Combatting Cocoa Swollen Shoot Virus Disease: What do we know?

Christian Andres a, b, *, Andreas Gattinger a, Henry K. Dzahini-Obiatey c, Wilma J. Blaser b, Samuel K. Oftei d, Johan Six a

a Research Institute of Organic Agriculture (FiBL), Ackerstrasse 113, Postfach 219, 5070 Frick, Switzerland
b Department of Environmental Systems Science, Swiss Federal Institute of Technology, ETH Zurich, Tannenstrasse 1, 8092 Zürich, Switzerland
c Cocoa Research Institute of Ghana, P. O. Box 8, New Tafo-Akim, Eastern Region, Ghana
d University of Ghana, P.O. Box LG 25, Legon, Accra, Ghana

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Abstract
Cocoa Swollen Shoot Virus Disease (CSSVD) is one of the major factors limiting cocoa (Theobroma cacao L.) productivity in West Africa. The only cure for CSSVD is to cut out visibly infected trees and the official eradication campaign in Ghana has cut out more than 200 million trees since 1946. 80 years of research on preventive control measures have mainly focused on resistance breeding, mild strain cross-protection (inoculation of cocoa seedlings with a mild strain of the virus to protect against the severe strain) and control of mealybug vectors. Meanwhile, diversification measures such as agroforestry (for shading) or barrier (strip) cropping have received less attention. Despite promising results, CSSVD is more prevalent in the field than ever before. The large body of knowledge on preventive control measures for CSSVD is fragmented and many publications are not easily accessible. Furthermore, the literature has never been systematically evaluated and quantitatively assessed. Hence, we consolidated this knowledge with an extensive literature review followed by meta-analysis to identify the pertinent research gaps. Out of 423 publications on CSSVD-related issues, we selected 34 studies, which contained 52 datasets on seven different preventive control measures. Results showed that resistance breeding and mild strain cross-protection may reduce CSSVD infection by 30 percent, while the potential of diversification measures (shading/agroforestry and barrier (strip) cropping) seems to be considerably higher (40 and 85 percent, respectively). However, there is a lack of evidence because of a low number of studies about diversification measures, indicating that our results have to be interpreted with care and calling for more research in this area. Future testing is needed to evaluate the efficacy of barrier (strip) cropping to reduce CSSVD, and address the effect of shade on CSSVD symptom severity. Furthermore, the practical relevance of different preventive control measures for farmers needs to be assessed, and shade should be considered in current breeding programs for CSSVD resistance.

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1. Introduction
Cocoa swollen shoot virus disease (CSSVD) has plagued cocoa (Theobroma cacao L.) production in West Africa for more than eight decades (Dzahini-Obiatey et al., 2010). CSSVD is caused by the cocoa swollen shoot virus (CSSV), belonging to the genus Badnavirus (Lot et al., 1991). CSSV only occurs in West Africa, and has been reported in Côte d’Ivoire, Ghana, Nigeria, Sierra Leone and Togo (Fig. 1, (Muller, 2016)). The disease has been particularly severe in Ghana, where it was already observed in 1922 (Paine, 1945) and described in 1936 (Steven, 1936).

Several institutes in Nigeria, Togo and particularly in Ghana have done extensive research on CSSVD in virology, epidemiology and genetic improvement of cocoa germplasm. CSSV is genetically diverse; different isolates/strains can cause different symptoms, including transient red veins and mottling in young leaves, different shades of chlorosis in mature leaves and pods, root atrophy and stunting, as well as root and stem swellings. Most of these symptoms are unique to different strains and symptom expression depends on host genotype. Highly pathogenic strains cause severe leaf chlorosis, which may result in rapid death of cocoa trees (Dzahini-Obiatey et al., 2010).

Different species of mealybugs (Pseudococcidae spp.), the most important ones being Formicococcus njalensis (Laing) and
Planococcus citri (Box, 1945; Cornwell, 1953, 1958, 1960; Thresh and Tinsley, 1959; Roivainen, 1971; Bigger, 1981) spread CSSVD. The spread of CSSVD can happen in two ways: either through "radial spread", caused by relatively immobile adult mealybugs that move along interlocking branches of adjacent trees, or through "jump spread", caused by more mobile first instar nymphs transported by wind, which create new outbreaks (Jeger and Thresh, 1993).

