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Oman: a case for a sink of begomoviruses of geographically diverse origins

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Oman is a trading nation and intensive agriculture is only a recent phenomenon. Exotic geminiviruses have recently emerged as a constraint to horticultural crops, and can be traced to trade and human migration. Greater phytosanitary precautions need to be implemented to limit future problems and prevent their outward spread.

The whitefly (*Bemisia tabaci*)-transmitted begomoviruses (family: *Geminiviridae*) emerged as significant pathogens of all dicotyledonous crops across all tropical, subtropical, and warmer temperate regions of the world during the late 20th century. Prominent examples of disease problems caused by begomoviruses include ongoing epidemics of cassava mosaic disease across sub-Saharan Africa [1], tomato yellow leaf curl disease, which has spread to almost all tomato (*Solanum lycopersicum*)-producing regions of the world [2], and cotton leaf curl disease in Pakistan and India [3]. Factors that are believed to drive the emergence and subsequent spread of begomoviruses include extensive virus mutation and/or recombination, the spread of polyphagous vector biotypes, intensive agricultural practices (particularly monoculture of highly susceptible crop varieties), and the global movement of agricultural products and plant material [4]. Begomoviruses pose a serious threat to global food security and, thus, strategies should be developed to stop ongoing crop losses due to begomoviruses and prevent the movement and the emergence of future begomoviral diseases. Here, we discuss a developing problem for agriculture in Oman that highlights the need for stricter phytosanitary controls for countries at the center of our global transport network, such as Oman,.

Agriculture in Oman

With few natural resources, save for recent oil and gas production, Oman has relied on international trade for its income. Since ancient times, the country has had extensive trading links by sea with East Africa, Persia, South and East Asia, and beyond. More recently, Oman, together with its neighbors, has benefited from the explosion in international air travel, providing airport hubs for the transport of peoples and goods between all regions of the Eastern Hemisphere.

Oman has an ancient fishing industry, which has been a major source of food, but has depended on the import of agricultural produce, mainly from its trading partners, which include Iran, Pakistan, India, and countries of East Africa. There is little recorded history of agriculture in Oman and intensive agriculture is a relatively recent innovation driven by the need to feed an increasing population; up from 2 million in 1993 to 2.77 million in 2010 (Ministry of National Economy, Government of Oman; www.moneoman.gov.om). The agricultural output of Oman is almost entirely for local consumption.

The cultivation of crops is possible only in the fertile Al-Batinah region, north of the Al Hajar Mountains, and the southern Dhofar region bordering Yemen (Figure 1). The major crops produced are vegetables and fruits, mainly dates. The area under cultivation is small (67 000 ha; Ministry of Agriculture & Fisheries, 2012; www.maf.gov.om) and most planting material is imported. Most commercial farms in Oman operate a monoculture and, as a social and/or cultural courtesy, farmers regularly exchange planting materials. Many expatriate Omanis returning to Oman have also brought their own planting materials. A large number of expatriate workers, 29% of the population in 2010, mostly from the subcontinent, work in Oman and many grow herbs and vegetables in kitchen gardens. All these aspects contribute to the risk of introducing and/or spreading plant viruses.

The emergence of geminiviruses in Oman

Evidence of the presence of geminiviruses in Oman first surfaced in 1993, when the Ministry of Agriculture and Fisheries (Government of Oman) detected problems with tomato leaf curl disease (ToLCD), although the etiology of the disease was determined only recently [5–9]. However, problems with ToLCD and leaf curl diseases of okra (*Abelmoschus esculentus*) and papaya (*Carica papaya*) had been noted by farmers before 1993. The diseases that were encountered are typically caused by whitefly (*B. tabaci*)-transmitted geminiviruses. Geminiviruses are characterized by small twinned icosahedral particles that encapsidate single-stranded circular DNA genomes and are transmitted by insect vectors [10]. Whitefly-transmitted geminiviruses (genus *Begomovirus*) form the largest and, economically, the most important group. They include viruses with either a single (monopartite) or two-component (bipartite) genomes,

