Validation of high rates of nucleotide substitution in geminiviruses: phylogenetic evidence from East African cassava mosaic viruses

Siobain Duffy¹,² and Edward C. Holmes¹,³

¹Center for Infectious Disease Dynamics, Department of Biology, The Pennsylvania State University, University Park, PA 16802, USA
²Department of Ecology, Evolution and Natural Resources, School of Environmental and Biological Sciences, Rutgers University, New Brunswick, NJ 08901, USA
³Fogarty International Center, National Institutes of Health, Bethesda, MD 20892, USA

Whitely-transmitted geminiviruses are major pathogens of the important crop cassava in Africa. The intensive sampling and sequencing of cassava mosaic disease-causing viruses that occurred in the wake of a severe outbreak in Central Africa (1997–2002) allowed us to estimate the rate of evolution of this virus. East African cassava mosaic virus and related species are obligate bipartite (DNA-A and DNA-B segments), and these two genome segments have different evolutionary histories. Despite these phylogenetic differences, we inferred high rates of nucleotide substitution in both segments: mean rates of $1.60 \times 10^{-3}$ and $1.33 \times 10^{-4}$ substitutions site⁻¹ year⁻¹ for DNA-A and DNA-B, respectively. While similarly high substitution rates were found in datasets free of detectable recombination, only that estimated for the coat protein gene (AVf1), for which an additional DNA-A sequence isolated in 1995 was available, was statistically robust. These high substitution rates also confirm that those previously estimated for the monopartite tomato yellow leaf curl virus (TYLCV) are representative of multiple begomoviruses. We also validated our rate estimates by comparing them with those depicting the emergence of TYLCV in North America. These results further support the notion that geminiviruses evolve as rapidly as many RNA viruses.

INTRODUCTION

Despite intensive study, our understanding of the evolution of plant viruses has lagged behind that of animal viruses. For instance, while many rigorous estimates of rates of nucleotide substitution exist for mammalian RNA viruses (e.g. Chen & Holmes, 2006; Hanada et al., 2004; Jenkins et al., 2002; Ramsden et al., 2008), only in the past year have well-supported estimates of substitution rates of plant viruses been published: for the positive-sense single-stranded RNA (ssRNA+) viruses rice yellow mottle virus (Fargette et al., 2008), zucchini yellow mosaic virus (Simmons et al., 2008), a broad group of potyviruses (Gibbs et al., 2008), and the single-stranded DNA (ssDNA) tomato yellow leaf curl virus (TYLCV; Duffy & Holmes, 2008). Importantly, these data challenge earlier ideas that plant viruses evolve more slowly than animal viruses (Blok et al., 1987; Fraile et al., 1997), as their substitution rates [$5 \times 10^{-4}$ substitutions site⁻¹ year⁻¹ (sub site⁻¹ year⁻¹) in the capsid proteins] are very similar to those observed in mammalian RNA viruses (Jenkins et al., 2002).

These new estimates also suggest that ssDNA and RNA viruses evolve at similar rates. Because ssDNA viruses replicate using their host cell’s DNA polymerases, it has long been thought that ssDNA viruses mutate, and thereby evolve, more slowly than RNA viruses. However, the rates of mutation estimated in the ssDNA bacteriophages $\Phi X$174 [single site reversions $\geq 1 \times 10^{-8}$ mutation site⁻¹ replication⁻¹ (mut site⁻¹ rep⁻¹); Denhardt & Silver, 1966; Fersht, 1979; Raney et al., 2004] and M13 ($7 \times 10^{-7}$ mut base⁻¹ rep⁻¹; Drake, 1991) are broadly similar to those estimated for the plant RNA virus tobacco mosaic virus (TMV) at $7.26 \times 10^{-6}$ mut base⁻¹ rep⁻¹ (Malpica et al., 2002). Hence, both RNA and ssDNA viruses might be expected to show similar evolutionarv dynamics.