The only treatment for CSSVD-infected cocoa is to cut out visibly infected trees (eradication). Thereby, symptomatic trees are removed together with all adjacent, apparently healthy trees. When large outbreaks occur, extensive areas are cleared and replanted (Thresh and Owusu, 1986). The official eradication campaign in Ghana, launched in 1946, has cut out more than 200 million trees by 2010, and has been called the costliest campaign of its kind anywhere in the world (Thresh et al., 1988; Ampofo, 1997). However, the eradication campaign failed due to various reasons, such as the campaign being disrupted and discontinued several times (Ollennu et al., 1989; Dzahini-Obiatey et al., 2006), and because of deficient eradication procedures (Thresh et al., 1988). Consequently, the disease continues to spread into new areas (Domfeh et al., 2011).

Past research has had some focus on the development of preventive control measures to be implemented along with eradication (Table 1). However, farmers have only to a limited extend implemented those measures, which may be due to their perspective and situation not sufficiently being taken into account. For example, farmers said they would not do barrier (strip) cropping with oil palm because it attracts rodents, which can damage cocoa pods (Wetten, pers. comm.). The selection of the suitable trees that match farmers’ preferences and expectations is most likely to be successful when done in a participatory manner together with farmers, so that their views and knowledge are taken into account (Vaast and Somarriba, 2014).

There is a lot of anecdotal knowledge about preventive control measures for CSSVD, especially in the library of African institutions such as the Cocoa Research Institute of Ghana (CRIG). However, this information is fragmented and has never been systematically evaluated and quantitatively assessed. In this study, we consolidated this knowledge in order to provide a basis for future research and development. We conducted an extensive literature review followed by meta-analysis to elaborate the relative effectiveness of different preventive control measures for CSSVD. We hypothesised that preventive control measures related to diversification (barrier (strip) cropping, shading/agroforestry) reduce CSSVD infection significantly more than preventive control measures related to breeding and mild strain cross protection.

2. Materials and methods

2.1. Data collection

To identify studies reporting preventive control measures for CSSVD we searched the databases of Web of Science, Scopus and Google Scholar using the following keywords: "Cocoa Swollen Shoot Virus Disease", "Cocoa Swollen Shoot Virus", "Swollen Shoot Virus", "Swollen Shoot Disease", "CSSVD" and "CSSV". We gathered further articles from the reference sections of already collected articles, and from an Endnote library on CSSVD.
related literature, which was compiled by researchers from CRIG (Ameyaw, pers. comm.), and the University of Reading, UK (Cryer, pers. comm.). These were often technical or annual reports, which were only available as hardcopies in the CRIG library (grey literature). These were often technical or annual reports, which were only available as hardcopies in the CRIG library (grey literature). These were often technical or annual reports, which were only available as hardcopies in the CRIG library (grey literature). These were often technical or annual reports, which were only available as hardcopies in the CRIG library (grey literature). These were often technical or annual reports, which were only available as hardcopies in the CRIG library (grey literature).

We screened all articles and selected those for meta-analysis (in the following referred to as "eligible studies") that met the following criteria: i) an improved practice was compared to a control under the same pedo-climatic conditions, ii) the data presented values of visible CSSVD symptoms (of seedlings/trees) in the improved practice and control treatment, respectively, and iii) the mean values of improved practice and control were reported together with a measure of variability (standard deviation, standard error of the mean or \( p \) value) and number of replications (n). This led to the selection of 34 studies with 52 sub-studies (Table 2) that reported data on seven different improved practices (Table 1). A full reference list of the papers included in the meta-analysis is provided in Appendix A. In this paper, the term "study/studies" refers to individual papers/publications, while the term "sub-study/sub-studies" refers to different experiments/trials presented in the same study. Furthermore, we used visible CSSVD symptoms as a proxy for CSSVD infection. Actual CSSVD infection can only be confirmed by serology or nucleic acid-based testing. However, for ease of understanding we used the term "CSSVD infection" in the text.

