Vectors of swollen shoot virus

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- Mealybugs are the only known vectors of cacao viruses worldwide.
- All other arthropods tested either failed to transmit CSSV or if any transmission occurred the result was not repeatable.
- Roivainen concluded that CSSV is circulative within vectors as infectivity persists after the 1st nymphal moult.
- However, mealybugs lose the ability to transmit CSSV if starved for 48h and sometimes after a single feed on a healthy plant, which suggests that it is probably stylet borne and not circulative within the endocoel.
- Several mealybug genera vector CSSV which also suggests no intimate association between virus and vectors.

24 Mealybug species are reported from cacao in West Africa: Synonymy

Delococcus (Formicococcus) tafoensis (Strickland)	Ghana/Togo
Delottococcus (Pseudococcus, Paracoccus) sp. nr *proteae* (Hall)	Ghana/Nigeria
*Dysmicoccus brevipes (*Cockerell) = *Pseudococcus bromeliae* Bouche	Ghana/Togo/Nigeria
Ferrisia (Ferrisiana) virgata (Cockerell)	West Africa
Formicococcus (Planococcoides, Planococcus, Pseudococcus) celtis (Strickland)	Sierra Leone/Ghana
F. (Planococcoides, Pseudococcus) njalensis (Laing) = *F. (Planococcus, Planococcoides) lamabokensis* (Balachowsky & Ferrero); *Pseudococcus exitiabilis* Laing	West Africa
Geococcus coffeae Green	Ghana/Nigeria
Heliococcus sp.	Nigeria
Maconellicoccus hirsutus (Green) = *M. perforatus* (De Lotto)	Togo
M. (Pseudococcus) ugandae (Laing); *Phenacoccus* sp. H6418	Ghana/Togo
Paraputo anomala (Newstead) *= P. multispinosa* James; *P. ritchei* James	Ghana
P. (Cataenococcus, Farinococcus) loranthi (Strickland)	Ghana
Phenacoccus (Pseudococcus) hargreavesi (Laing) = *Pseudoccus bukobensis* Laing	West Africa
P. madeirensis Green	Ghana
Planococcus (Tylococcus) boafoensis (Strickland)	Ghana
P. (Pseudococcus) citri (Risso)	West Africa
P. principe Cox	Sao Tome and Principe
P. kenyae (Le Pelley)	West Africa/Zaire
Pseudococcus calceolariae (Maskell) = *P. gahani* Green; *P. fragilis* Brain	Ghana/Togo/Nigeria
P. comstocki (Kuwana)	Ghana
P. concavocerarii James	West Africa
P. longispinus (Targioni-Tozzetti) = *P. (Dactylopius) adonidum* L.	Ghana/Togo/Nigeria
Rhizoecus spelaeus (Strickland) = *Coccidella spelaea* Strickland	Ghana
Tylococcus westwoodi Strickland	Ivory Coast/Ghana/Togo

Morphological identification of cacao mealybugs:

- My draft field key to adult females will be made available.†

- Currently the only accurate method of confirming the identity of adult female mealybugs from cacao is by microscopic examination of mounted specimens. Making usable slide mounts takes much practice as the key differences are often small!

- My draft key to adult females of all species known on cacao will be made available (but see caviat below! †).

Molecular identification:

- Simple and accurate identification of any stage, but not available yet. Work is ongoing.

† These keys await exhaustive testing. Please e-mail me if/when teething problems occur at cam_campbell@tiscali.co.uk

Known CSSV vectors	**% cacao trees infested †**
Delococcus tafoensis	< 1%
Delottococcus sp. nr *proteae*	< 1%
Dysmicoccus brevipes	< 1%
Ferrisia virgata	7 %
Formicococcus celtis	< 1%
Formicococcus njalensis	69%
Maconellicoccus ugandae	8%
Paraputo anomala	< 1%
Phenacoccus hargreavesi	72%
Planococcus citri / *Pl. kenyae*	93%
Pseudococcus calceolariae	3%
Ps. concavocerarii	21%
Ps. longispinus	10%
Tylococcus westwoodi (with *Crematogaster stadelmanni* only)	7%

NB: All of these vectors are polyphagous colonising a range of host plants

† Abundance data for CRIG from Campbell (1983)

Vector status unknown (but almost certainly unimportant)	% cacao trees infested
Geococcus coffeae	? (On roots only)
Heliococcus sp.	Probably misidentified †
Maconellicoccus hirsutus	?
Paraputo loranthi	Common on mistletoe on cacao
Planococcus boafoensis	< 1%
Pl. principe	? Known only in sao Tome and Principe
Ps. comstocki	< 1%
Rhizoecus spelaeus	? (On roots only)

† *Heliococcus phaseoli* is the only West African representative of the genus. It feeds exclusively on *Phaseolus* and some related beans.