To determine whether the high substitution rates observed in TYLCV are widely applicable to other ssDNA plant viruses, we estimated the evolutionary rate of another whitely-transmitted begomovirus: the East African cassava mosaic disease (CMD)-causing viruses. CMD has a huge economic impact on the staple crop of sub-Saharan Africa (Fauquet & Fargette, 1990; Legg & Fauquet, 2004), and an emergent recombinant of East African cassava mosaic virus
(EACMV) and African cassava mosaic virus (ACMV) destroyed cassava production in Uganda and nearby nations in the late 1990s (Zhou et al., 1997). This led to intensive sampling and sequencing of field isolates of CMD-causing viruses, creating a database of genome sequences sampled over an 8 year period.

Unlike TYLCV, which is frequently monopartite, EACMV and its related species are obligately bipartite, as is more typical of begomoviruses (Gutierrez, 1999). These two circular segments, DNA-A and DNA-B, can reassort amongst genotypes and have distinct evolutionary histories, reflected in non-identical phylogenies (Maruthi et al., 2004; Ndunguru et al., 2005). On the sense strand, the DNA-A encodes two partially overlapping genes for the coat protein (AV1) and a pre-coat protein (AV2, Gutierrez, 1999). In complement, the DNA-A encodes the replication-associated protein (AC1), a transcriptional activator of the coat protein (AC2), a replication enhancer (AC3) and a protein that assists in inter-cell movement (AC4; Gutierrez, 1999). AC2 and AC3 partially overlap and AC4 is entirely encoded in a different reading within AC1. The DNA-B segment contains only two non-overlapping genes for BV1: a nuclear shuttle protein involved in export of DNA from the nucleus, and BC1, another protein involved in inter-cell movement (Gutierrez, 1999).

We estimated rates of nucleotide substitution for the entire DNA-A and DNA-B genome segments of four East African CMD-causing viral species (EACMVs), and for individual genes on both segments: AV1, AC1, BV1 and BC1. This allowed us to assess whether EACMVs evolve at similar rates to TYLCV, and whether there were gene-specific variations in substitution rate, perhaps reflecting functional differences. Unfortunately, we found no evidence of temporal structure in the DNA-B sequences available, nor in the AC1 dataset, so we were unable to make such comparisons in these cases. We also compared our more robust estimates of substitution rate for the EACMVs’ DNA-A and AV1 gene with epidemiologically determined rates of nucleotide substitution in recently isolated TYLCV.

**METHODS**

Complete sequences of DNA-A and DNA-B segments of EACMVs with known dates of isolation were downloaded from GenBank (Supplementary Table S1, available in JGV Online). As the DNA-A segment determines which ‘species’ a geminivirus is, only DNA-B segments isolated with an EACMVs DNA-A were included in this analysis. Further, we only used sequences from viruses that had not been extensively passaged in the laboratory before sequencing, so that the sequences accurately reflected the sequence of the virus in nature. The years of viral isolation (between 1995 and 2002) are given in Supplementary Table S1. The final alignment length and number of taxa in each alignment are given in Table 1.

The circular genome sequences of the whole DNA-A and DNA-B segments were arranged so that each alignment began at the nick-site in the common origin of replication (TAATATT 3’ / 5’AC, Padidam et al., 1995). Datasets were then aligned using MUSCLE (http://www.drive5.com/muscle/, Edgar, 2004), and manually adjusted using Se-Al (http://tree.bio.ed.ac.uk/software/).

**Individual gene datasets.** Two protein-coding gene alignments were derived from the DNA-A alignment: AV1 (coat protein gene) and AC1 (replication-associated protein, which is encoded in the complement to the ssDNA genome), which make up 66% of the DNA-A. The DNA-A alignment was truncated to create preliminary alignments for these genes. Similarly, the DNA-B alignment was truncated to preliminary alignments for BV1 (nuclear shuttle protein gene) and BC1 (movement protein, which is encoded in the complement to the ssDNA genome), which comprise 61% of the DNA-B. The BV1 alignment was trimmed by six 5’ codons, because half of the genes began at the seventh codon of BV1 of the annotated EACMV DNA-B (GenBank accession no. AF112355). This ensures that all of the sequence in each of the individual gene alignments is protein-coding.