2.2. Data analysis

We extracted the data from the 52 eligible sub-studies manually and compiled them in a common Microsoft Excel data matrix. We calculated the reduction of CSSVD infection as follows:

\[
\text{Reduction of infection} \% = \left( 1 - \frac{\text{Infection}_{\text{IP}}}{\text{Infection}_{\text{control}}} \right) \times 100
\]

where Infection\(_{\text{IP}}\) and Infection\(_{\text{control}}\) = absolute (number of seedlings/trees) or relative (percentage) values of CSSVD infection in improved practice and control treatment, respectively.
Table 2
Overview of the studies on preventive control measures for cocoa swollen shoot virus disease included in the meta-analysis (Appendix A).

<table>
<thead>
<tr>
<th>Reference</th>
<th>Institution and location of study</th>
<th>Improved practice (IP)</th>
<th>Type of publication</th>
<th>Scale of comparison</th>
<th>Number of sub-studies</th>
<th>Age IP</th>
<th>Duration of measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adomako and Owusu, 1974</td>
<td>CRIG, Tafo, Ghana</td>
<td>Antiviral substance</td>
<td>0</td>
<td>Greenhouse/lab</td>
<td>1</td>
<td>n.a.</td>
<td>1 yr</td>
</tr>
<tr>
<td>Dzahini-Obiatey et al., 2005</td>
<td>CRIG, Tafo, Ghana</td>
<td>Antiviral substance</td>
<td>1</td>
<td>Greenhouse/lab</td>
<td>1</td>
<td>n.a.</td>
<td>1 yr</td>
</tr>
<tr>
<td>Ollennu et al., 2005</td>
<td>CRIG, Bunso, Ghana</td>
<td>Barrier (strip) cropping</td>
<td>1</td>
<td>Plot</td>
<td>1</td>
<td>5 yr</td>
<td>11 yr</td>
</tr>
<tr>
<td>Adomako, 1977</td>
<td>CRIG, Tafo, Ghana</td>
<td>Breeding</td>
<td>1</td>
<td>Greenhouse/lab</td>
<td>1</td>
<td>n.a.</td>
<td>84 d</td>
</tr>
<tr>
<td>Adu-Ampomah et al., 1996</td>
<td>CRIG, Tafo, Ghana</td>
<td>Breeding</td>
<td>1</td>
<td>Plot</td>
<td>2</td>
<td>3.5 yr</td>
<td>3 yr</td>
</tr>
<tr>
<td>Citas et al., 1988</td>
<td>IRCC, Kpalime, Togo</td>
<td>Breeding</td>
<td>0</td>
<td>Greenhouse/lab</td>
<td>1</td>
<td>n.a.</td>
<td>1 yr</td>
</tr>
<tr>
<td>Dale, 1957</td>
<td>CRIG, Tafo, Ghana</td>
<td>Breeding</td>
<td>1</td>
<td>Greenhouse/lab</td>
<td>1</td>
<td>n.a.</td>
<td>2 yr</td>
</tr>
<tr>
<td>Dziekpor et al., 1995</td>
<td>IRCC, Kpalime, Togo</td>
<td>Breeding</td>
<td>0</td>
<td>Greenhouse/lab</td>
<td>1</td>
<td>n.a.</td>
<td>1 yr</td>
</tr>
<tr>
<td>Kenten and Legg, 1970</td>
<td>CRIG, Tafo, Ghana</td>
<td>Breeding</td>
<td>0</td>
<td>Greenhouse/lab</td>
<td>1</td>
<td>n.a.</td>
<td>1 yr</td>
</tr>
<tr>
<td>Kenten and Lockwood, 1977</td>
<td>CRIG, Tafo, Ghana</td>
<td>Breeding</td>
<td>0</td>
<td>Greenhouse/lab</td>
<td>1</td>
<td>n.a.</td>
<td>1 yr</td>
</tr>
<tr>
<td>Legg and Knten, 1970</td>
<td>CRIG, Tafo, Ghana</td>
<td>Breeding</td>
<td>0</td>
<td>Greenhouse/lab</td>
<td>1</td>
<td>n.a.</td>
<td>1 yr</td>
</tr>
<tr>
<td>Legg and Kenten, 1971a</td>
<td>CRIG, Tafo, Ghana</td>
<td>Breeding</td>
<td>0</td>
<td>Plot</td>
<td>1</td>
<td>3.5 yr</td>
<td>9 yr</td>
</tr>
<tr>
<td>Legg and Lockwood, 1971b</td>
<td>CRIG, Tafo, Ghana</td>
<td>Breeding</td>
<td>1</td>
<td>Plot</td>
<td>1</td>
<td>4 yr</td>
<td>10 yr</td>