Non-vector of CSSV

Phenacoccus madeirensis	< 1%

Principal CSSV vectors	% cacao trees infested
Delococcus tafoensis	< 1%
Delottococcus sp. nr *proteae*	< 1%
Dysmicoccus brevipes	< 1%
Ferrisia virgata	7 %
Formicococcus celtis	< 1%
Formicococcus njalensis	69%
Maconellicoccus ugandae	8%
Paraputo anomala	< 1%
Phenacoccus hargreavesi	72%
Planococcus citri]	93%
Pl. kenyae]	
Pseudococcus calceolariae	3%
Ps. concavocerarii	21%
Ps. longispinus	10%
Tylococcus westwoodi (with *Crematogaster stadelamanni* only)	7%

Abundance data from Campbell (1983)

Percentages of principal CSSV vector populations in the cacao canopy

	Strickland (1951)	Donald (1955)	Campbell (1983)
Ferrisia virgata	-	28	36
Formicococcus njalensis	87	97	87
Planococcus citri/kenyae	-	66	66
Phenacoccus hargreavesi	-	100	99
Pseudococcus concavocerarii	-	87	100

Radial spread of CSSV is achieved by mealybugs walking across canopy bridges from infected to healthy trees.
Jump spread is by wind-borne nymphs. *Pl. citri* and *F. virgata* are the only cacao species proven to spread aerially.
Transport by attendant ants: Rare. Not proven in cacao.

	Ant attended	Female length † (mm)	Principal feeding sites
Ferrisia virgata	-	5 x 2.8	Flaccid leaves
Formicococcus njalensis	+++	2 x 1.7	All
Planococcus citri/kenyae	++	2.5 x 1.3	All
Phenacoccus hargreavesi	+-	4 x 2.2	Buds/shoots
Pseudococcus concavocerarii	-	3 x 1.5	Pods/shoots

† Mean dimensions of mounted specimens so minus cerarial wax filaments.

CSSV Transmission by mealybugs

Most information is on *Fo. njalensis*, followed by *Fe. virgata*

- 1st instar *Fo. njalensis* walk 6mm/min on smooth paper but slower on sand. *Fe. virgata* are 2.5x bigger with 5x longer legs.
- Speed of walking should be proportional to size. Adult female *Fo. njalensis* rarely disperse unlike those of *Fe. virgata.*
- Cornwell showed 1st instar *Fo. njalensis* readily cross simple twig bridges – the importance of other canopy bridges such as flush leaves is unknown for any species.
- Maximum transmission ability for *Fo. njalensis* occurs after 16 h feeding, but can occur after 5 h acquisition feed (AAT).
- Starving 1st instar *Fo. njalensis* for 24 h prior to a 6 h AAT more than doubled transmission (from 24% to 56%).

Possible control opportunities via vector manipulation:

1. Insecticides. - Failed for insurmountable reasons.

2. Biological control by exotic parasitoids, pathogens and/or predators.
   - All attempts to introduce exotic predators and pathogens on cacao in Ghana failed completely.

3. Manipulation of the ant mosaic. – Failed using insecticides but may be possible by introducing other soft scales.

4. Host plant resistance.

5. Separating cocoa plantings by other tree crops to halt CSSV spread by isolating potential vectors.

6. Semiochemicals (eg sex pheromones).
   - Not studied in cacao, but the complexity of species present as potential vectors may rule out this approach.

Host plant resistance to mealybug vectors:

- Roivainen showed that 5 cocoa progenies differed in their susceptibility to *Fo. njalensis* , with seedling Amazon x Amelonado supporting 44% fewer than Amelonado (*P*<0.001).

- Campbell studied the 68 progenies in the BRT CSSV rate of spread trials and found up to a 5-fold difference in mealybug numbers in buds.
  - Progenies resistant to *Fo. njalensis* were also resistant to *Pl. citri* and probably to other mealybug species also.
  - Host plant resistance to the vectors helps explain why some cacao progenies such as IMC's and Nanay's show greater field resistance to CSSV infection than expected from laboratory studies.

- Firempong found that survival of *Fo. njalensis* nymphs was reduced by 73% and adult body weight by 87% between susceptible Amelonado and the most resistant crosses. Firempong's method could be used to screen cacao progenies in the laboratory.

Separating cocoa plantings by other tree crops to halt CSSV spread by filtering the virus from potential vectors.

- In a 5-year study, Ollennu found that barriers of citrus and oilpalm largely prevented spread of CSSV from graft-infected cacao. Kola was less effective in Ollennu’s study, but was effective in Togo (Tsatsu & Bekou, 2005) as was coffee in a later experiment (Oro *et a*l. 2012).

- Rubber, citrus, coffee and cacao host two mealybug species in common (*Pl. citri* and *Fe. virgata*). Such interplants could act as traps for these species, arresting further dispersal. Nymphs of other species are unlikely to traverse such a barrier and remain viable.

- As over 80% of mature cacao trees are mealybug infested already, it is unlikely that such interplants would have any detectable effect on overall mealybug populations.

- The depth necessary to provide an effective barrier to spread of CSSV remains unstudied.

Conclusions
Entomology research priorities

1. Separating new from old cacao plantings by a physical barrier of an alternative tree crop should can reduce radial spread of CSSV. Any research project should include studies of mealybug dispersal similar to those by Cornwell (1956).

2. The genetic basis of host plant resistance to mealybugs needs elucidating in order to speed-up the selection process.

3. Accurate morphological identification of mealybug vectors is a specialist skill. Identification using DNA markers will provide an easily accessible and less error prone alternative.