**Detection of recombination.** Putative recombinant genomes were identified using six recombination detection programs within the RDP3 package (http://darwin.uvigo.es/rdp/rdp.html): RDP, GENECONV, MaxChi, Chimaera, Bootscan and 3Seq (Martin et al., 2005). The

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**Table 1. Details of sequence alignments and parameter estimates**

<table>
<thead>
<tr>
<th></th>
<th>Full DNA-A</th>
<th>AV1</th>
<th>AC1</th>
<th>Full DNA-B</th>
<th>BV1</th>
<th>BC1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recombination detected</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Best-fit population growth model</td>
<td>Exponential</td>
<td>Exponential</td>
<td>Exponential</td>
<td>Exponential</td>
<td>Exponential</td>
<td>Exponential</td>
</tr>
<tr>
<td>Sequence length (nt)</td>
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<td>771</td>
<td>1077</td>
<td>2814</td>
<td>774</td>
<td>921</td>
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<td>Number of sequences</td>
<td>72</td>
<td>71</td>
<td>39</td>
<td>46</td>
<td>46</td>
<td>33</td>
</tr>
<tr>
<td>Chain length, in millions</td>
<td>50</td>
<td>15</td>
<td>13</td>
<td>50</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Mean substitution rate</td>
<td>1.60 × 10^-3</td>
<td>1.37 × 10^-3</td>
<td>1.24 × 10^-3</td>
<td>1.33 × 10^-4</td>
<td>2.77 × 10^-4</td>
<td>3.45 × 10^-4</td>
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<tr>
<td>95% HPD substitution rate</td>
<td>6.13 × 10^-4</td>
<td>4.69 × 10^-4</td>
<td>6.88 × 10^-5</td>
<td>1.06 × 10^-5</td>
<td>9.18 × 10^-6</td>
<td>6.72 × 10^-6</td>
</tr>
<tr>
<td>Mean TMRCA (ybp)</td>
<td>71</td>
<td>91</td>
<td>935</td>
<td>896</td>
<td>341</td>
<td>291</td>
</tr>
<tr>
<td>95% HPD TMRCA (ybp)</td>
<td>34–127</td>
<td>34–175</td>
<td>79–2754</td>
<td>90–2592</td>
<td>37–1147</td>
<td>26–1031</td>
</tr>
<tr>
<td>dS/dF ratio</td>
<td>–</td>
<td>0.11</td>
<td>0.18</td>
<td>–</td>
<td>0.18</td>
<td>0.14</td>
</tr>
</tbody>
</table>
default detection thresholds were employed in all cases. All putative recombinant sequences identified by at least two of these programs were removed from the gene alignments, but not the genomic segment alignments. This was a conservatively low threshold of detectable recombination, ensuring that our results have a high likelihood of being unaffected by recombination. The final numbers of taxa and the length of each alignment are given in Table 1.

**Phylogenetic and coalescent analyses.** The best-fitting model of nucleotide substitution for each alignment was determined using **MODELLTEST** (Posada & Crandall, 1998). For each dataset, this was the general time-reversible model with invariant sites (GTR + I + F).

The rates of nucleotide substitution per site and the times to most recent common ancestor (TMRCA) were estimated with the Bayesian Markov chain Monte Carlo (MCMC) method available in the **BEAST** package (http://beast.bio.ed.ac.uk/, Drummond & Rambaut, 2007). Both strict and relaxed (uncorrelated lognormal) molecular clocks were utilized for each dataset (Drummond et al., 2006). In addition, five demographic models (constant population size, expansion, exponential, and logistic population growth, and a piece-wise Bayesian skyline plot) were used as coalescent priors, although demographic history is a nuisance parameter in this study. We used Bayes factors (log$_{10}$BF) on tree likelihoods to choose the best-fitting models (in Tracer 1.4, http://beast.bio.ed.ac.uk/Tracer), and assumed a threshold of logBF > 2 for significance (http://beast.bio.ed.ac.uk/Model_comparison). Sufficient MCMC chains were run to ensure convergence, with an initial 10% of the MCMC chains discarded as burn-in. Statistical uncertainty around the mean estimates was calculated using **Tracer** 1.4, http://beast.bio.ed.ac.uk/Tracer, and assumed a threshold of logBF > 2 for significance (http://beast.bio.ed.ac.uk/Model_comparison).