</tr>
<tr>
<td>Legg and Lockwood, 1977a</td>
<td>CRIG, Tafo, Ghana</td>
<td>Breeding</td>
<td>0</td>
<td>Plot</td>
<td>1</td>
<td>3 yr</td>
<td>9 yr</td>
</tr>
<tr>
<td>Lockwood, 1981a</td>
<td>CRIG, Tafo, Ghana</td>
<td>Breeding</td>
<td>1</td>
<td>Plot</td>
<td>1</td>
<td>n.a.</td>
<td>1 yr</td>
</tr>
<tr>
<td>Lockwood, 1981b</td>
<td>CRIG, Tafo, Ghana</td>
<td>Breeding</td>
<td>0</td>
<td>Greenhouse/lab</td>
<td>1</td>
<td>n.a.</td>
<td>1 yr</td>
</tr>
<tr>
<td>Longworth et al., 1965</td>
<td>CRIG, Tafo, Ghana</td>
<td>Breeding</td>
<td>0</td>
<td>Greenhouse/lab</td>
<td>1</td>
<td>n.a.</td>
<td>1 yr</td>
</tr>
<tr>
<td>Paulin et al., 1994</td>
<td>IRCC, Kpalime, Togo</td>
<td>Breeding</td>
<td>1</td>
<td>Greenhouse/lab</td>
<td>3*</td>
<td>n.a.</td>
<td>1 yr</td>
</tr>
<tr>
<td>Posnette and Todd, 1951</td>
<td>CRIG, Tafo, Ghana</td>
<td>Breeding</td>
<td>0</td>
<td>Greenhouse/lab</td>
<td>4</td>
<td>n.a.</td>
<td>1 yr</td>
</tr>
<tr>
<td>Tsatsu and Bekou, 2003</td>
<td>IRCC, Kpalime, Togo</td>
<td>Breeding</td>
<td>1</td>
<td>Plot</td>
<td>3**</td>
<td>15 yr</td>
<td>15 yr</td>
</tr>
<tr>
<td>Hanna and Heatherington, 1957</td>
<td>Chesterford Research Park, Atukrum, Ghana</td>
<td>Insecticide (vector control)</td>
<td>0</td>
<td>Farm</td>
<td>1</td>
<td>2 yr</td>
<td>2 yr</td>
</tr>
<tr>
<td>Crowdy and Posnette, 1947</td>
<td>CRIG, Tafo, Ghana</td>
<td>Mild strain cross protection</td>
<td>0</td>
<td>Plot</td>
<td>1</td>
<td>6 yr</td>
<td>3 yr</td>
</tr>
<tr>
<td>Ollennu and Owusu, 1997</td>
<td>CRIG, Tafo, Ghana</td>
<td>Mild strain cross protection</td>
<td>1</td>
<td>Plot</td>
<td>1</td>
<td>6 yr</td>
<td>7 yr</td>
</tr>
<tr>
<td>Ollennu and Owusu, 2002</td>
<td>CRIG, Tafo, Ghana</td>
<td>Mild strain cross protection</td>
<td>1</td>
<td>Plot</td>
<td>1</td>
<td>0.5 yr</td>
<td>8 yr</td>
</tr>
<tr>
<td>Ollennu and Owusu, 2003</td>
<td>CRIG, Tafo, Ghana</td>
<td>Mild strain cross protection</td>
<td>0</td>
<td>Plot</td>
<td>1</td>
<td>4 yr</td>
<td>3.5 yr</td>
</tr>
<tr>
<td>Ollennu et al., 1996</td>
<td>CRIG, Tafo, Ghana</td>
<td>Mild strain cross protection</td>
<td>1</td>
<td>Plot</td>
<td>1</td>
<td>1.5 yr</td>
<td>1 yr</td>
</tr>
<tr>
<td>Ollennu et al., 1999</td>
<td>CRIG, Tafo, Ghana</td>
<td>Mild strain cross protection</td>
<td>0</td>
<td>Plot</td>
<td>1</td>
<td>4 yr</td>
<td>1 yr</td>
</tr>
<tr>
<td>Owusu et al., 1999</td>
<td>CRIG, Tafo, Ghana</td>
<td>Mild strain cross protection</td>
<td>1</td>
<td>Greenhouse/lab</td>
<td>3*</td>
<td>n.a.</td>
<td>1 yr</td>
</tr>
<tr>
<td>Owusu, 1971</td>
<td>CRIG, Tafo, Ghana</td>
<td>Mild strain cross protection</td>
<td>1</td>
<td>Plot</td>
<td>2***</td>
<td>17 yr</td>
<td>1 yr</td>
</tr>
<tr>
<td>Adegbola, –</td>
<td>CRIN, Ibadan, Nigeria</td>
<td>Shading/agroforestry</td>
<td>1</td>
<td>Greenhouse/lab</td>
<td>1</td>
<td>n.a.</td>
<td>56 d</td>
</tr>
<tr>
<td>Quainoo et al., 2008</td>
<td>University for Development Studies, Tamale, Ghana</td>
<td>Somatic embryogenesis</td>
<td>0</td>
<td>Greenhouse/lab</td>
<td>2</td>
<td>n.a.</td>
<td>1 yr</td>
</tr>
</tbody>
</table>