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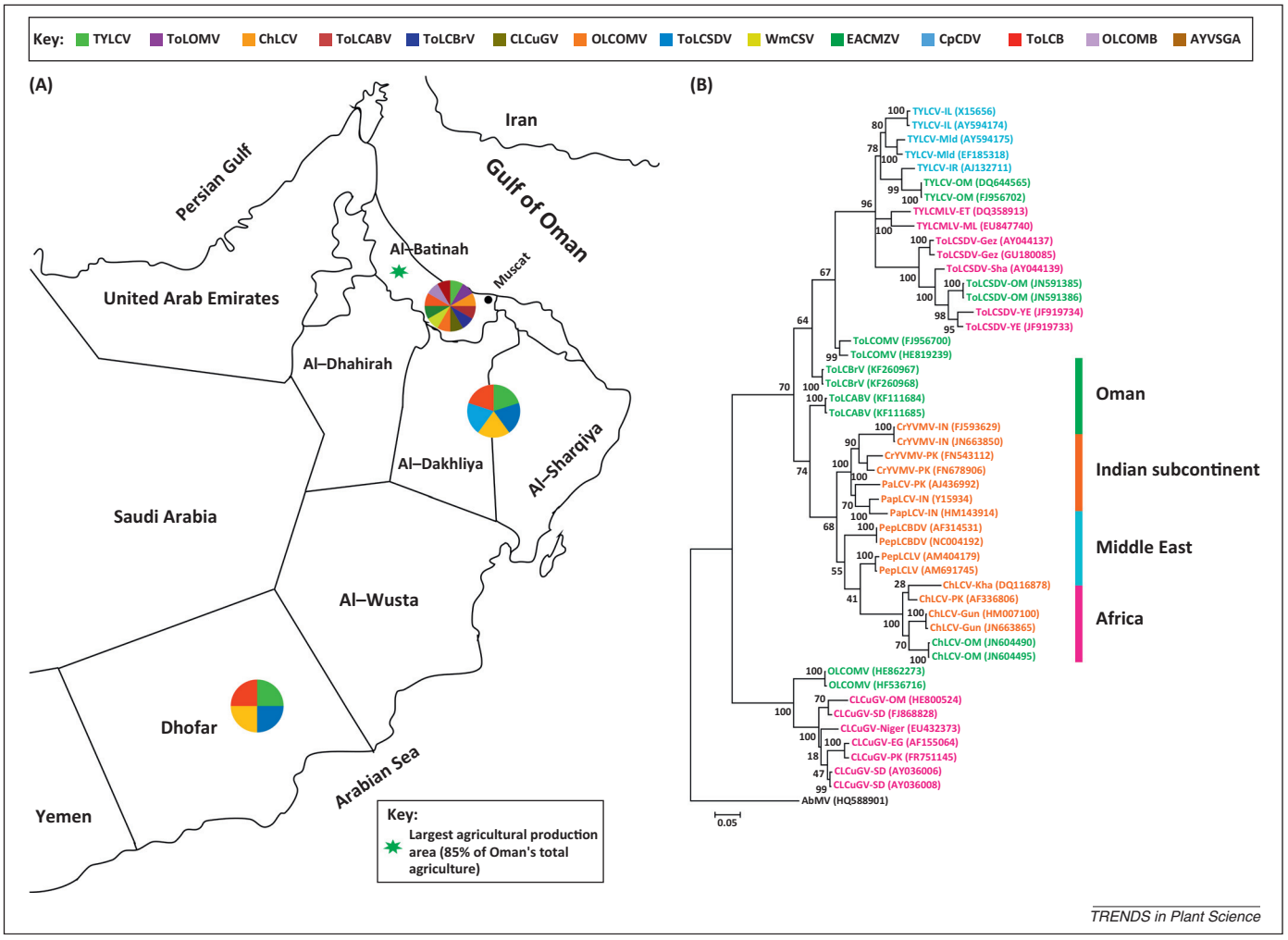

Figure 1. Geminivirus and satellite diversity in Oman. **(A)** Map of Oman showing the regions in which geminiviruses have been identified. The fertile Al-Batinah region with intensive agriculture has the highest level of virus diversity, whereas the Al-Dakhliya and Dhofar regions have less intense agriculture with lower levels of virus diversity. Viruses and satellites are shown in different colors to highlight their distribution. **(B)** Phylogenetic tree using the maximum likelihood algorithm and bootstrapping (1000 iterations) showing that begomoviruses occurring in Oman cluster with their closest relatives originating from the Middle East, Asia, and Africa. *Abutilon mosaic virus*, a distinct bipartite begomovirus from the New World, was included as an outgroup to root the tree. Abbreviations: AbMV, *Abutilon mosaic virus*; AYVSGA, Ageratum yellow vein Singapore alphasatellite; CpCDV, *Chickpea chlorotic dwarf virus*; ChLCV, *Chili leaf curl virus*; CLCuGV, *Cotton leaf curl Gezira virus*; EACMZV, *East African cassava mosaic Zanzibar virus*; OkLCOMV, *Okra leaf curl Oman virus*; OLCuOMB, Okra leaf curl Oman betasatellite; OLCuOMA, Okra leaf curl Oman alphasatellite; ToLCSDV; *Tomato leaf curl Sudan virus*; WmCSV, *Watermelon chlorotic stunt virus*; ToLCABV, *Tomato leaf curl Al-Batinah virus*; ToLCB, Tomato leaf curl betasatellite; ToLCOMV, *Tomato leaf curl Oman virus*; TYLCV, *Tomato yellow leaf curl virus*.

with each component being approximately 2.8 kb in size. Most monopartite begomoviruses are associated with DNA satellites that are half the size of helper virus. The satellites are of two types: (i) the symptom modulating betasatellites; and (ii) the satellite-like alphasatellites (the precise function of which remains unclear) [11]. Begomoviruses and their associated satellites from Africa, the Middle East, and Asia are genetically distinct (Figure 1). Since detailed examination of the geminiviruses occurring in Oman was initiated during the late 1990s, a range of monopartite and bipartite begomoviruses has been shown to cause problems. What is evident is that most are not native to Oman and many are

Table 1. Geminiviruses identified in Oman

Virus	Acronym	Origin of virus	Strain found in Oman	Refs
East African cassava mosaic Zanzibar virus	EACMZV	East Africa	EACMZV	[14]
Chili leaf curl virus	ChLCV	Indian subcontinent	ChLCV-OM	[6]
Cotton leaf curl Gezira virus	CLCuGV	North Africa	CLCuGV	[17]
Okra leaf curl Oman virus	OLCOMV	North Africa	OLCOMV	[12]
Tomato leaf curl Sudan virus	ToLCSDV	North Africa	ToLCSDV-OM	[7]
Tomato leaf curl Al-Batinah virus	ToLCABV	Middle East and/or Indian subcontinent	ToLCABV	[8]
Tomato leaf curl Barka virus	ToLCBrV	Middle East and/or Indian subcontinent	ToLCBrV	[9]
Tomato leaf curl Oman virus	ToLCOMV	Middle East and/or Indian subcontinent	ToLCOMV	[15]
Tomato yellow leaf curl virus	TYLCV	Mediterranean and/or Middle East	TYLCV-OM	[5]
Watermelon chlorotic stunt virus	WmCSV	Middle East and/or Africa	WmCSV	[18]