**Assessing temporal structure.** To test the strength of temporal signal in these data, which is essential to the estimation of substitution rates, we repeated the **BEAST** analysis (using identical parameters) on a dataset in which sampling times were randomized on the tips (Ramsden et al., 2008). The HPDs of these randomized sequences were then compared with those of the real data. If these samples contain clear temporal structure, then the real and resampled data would have different mean estimated substitution rates, and different distributions. As it was not practical to run a large enough number of these resampled runs to garner rigorous statistical comparisons, we compared our results with those of a single resampled run.

**Additional sequence analyses.** The mean number of non-synonymous ($d_{K}$) to synonymous ($d_{S}$) nucleotide substitutions per site ($d_{K}/d_{S}$ ratio) in each gene alignment was estimated using the appropriate nucleotide substitution model determined by **MODELLTEST** on an initial neighbour-joining phylogenetic tree (Pond & Frost, 2005).

We also employed a phylogenetic approach to detect any mutational bias in the full DNA-A genome dataset. Detailed methods are as published previously (Duffy & Holmes 2008). Briefly, we aligned the DNA-A dataset with its sister taxon [South African cassava mosaic virus (SACMV), GenBank accession number AF155806] as the outgroup (Berrie et al., 2001; Legg & Fauquet, 2004; Maruthi et al., 2004; Ndunguru et al., 2005), and inferred the maximum-likelihood (ML) tree using **PAUP* 4.0** (Swofford, 2003), employing tree bisection-reconnection (TBR) branch-swapping. We then tallied the numbers of each kind of substitution and determined deviations from expected values with $\chi^2$ tests of significance. A similar analysis was not conducted for the full DNA-B genome dataset because the published sister taxa aligned very poorly with the dataset.

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**RESULTS**

**Frequent recombination in EACMVs’ genomes**

Frequent recombination, manifest as topological incongruence of different subgenomic regions, was detected in the DNA-A full segment alignment. This included confirmation of the recombinant origins of EACMV-UG (Zhou et al., 1997), which includes EACMV-TZ10 (Ndunguru et al., 2005), EACMV-KE2 (Bull et al., 2006), East African cassava mosaic Zanzibar virus (EACMZV; Maruthi et al., 2004) and African cassava mosaic Kenya virus (EACMKV; Bull et al., 2006), which were all supported by all six methods in **RDP** (data not shown).

The strong monophyly of these species and subspecies can be seen in the MCC tree in Fig. 1. However, the effects of recombination of the entire coat protein gene are evident in the MCC tree for **AVI**, in which EACMV-like coat protein genes were found in some EACMZV isolates, EACMKV-like coat protein genes were found in some EACMV isolates, and the EACMV-KE2 subspecies is no longer monophyletic (Fig. 2). The MCC tree for the smaller number of non-recombinant **AC1** sequences provides limited support for species monophyly (Supplementary Fig. S1, available in JGV Online). Strong evidence of recombination was also detected in 20 of the 46 DNA-B sequences (MCC tree shown in Supplementary Fig. S2), although similar tree topologies were observed in the **BV1** (Supplementary Fig. S3) and **BC1** (Supplementary Fig. S4) datasets. ML trees showed very similar topologies to the MCC trees, with many nodes in the DNA-A and DNA-B trees receiving both strong bootstrap support and high posterior probabilities (data not shown).

For both genomic segments, removing recombinants would have created datasets too small for an analysis of substitution rates. Therefore, with the caveat that recombination violates the assumptions of coalescent-based analyses (although it does not necessarily alter the results), we continued with an analysis of the recombination-loaded whole segment alignments. However, to check the validity of these rate estimates, we pruned detectable recombinants from alignments for each of the four genes. As many of the recombinant breakpoints occurred in the intergenic regions, the number of sequences in each gene alignment was not unduly reduced (Table 1).