CRIG — Cocoa Research Institute of Ghana, IRCC — Institut de Recherches du Cafe et du Cacao, CRIN — Cocoa Research Institute of Nigeria; n.a. — not applicable (in greenhouse/lab studies improved practice is implemented directly); *two greenhouse/lab experiments, one plot comparison; **two plot comparisons, one greenhouse/lab experiment; ***one greenhouse/lab experiment, one plot comparison.

* a = scientific journal article, 1 = books chapter/proceeding/technical report.
* b = Sub-studies are different experiments/trials presented in the same study.
* c = Time period since adoption of improved practice in years (yr).
* d = Time period of measurements in days (d)/years (yr).
Thereby, each data pair corresponded to one comparison of an improved practice with the control. For example, if one study presented data for five partially resistant varieties versus a susceptible control, this resulted in five data pairs (comparison of each variety with the control). This led to a total number of 400 data pairs (see legend in Fig. 2).

In some cases, there were multiple comparisons of different levels of improved practices with the same control in one study (e.g., five partially resistant varieties each time versus the same susceptible control). Since these data are not independent from each other, creating an individual data pair from each level of the improved practice with the same control led to an overestimation of the control value’s confidence through artificial repetitions in the dataset. This overestimation was avoided by aggregating the data pairs to sub-study level at the cost of losing some information from the individual values of the different levels of the improved practices. We chose this procedure because the number of replications (n) was equal among different levels of the improved practices and the control in most studies. Therefore, we did not risk to lose information from the weighing of the mean values of the different levels of the improved practices (which depends on the value of n).

Among the eligible studies, there were two groups of studies: studies, which were carried out at the greenhouse-/lab-scale, and studies, which were carried out at the plot/farm-scale. To account for the compilation of all studies in one common data matrix, we run two separate meta-analyses for the two subgroups. This allowed us to check whether their outcomes would differ from the outcome of the single meta-analysis performed on the pooled dataset. Since the outcomes did not differ, we pursued the single meta-analysis of the pooled dataset at sub-study level.

