronology, environment and residential life. The maps provide a framework for conducting extensive and systematic field investigations to document ceramics and other time-diagnostic material. The new data are being integrated with existing archives of archaeological and environmental data within a geographic information system (GIS). The net result of this work is a uniquely

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comprehensive spatio-temporal database of urban morphology spanning nearly two millennia, from prehistory to the transition to modernity in Southeast Asia. Spatial analytical techniques are being used to interrogate the database, in order to analyse the growth and decline of early urban centres and reveal long term patterns of human-environment interactions at the regional scale.

2. Background & rationale

One of the main issues in the archaeology of the pre-modern Khmer world is that masonry was used almost exclusively for the construction of religious monuments (with the exception of bridges and other features related to water management such as culverts and spillways). The urban and agricultural networks extending between and beyond those monuments—including structures as significant as the royal palaces of Angkorian kings—were almost entirely made of earth and of non-durable materials such as wood and thatch (Fletcher and Pottier, 2002). As a result, most scholarship on early Khmer societies has come from the fields of architecture, art history and epigraphy, and the urban context of the monumental remains is relatively poorly understood. The construction of these extended agro-urban environments, however, involved re-engineering the landscape on a scale perhaps unparalleled in the pre-industrial world: wooden neighbourhoods, for example, were built on top of mounds of earth designed to keep them above floodwaters in the wet season; many thousands of ponds and canals were excavated; and roads, field walls and dykes were made of earthen embankments. Cultural deposits are relatively shallow in Cambodia, and (compared to neighbouring countries) remain relatively undisturbed by modern development, which means that the traces of these agro-urban landscapes remain inscribed on the terrain with considerable clarity in the form of patterned undulations on the surface, or what we might term 'archaeological topography' (Opitz and Cowley, 2013).

In recent years, using an integrated suite of methodologies ranging from remote sensing to excavation, archaeological maps of Angkor have been produced which, for the first time, provide a holistic picture of the settlement, including residential areas, agricultural systems, infrastructural networks, ritual spaces, and a fivefold increase in the number of documented temples (Evans, 2007; Evans et al., 2013; Pottier, 1999).

The work at Angkor has had far-reaching implications for our understanding of interactions between humans and their environment in medieval Southeast Asian landscapes. As has been argued for many years (Diamond, 2009; Fletcher, 1995, 2012; Groslier, 1979), "resolving questions relating to the scale, structure, and population density of Angkor is critically important not only for evaluating the sustainability of settlement growth there, but also for explaining the collapse of classical Angkorian civilisation and for understanding the nature of early urbanism in tropical forest environments in general" (Evans et al., 2013). One of the conclusions to be drawn from Angkor is that its immense 'engineered landscape' may have imposed a kind of inertia that limited its adaptive capacity in the face of rapid socio-ecological change. Sophisticated technologies of water management may have provided a degree of resilience on an annual scale by ensuring food and water security for an ever-larger and increasingly urbanised population; paradoxically, however, those same systems would also have created a systemic vulnerability to longer-term climatic variation on the decadal scale or greater (Buckley et al., 2010; Day et al., 2012; Diamond, 2009; Evans et al., 2013; Fletcher et al., 2008; Lieberman and Buckley, 2012; Penny et al., 2007).

Recent research (Evans, 2010; Evans, 2010–2011 [2013]; Evans and Traviglia, 2012) has indicated that massive investments in water engineering were not unique to Angkor, but may have been a common characteristic of many early Khmer cities from the pre-Angkorian period (~5th to 8th centuries AD) through the Angkor period (9th to 15th centuries AD) and possibly even into the post-Angkorian period (15th to 19th centuries AD).

Almost all of those places, however, remain poorly understood beyond their civic-ceremonial centres, much the same as Angkor itself until recently. Projects of archaeological mapping have been set in motion by various international teams in association with Cambodian colleagues, and have made significant progress in beginning to come to terms with archaeological landscapes at provincial centres of the Angkor period, and at the settlement complexes that came before and after Angkor (Evans, 2010; Evans and Traviglia, 2012; Heng, 2012; Phann et al., 2007; Shimoda, 2010). Until 2012, however, the key limitation of all this work—including at Angkor itself—was the inability of conventional sensors, and even more advanced active sensors such as high-resolution polarimetric/interferometric synthetic aperture radar, to penetrate the vegetation that obscures much of the archaeological topography. Even at Angkor, where projects of archaeological mapping had been underway for a century and a half, large blank spaces remained on the map (Evans, 2007).

The 2012 ALS campaign over Cambodia undertaken by the Khmer Archaeology LiDAR Consortium (KALC) showed clearly that laser-scanning technology provides an extremely effective solution to this problem (Evans et al., 2013). The application of ALS completely transformed our view of all of the covered areas, in some cases unexpectedly revealing entire urban landscapes beneath dense jungle canopy (Evans et al., 2015). The campaign has resulted in a range of significant research outcomes in archaeology as well as other domains such as forest ecology (Singh et al., 2015a, 2015b), and ALS-derived datasets now play a key role in the management of the World Heritage site. Analysis and interpretation of the 2012 data will continue for years to come. Because of the incredible richness of the archaeological topography, it has become clear that Cambodia has a heritage landscape that is perhaps without parallel in Southeast Asia, although it is under threat from modern development. The 2012 ALS campaign in Cambodia, even though limited in extent, for the first time allowed us to envisage that assemblage of engineered landscapes as a unique laboratory for exploring socio-cultural adaptations to environmental variability and change, within the theoretical framework of modelling vulnerability, risk, and adaptation in human systems. Such a program requires a comprehensive understanding of urban form over the widest possible scale of time and space, and this understanding can only be derived from extremely detailed archaeological maps followed by a program of ground-work to enhance the temporal dimensions of the data. This provided the overall rationale for launching a greatly-expanded ALS campaign in 2015, funded by the European Research Council (Fig, 1).

3. Methodology

The KALC program in 2012 acquired ~370 km^2 over northwest Cambodia in a campaign that was specifically designed to maximise the resolution and accuracy of the resulting terrain models and highlight archaeological topography (Evans et al., 2013). The methodology and parameters used for the 2015 campaign were much the same as for 2012. Acquisition was completed at the end of the dry season in March/April in order to take advantage of peak 'leaf-off' conditions in deciduous trees, and also towards the end of the annual burn-off of vegetation by the rural population, with a view to maximising ground returns. This period is also the cusp of the dry and wet seasons, so the first rains of the year had extinguished many of those fires, reduced the levels of smoke and haze, and compacted leaf litter and other debris on the forest floor. The