**Estimation of nucleotide substitution rates**

Relaxed molecular clocks described all of the six datasets better than strict molecular clock models, though not significantly for **AC1** and **BV1** (Table 1). There were similar, insignificant differences among the fits of the various demographic models, though exponential population growth models were the best-fit for the DNA-A and **AVI** alignments; the flexible Bayesian skyline models were the best-fit for **AC1** and the three DNA-B alignments (Table 1).
The mean rates of nucleotide substitution estimated for the full genome segments were high, at $1.60 \times 10^{-3}$ sub site$^{-1}$ year$^{-1}$ (DNA-A, 95% HPD: $6.13 \times 10^{-4}$ to $2.64 \times 10^{-3}$) and $1.33 \times 10^{-4}$ sub site$^{-1}$ year$^{-1}$ (DNA-B, 95% HPD: $1.06 \times 10^{-5}$ to $3.39 \times 10^{-4}$) (Table 1). These rates are within the range documented in RNA viruses (Jenkins et al., 2002), and, for the DNA-A segment, somewhat higher than that estimated for TYLCV-causing viruses (TYLCVs; Duffy & Holmes, 2008)). High rates of nucleotide substitution were also apparent in the four gene datasets that excluded recombinants. The mean substitution rates for AV1 ($1.37 \times 10^{-3}$ sub site$^{-1}$ year$^{-1}$) were higher than the other genes ($ACI=1.24 \times 10^{-3}$, $BV1=2.77 \times 10^{-4}$, $BCI=3.45 \times 10^{-4}$ sub site$^{-1}$ year$^{-1}$), though all estimates had overlapping HPDs. These four genes were also shown to be subject to strong purifying selection ($d_{SN}/d_{SY} \leq 0.18$, Table 1), and there were no positively selected sites in any of the four gene datasets ($P > 0.05$). Consequently, these high nucleotide substitution rates are unlikely to result from strong positive selection. The lowest $d_{SN}/d_{SY}$ ratio (0.11) was detected in the gene encoding the coat protein which interacts with both the host and vector, supporting earlier studies (Garcia-Arenal et al., 2001; Seal et al., 2006).

**Strength of temporal signal**

To determine whether our estimates of substitution rate are robust, and do not simply result from the choice of particular prior values, we randomly reshuffled the dates of isolation for viruses in each of the six datasets and reran BEAST using the best-fitting parameters from the actual analyses. While the HPD intervals of all the resulting reshuffled control datasets overlapped with those of the real data, there were greater differences between the DNA-A and AV1 analyses and their reshuffled controls. For these two datasets, the reshuffled control 95% HPD values excluded the mean nucleotide substitution rates estimated from the actual data (Fig. 3). This was not the case for the other four datasets, for which the reshuffled results superimpose on the substitution rates from the real data, indicating that there was insufficient temporal structure to reliably estimate substitution rates. Importantly, these four datasets were sampled over only a 6 year span. In contrast, the DNA-A and AV1 sequences were sampled over an 8 year span and had more distinct substitution rate estimates from their reshuffled controls, reflecting clear temporal signal (Fig. 3). In addition, this signal was not simply an artefact of the particular reshuffled dates in the control analyses. The average difference between each
reshuffled date and the actual isolation date was similar between datasets with 6 years isolation (0.59, 0.87, 0.83 and 1.15 years for AC1, DNA-B, BV1 and BC1, respectively) and those isolated over 8 years (0.86 and 0.93 years for DNA-A and AV1, respectively). We concluded that our estimates for the DNA-A and AV1 were more robust than the others, and that our AC1 and all of our DNA-B results were potentially unreliable.

Ages of EACMVs

The DNA-A segments from the four EACMD-causing viral species (EACMVs) have a very short TMRCA \[\text{mean} = 71\text{ years before present (ybp), 95% HPD: 34–127 ybp, Table 1}\]. The detectable-recombinant-free, subgenomic AV1 dataset produced very similar estimates (TMRCA = 91 ybp, 95% HPD: 23–175 ybp). The remaining major gene on the DNA-A had an older estimated TMRCA of 935 ybp, but the AC1 analysis was very similar to its reshuffled dates control, and so its estimates are probably not credible. Similarly, as the DNA-B results are not significantly better than a randomly reshuffled date of isolation analysis, we did not consider the TMRCA of these datasets to be reliable.