We calculated the magnitude of effects ("effect sizes") as the raw mean difference (MD) of improved practices over the control using their respective standard deviations and numbers of replications (n). We chose the random-effects model because it assumes that single effect sizes depend on the study context (differences in methods and sampling), which was very much the case in our heterogeneous dataset. We estimated the average true effect and variance $\tau^2$ with the restricted maximum-likelihood estimator (REML), and used the Knapp-Hartung adjustment to account for uncertainties when estimating (residual) heterogeneity. We found no outliers in our dataset by DFBETAS value analysis (Viechtbauer, 2010). We defined the weighted MDs of the improved practices to be significantly different from zero or from each other when the 95% confidence interval (CI) did not overlap zero or the 95% CI of another improved practice. We conducted all analyses with the "metafor" package of the R statistical software, version 3.3.1 (Viechtbauer, 2010).

3. Results

From the five countries with reported CSSVD cases, only three had eligible studies that we included in the meta-analysis (Fig. 1), and the vast majority of the eligible studies were conducted in Ghana (Table 2). Most of the studies focused on the two improved practices breeding and mild strain cross protection (56% and 26%, respectively), both of which showed a potential to reduce CSSVD by about 30% (Fig. 2). There were only two studies concerning diversification measures (shading/agroforestry and barrier (strip) cropping). Both improved practices showed a higher potential to reduce CSSVD by 40% (shading/agroforestry) and 85% (barrier (strip) cropping), respectively (Table 2).

Further, we only found one study about the effect of insecticide (vector control) on the number of visibly infected trees, which was also the only farm-scale study we included in the meta-analysis. The mean value of 86% (of the 11 consecutive field observations conducted on a monthly interval), shows a trend towards a high potential of this improved practice (Fig. 2). Regarding screening methods for resistance breeding, we had only one eligible study for somatic embryogenesis and two for antiviral substance. With a mean value of 89%, the potential of somatic embryogenesis was clearly superior to antiviral substance (4%).

4. Discussion

We first discuss our results’ implications and knowledge gaps for each improved practice, then outline the limitations of our dataset and finally provide an outlook on solving the CSSVD problem.

4.1. Best practices and knowledge gaps in the combat of CSSVD

Our results show that all preventive measures included in the meta-analysis significantly reduced CSSVD infection under
researcher managed conditions, except for antiviral substance (Fig. 2). Furthermore, they depict that the focus of past research activities has been on breeding and mild strain cross protection, while the other improved practices, which could be very much of practical relevance for farmers (i.e., barrier (strip) cropping, shading/agroforestry and insecticide (vector control)), are only represented by a single study each. According to Posnette (1981), no other feasible measures would be as effective in reducing the losses caused by CSSVD as an increase in varietal resistance, which may decrease the rate of spread by up to 20%. Our results for breeding confirm this, and even show a higher potential for this improved practice (30%) than claimed by the author. Many viral diseases in other crops such as potato, tobacco and tomato have effectively been managed by increasing varietal resistance (Swaminathan, 1993; Moury et al., 2010). However, a recent publication in this field of research by Padi et al. (2013) shows no significant differences in resistance between existing and new varieties, underlying the limitations inherent in recycling the minimal resistance available within a narrow genetic base, and calls for a re-appraisal of variety recommendations.

Our results suggest that the potential of mild strain cross protection is just as high as breeding. Preventing the adverse effects of severe virus strains by inoculating cocoa beans or seedlings with mild strains is certainly promising (Ollenu et al., 1999; Dzahini-Obiatey et al., 2010; Muller, 2016). However, implementing this improved practice on a large scale is very laborious and costly, and entails several technical and logistical challenges such as inoculating and distributing several millions of cocoa seedlings to farmers every year (Domfeh, pers. comm.). Furthermore, the high genetic diversity of CSSV makes it difficult to find appropriate mild strains for different severe strains, and simultaneous protection against several different severe strains is practically not feasible (Ollenu et al., 1999; Dzahini-Obiatey et al., 2010; Muller, 2016). In contrast, diversification measures (barrier (strip) cropping and shading/agroforestry) showed a higher potential in our study. However, our results have to be interpreted with care due to the limited number of studies, which is also reflected in the wide confidence intervals of these improved practices, and explains why the positive error bar of barrier (strip) cropping goes beyond 100% reduction of infection (Fig. 2). Nevertheless, the most recent publication in the field of barrier (strip) cropping confirms our results (Domfeh et al., 2016). The promising trend we show here, coupled with the fact that the implementation of these improved practices by smallholders may be relatively easy (i.e., no need for costly inputs), calls for further research in this area. Furthermore, it would be important to consider shade as a factor in currently ongoing breeding programs for CSSVD resistance.