The DNA-A MCC tree reveals that all completely sequenced isolates of EACMZV share a most recent common ancestor within the last 30 years (95% HPD: 17–49 ybp, Fig. 1). CMD has been present on Zanzibar...
since 1933, but has been replaced by the milder EACMZV (Maruthi et al. 2004), and our results confirm that the first CMD-causing viruses on this island could not have been EACMZV. EACMKV probably dates back 26 years (95 % HPD: 14–43 ybp). The EACMV-KE2 subspecies is approximately as old (25 years B.P., 95 % HPD: 13–42 ybp), meaning that two major clades of CMD-causing viruses were founded in Kenya at approximately the same time. All the sequences of the severe EACMV-UG variant have a more recent TMRCA of 16 ybp (95 % HPD: 13–23 ybp), or 1993. However, the severe disease symptoms associated with this variant were first observed in north-eastern Uganda in 1988, close to the upper 95 % HPD value of the TMRCA (Zhou et al., 1997). The two dated EACMCV isolates, which were sampled in Tanzania (Ndunguru et al., 2005), also have a recent common ancestor (mean TMRCA of 15 years, 95 % HPD: 10–22 ybp). That these isolates, which differ at ~8 % of sites (Ndunguru et al., 2005), probably diverged within the last 22 years, means there could be a fairly recent TMRCA for the EACMCV isolated on both the Western and Eastern coasts of Africa (~10 % sequence difference). While we cannot provide more conclusive evidence for this without dated sequences of EACMCV from West Africa, our results do call into question the current notion that the Western and Eastern EACMCV isolates 'have been separated for a very long time' (Ndunguru et al., 2005).

**Substitution bias in the EACMVs’ genome**

As EACMVs exhibited RNA virus-like rates of nucleotide substitution in a similar manner to TYLCVs, we tested whether they also show the same substitution biases. After adjusting for the initial nucleotide frequency, six of the 12 substitutions were significantly (P < 0.01) over- (C → T, G → A, T → G) or under- (A → G, G → T, T → C) represented compared with expectation over the evolution of the DNA-A (Table 2).

**Validation of high rates of evolutionary change in begomovirus**

The introduction of TYLCV into the New World from the Old World more than 15 years ago (Duffy & Holmes, 2007; Gilbertson et al., 2007) provided a unique opportunity to validate our estimated substitution rates for EACMVs and our prior rates for TYLCVs. We therefore compared recently isolated full-length genomic sequences of TYLCV with the oldest isolate with a full-length genome sequence from the New World (TYLCV-[DO], GenBank accession no. AF024715, isolated in the Dominican Republic in 1994; Nakhla et al., 1994).

The most recently isolated North American TYLCV genomes in GenBank were sampled in Texas in 2006 (TYLCV-US:TX, GenBank accession no. EF110890; Isakeit et al., 2007) and Arizona in 2007 (TYLCV-US:AZ, EF210554; Idris et al., 2007). Both these sequences were too recent to have been included in the dataset from which our TYLCVs substitution rates were originally estimated (Duffy & Holmes, 2008), and therefore offer an independent measure with which to validate these estimates. However, they are more closely related to each other than to other North American isolates (99.3 % nt identity, Idris et al., 2007), and therefore the calculated substitution rates from these two isolates are not independent. Crucially, the intergenic region and coat protein gene of TYLCV-US:TX, and by extension TYLCV-US:AZ, are directly descended from those of TYLCV-[DO] (i.e. this sequence falls at the node of the tree; Duffy & Holmes, 2007), which is necessary for such an analysis to be accurate.

There were 25 sites that differed between TYLCV-[DO] and TYLCV-US:TX and 22 between TYLCV-[DO] and TYLCV-US:AZ. Of these, 15 were shared by TYLCV-US:TX and TYLCV-US:AZ, including a deletion of 29 bases in the large intergenic region. Each recent isolate had three substitutions in the 777 nt of the coat protein-coding gene, and

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**Table 2.** Nucleotide substitutions inferred from the outgroup-rooted ML phylogeny of EACMVs’ DNA-A, evaluated with χ² tests of significance