There is a knowledge gap about the potential of more diversified production systems such as agroforestry or strip crop systems to reduce the spread and/or severity of CSSVD. In general, the effects of shade trees on incidences of pests and diseases in cocoa production systems are complex and ambiguous (Beer et al., 1998; Staver et al., 2001; Bedimo et al., 2012). Many studies have shown that self-regulation, the natural control of pests and diseases, is enhanced in diversified cocoa production systems (Sperber et al., 2004; Isaac et al., 2007; Lin, 2011; Tscharntke et al., 2011; Bieng et al., 2013; Gidoin et al., 2014; Mbow et al., 2014; Vaast and Somarriba, 2014). However, the effects of different commonly used shade tree species on mealybug populations and CSSVD infection have not been investigated so far, and they may vary depending on individual shade tree species (Franzen and Mulder, 2007). Furthermore, it is difficult to identify adequate shade levels and tree species compositions that minimize mealybug populations and thus likelihood of CSSVD infection while ensuring favourable growing conditions for cocoa trees. This is because both optimal shade levels for cocoa trees and mealybug populations vary in the course of the year. Therefore, more research on effective agroforestry designs to combat CSSVD is needed. In this respect, it might be worthwhile to facilitate exchange between CSSVD specialists and ongoing agroforestry systems research in the humid tropics such as the project “agroforestry for food security” (AFS4-Food) by CIRAD. AFS4Food assesses the performance of agroforestry systems to understand the compromises farmers have to strike between the products and the different services provided by such systems.

Interestingly, the result from the only study we included in the meta-analysis about vector control, suggests a high potential of a systemic insecticide to control the mealybug vectors and thus reduce CSSVD. This is particularly interesting, as it is the only farm-scale study (i.e., conducted under actual farmers’ field conditions) we included in the meta-analysis. Systemic insecticides have also been found to be effective under researcher-managed conditions. However, a number of problems associated with their use have been reported, such as their high cost, toxicity to mammals and residues in cocoa beans (Domfeh, pers. comm.). Unfortunately, most studies on vector control (e.g., Hanna et al., 1952; Nicol, 1952) have only reported the effect of a particular insecticide on the abundance of mealybugs, and not on CSSVD infection. However, reporting CSSVD infection is crucial, as lower numbers of mealybugs do not necessarily translate into reduced CSSVD infection, especially due to the very patchy distribution of mealybugs in the field (Campbell, 1990). Therefore, such studies should be repeated under field conditions and in addition to the effects on mealybug populations, the number of symptomatic trees should also be reported.

Regarding screening methods for resistance breeding, our results suggest that somatic embryogenesis is superior to antiviral substances (quercetin, cocoa leaf and embryo extracts). However, care has to be taken in the interpretation of our results due to the limited number of studies, which also explains the high confidence intervals of these improved practices and the fact that the negative error bar of antiviral substance and the positive error bar of somatic embryogenesis are below 0% and beyond 100% reduction of infection, respectively (Fig. 2). This is because in a meta-analysis, the confidence intervals of each mean are weighted with the number of replications and the measure of variability presented in the original studies. Hence, the credible intervals may go below or beyond a certain meaningful value (like in our case) because of estimates done by the software.

Besides the effect of individual improved practices, the factor age (i.e., the period since adoption of an improved practice) may correlate with the reduction of infection. We checked this for the 16 studies where data on “Age IP” (Table 2) was available. The results showed that there is a slight trend towards lower reduction of infection with increasing time since adoption, but this was statistically not significant. However, other works suggest that both breeding and mild strain cross protection may be effective in delaying the spread of CSSVD, but not to completely prevent it (Posnette, 1981; Ameyaw et al., 2016).