<table>
<thead>
<tr>
<th>Original base</th>
<th>A</th>
<th>C</th>
<th>G</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>–</td>
<td>53 (59.3)</td>
<td>151 (201.4)</td>
<td>73 (93.4)</td>
</tr>
<tr>
<td>χ²</td>
<td>0.67</td>
<td>12.6</td>
<td>4.44</td>
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</tr>
<tr>
<td>P</td>
<td>0.42</td>
<td>3.9 × 10⁻⁴</td>
<td>0.04</td>
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</tr>
<tr>
<td>C</td>
<td>53 (46.7)</td>
<td>–</td>
<td>69 (57.7)</td>
<td>338 (256.6)</td>
</tr>
<tr>
<td>χ²</td>
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<td>2.21</td>
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<td></td>
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<tr>
<td>P</td>
<td>0.36</td>
<td>0.14</td>
<td>3.8 × 10⁻⁷</td>
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</tr>
<tr>
<td>G</td>
<td>252 (201.6)</td>
<td>62 (73.3)</td>
<td>–</td>
<td>242 (354.1)</td>
</tr>
<tr>
<td>χ²</td>
<td>1.74</td>
<td>35.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>3.9 × 10⁻⁴</td>
<td>0.19</td>
<td>2.57 × 10⁻⁹</td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>122 (101.6)</td>
<td>273 (354.4)</td>
<td>497 (384.9)</td>
<td>–</td>
</tr>
<tr>
<td>χ²</td>
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<td>32.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>0.04</td>
<td>1.6 × 10⁻⁶</td>
<td>1.1 × 10⁻⁸</td>
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</tr>
</tbody>
</table>
treating the 29 base indel as a single substitution, there were five and four substitutions in the 285 nt of the large intergenic region of the recent isolates, respectively. The differences between these genomes, over the 12 or 13 years separating the sampling of the genomes, represent an evolutionary rate of $3 \times 10^{-4}$ for the coat protein-coding gene and one of $1 \times 10^{-3}$ for the intergenic region (Fig. 4). Strikingly, there was very good agreement between our earlier estimates for the rate of TYLCV evolution and the substitution rate of TYLCV in North America inferred here. However, our estimated rate of EACMV evolution was higher than that inferred for the DNA-A and coat protein gene of North American TYLCV.

**DISCUSSION**

Our analysis revealed that DNA-A of EACMVs, including the detectable-recombinant-free coat protein gene, AV1, had a substitution rate that is similar to both TYLCVs and RNA viruses. However, we could not draw any definitive conclusions about the evolutionary rate of the DNA-B because our dataset contained viral sequences sampled over too short a time span. EACMV and TYLCV are currently the only begomoviruses with sufficient dated sequences to infer substitution rates, although even these estimates were compromised in datasets sampled across only 6 years. Clearly, a far larger sample of viruses is required to increase the accuracy of all EACMVs rate estimates.

This short time span also likely explains why our estimated nucleotide substitution rates for EACMVs were somewhat higher than for TYLCVs, and why our mean TMRCA for the EACMV-UG clade is shorter than implied by epidemiological data. Sequences sampled over shorter timescales tend to produce increased rate estimates, as they are more likely to reflect the background rate of mutation, prior to the action of purifying selection (i.e. they include transient deleterious mutations), than sequences sampled over longer time periods which produce a better estimate of the true substitution rate (Duffy et al., 2008; Holmes, 2003). Indeed, the higher rates in EACMVs are unlikely to be explained by the alternative explanation of adaptive evolution, as there was no evidence for positive selection in these data.

Cassava mosaic disease was first reported in 1894, in Tanzania (Legg & Fauquet, 2004), and is thought to have originated from indigenous African geminiviruses that changed hosts to infect this introduced New World crop (Bull et al., 2006; Fauquet & Fargette, 1990). There are at least five related, geographically grouped clades of CMD-causing viruses: the Indian and Sri Lankan species are more related to each other than to African, East African and South African cassava mosaic viruses (Berrie et al., 2001; Maruthi et al., 2004; Ndunguru et al., 2005; Zhou et al., 1998). Unfortunately, there are very few published dates of isolation for Indian cassava mosaic virus (ICMV), Sri Lankan cassava mosaic virus (SLCMV), ACMV and SACMV sequences, so we could not explore when these clades diverged from one another. However, our mean estimate of 91 years ago (HPD: 34–175 years ago) for the TMRCA of the AV1 gene of EACMVs is consistent with the emergence of CMD in the nineteenth century, and implies that EACMD-causing viruses may be derived from another species of CMD-causing virus that arose earlier. Similarly, our analyses provide evidence against the idea that Eastern and Western African EACMV strains had diverged prior to the arrival of cassava to Africa in the sixteenth century (Ndunguru et al., 2005).

The measured rate of nucleotide substitution of TYLCV as it moved throughout North America validated our high, RNA virus-like, estimates of substitution rates in two begomoviruses (Fig. 4). While our estimated rates of DNA-A evolution were potentially influenced by recombination, the validation of the rate of evolutionary change in the coat protein gene provides strong evidence that begomovirus genes are indeed evolving rapidly. Similarly, the measured substitution rate of TYLCV validated that the large intergenic region is evolving an order of magnitude more quickly than the coat protein-coding gene, as expected given weaker purifying selection. No analyses of intergenic regions for EACMVs were reported because the two datasets only contained sequences from a 6 year span, and were not different from their reshuffled date controls (data not shown), and therefore were not considered reliable.

The high mutation frequency of geminiviruses (Arguello-Astorga et al., 2007; Ge et al., 2007; Isnard et al., 1998; Shepherd et al., 2005), the high estimated substitution rates of geminiviruses (Duffy & Holmes, 2008; van der Walt et
al., 2008), and the high mutation frequencies and nucleotide substitution rates of other families of ssDNA viruses (Shackelton & Holmes, 2006; Shackelton et al., 2005; Umemura et al., 2002) necessitate that ssDNA viruses have high mutation rates. The mutation frequencies and rates of the ssDNA phages φX174 (Denhardt & Silver, 1966; Raney et al., 2004) and M13 (Drake, 1993) approach that of tobacco mosaic virus (7.3–10.3 × 10−6 mut base−1 replication−1; Malpica et al., 2002). If all ssDNA viruses mutate at similar rates, geminiviruses should have mutation rates nearly as high as plant RNA viruses.

It is yet not known how geminiviruses, or any other ssDNA virus, achieve the high mutation rates necessary to explain their genetic variability and their high nucleotide substitution rates while replicating with their hosts’ DNA polymerases (Duffy et al., 2008). Possible explanations include the use of little-used, error-prone plant DNA polymerases, or that the geminivirus mutation rate reflects the polymerase mutation rate without subsequent correction by DNA repair enzymes (Duffy & Holmes, 2008), although there is, as yet, no evidence to support either notion. However, the biased substitution patterns found in EACMV indicate a potential source of mutation besides host polymerase error.

Two of the three significantly overrepresented substitutions from this study (C→T and G→A) were also overrepresented over the evolution of the TYLCVs (Duffy & Holmes, 2008), and are the exact transitions associated with deamination of nucleotide bases (Caulfield et al., 1998). While specific cellular enzymes are known to deaminate bases of viral RNA and DNA (Walsh & Xu, 2006), oxidative deamination can occur spontaneously, and is up to 100 times more likely to occur on ssDNA compared with dsDNA (Frederico et al., 1990). As geminivirus genomes spend time in single-stranded states, they would be susceptible to these spontaneous chemical reactions, and probably do not have access to host DNA-repair enzymes that would correct the damaged, deaminated bases. Evidence for another kind of mutagenic oxidative damage, causing overrepresentation of G→T substitutions, has been found on the virion strand of the mastrevirus maize streak virus (van der Walt et al., 2008) and TYLCVs (Duffy & Holmes, 2008). This was not the case in this study, where the reverse T→G transversion was over-represented. While we have no biochemical explanation for this over-represented substitution, this pattern has been supported by a recent experimental paper that detected only transition mutations and a single T→G transversion in EACMZV (Bull et al., 2007). Although which substitutions are overrepresented may vary among geminiviruses, spontaneous oxidative mutations could be adding to the polymerase-induced mutation rate in all geminiviruses. This mechanism can help to explain the difference between the low estimated per base mutation rate of plant DNA polymerases (Drake et al., 1998) and the necessarily high per base mutation rate of geminiviruses.

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