4.2. Limitations of the dataset

It is important to note that the effect size presented in this meta-analysis (reduction of infection as percentage) is a relative measure. As such, it may lead to an under- or overestimation of the potential of a particular improved practice to reduce CSSVD infection under field conditions. We accounted for this by aggregating the data pairs to sub-study level as explained in section 2.2. Finding an adequate effect size that would allow for comparison of the heterogeneous set of studies while accounting for the pooling of
comparisons at different scales (greenhouse/lab vs. plot/farm) was challenging, and the percentage reduction of infection we chose represented the best possible compromise to satisfy both. In this respect, we acknowledge that our meta-analysis is rather a descriptive analysis to identify overall patterns in the currently available dataset rather than an inferential statistical method delivering exact results. Another shortcoming of the dataset is that many of the studies are quite old (average year of publication was 1983). This is not to say that there are no recent publications on CSSVD. However, none of the more recent publications has looked at the effect size presented in this study, which is of practical relevance to farmers.

4.3. Solving the CSSVD problem: an outlook

80 years of disciplinary research and 70 years of official eradication campaign has been a very cost-intensive endeavour, which has not solved the CSSVD problem in Ghana (Dzahini-Obiatay et al., 2010). While the currently ongoing breeding efforts for CSSVD resistance and subsequent replacement of susceptible cocoa with resistant varieties may be part of the solution, there is certainly a long way to go until widespread implementation on the ground will be achieved, especially because resistance to the official eradication campaign by farmers remains strong.

However, the question about alternative, feasible options remains unresolved as of yet. As for research, the ongoing standardization of methodologies and protocols in breeding for CSSVD resistance and subsequent replacement of susceptible cocoa with resistant varieties may be part of the solution, there is certainly a long way to go until widespread implementation on the ground will be achieved, especially because resistance to the official eradication campaign by farmers remains strong.

In practice, on the other hand, an immediate strategy to deal with CSSVD infection is needed. As there are no short-term solutions to the problem, we need to find ways of living with CSSVD, especially in parts of the Eastern and Western Regions of Ghana, which were declared areas of mass infection where complete eradication and replanting is not feasible. Diversifying production systems and landscapes, which are not infected yet, while subsequently replacing diseased cocoa with more resistant varieties may be an interesting option for farmers.

Another interesting avenue for future research is biological control (Padi, 1997). After several initiatives in the 1950s had failed due to several reasons, such as the presence of secondary natural enemies, inefficient rearing and release methods, as well as introduction of ineffective host-specific parasitoids of other mealybug species, this topic was temporarily abandoned. However, efforts in biological control were recently revived at CRIG, and trials with the exotic predator Cryptoaenopsis montrouzieri and the pathogenic fungus Beauveria bassiana were conducted (Plantwise, 2016). Moreover, more attention should be given to the suggestion of farmers to control mealybugs by altering ant-complexes in the field, shifting the dominance from ant species, which are mealybug-tending (Crematogaster spp.) to those who are not (Oecophylla spp.) (Ayenor et al., 2004).

5. Conclusion

This is the first time the effectiveness of different preventive control measures for CSSVD are summarized and weighed versus each other in a quantitative way. Since only a fraction of the large body of literature on CSSVD investigated the efficacy of preventive measures, this meta-analysis is a stepping-stone for consolidating what we know about the combat of CSSVD, and for setting future research priorities. Our study clearly shows that there has been a strong focus on resistance breeding and mild strain cross protection. While these approaches certainly have their potential, they should be combined with other approaches to form an ensemble of solutions, which is needed to solve a problem as extensive as CSSVD. Barrier (strip) cropping and agroforestry systems (shading) might be well suited to complement breeding and mild strain cross protection, as they showed greatest potential to reduce CSSVD in our study. Moreover, these approaches could be implemented directly by farmers themselves. However, there is a severe knowledge gap about these approaches' potential to reduce the spread and/or severity of CSSVD, which has to be addressed by future research. Furthermore, shade should be considered in breeding programs for CSSVD resistance and the practical relevance of different preventive control measures for farmers needs to be studied.

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