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FALL ARMYWORM: MEASURING DAMAGE AND LOSS CAUSED BY A NOVEL INVASIVE PEST AS A GUIDE TO SUSTAINABLE MANAGEMENT

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Abstract

The rise in global trade and human mobility, along with climate change-induced shifts in weather patterns, has led to the rapid transmission of invasive insect species, causing threats to agriculture, crop productivity, and public health. The fall armyworm (FAW), originally from the Americas, has become an invasive and highly destructive pest, causing significant agricultural losses worldwide. This paper aims to present a comprehensive analysis of FAW-induced maize losses, drawing from a diverse source of both qualitative and quantitative assessments.

As a first step, a systematic review has been conducted to meticulously collate and synthesize data from diverse sources with a focus on experimental data.[1] It adheres to rigorous scientific standards and employs robust analytical techniques, offering a valuable resource for researchers, policymakers and stakeholders invested in addressing the challenges posed by this invasive pest. Based on this analysis and to enhance the comprehension of the correlation between yield reduction and key factors, particularly the intensity of pest pressure, a series of regression analyses have been conducted. To estimate the direct economic yield loss potential of FAW in the field in the absence of management, a model has been proposed.

The research on economic losses caused by FAW in Africa and Asia is currently limited in scope. Most studies have primarily focused on individual crops, notably maize, emphasizing quantity losses. It is imperative to expand the research to cover all key crops vulnerable to FAW infestations. Additionally, assessments should include quality losses and consider missed trade opportunities, particularly due to strict phytosanitary regulations for exporting agricultural products to regions such as Europe. This comprehensive approach is crucial for a more thorough understanding of the true economic impact of the FAW pest.

[1] Overton, K., Maino, J.L., Day, R., Umina, P.A., Bett, B., Carnovale, D., Ekesi, S., Meagher, R. & Reynolds, O.L. 2021. Global crop impacts, yield losses and action thresholds for fall armyworm (*Spodoptera frugiperda*): A review. *Crop Protection*, 145: 105641. doi.org/10.1016/j.cropro.2021.105641

Contents

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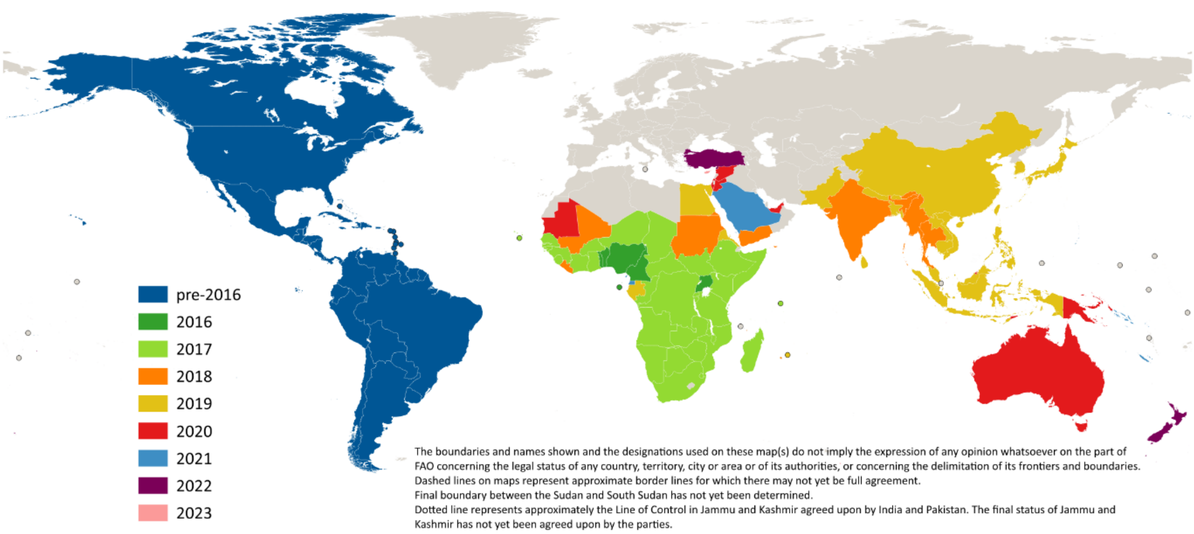
1 Introduction

Invasive insect species have always been a threat to agriculture, crop productivity and health. Human mobility and a rise in the global trade of agricultural commodities have resulted in the higher and faster transmission of agricultural pests, pathogens and weeds. Increasing temperatures and shifting weather patterns due to climate change also favour the conditions necessary for breeding and spreading endemic and invasive pests. Transboundary pest infestations are slow-onset disasters that are increasingly exerting significant losses in agriculture in many parts of the world, which is a challenge that is likely to worsen as trade and tourism expand, and as environmental stressors like climate change and biodiversity loss become more severe (IPPC, 2021).

The fall armyworm (FAW) (*Spodoptera frugiperda*, J.E. Smith) is a new pest outside of the Americas. It is invasive, highly mobile and destructive, and causes severe agricultural losses globally, posing a major threat to agricultural development efforts in several countries. Understanding the extent of losses caused by such pests is key to implementing cost-effective and sustainable pest management approaches (Savary *et al.*, 2019). FAW is native to tropical and subtropical America, where it has been a major crop pest for many decades. Its first appearance outside the Americas occurred in January 2016, when a severe outbreak was reported in Western Africa (Goergen *et al.*, 2016). FAW's presence has now been confirmed in almost all of sub-Saharan Africa. The first report of FAW in Asia was confirmed in Karnataka (India) in 2018. Since then, the pest has been reported in other Indian states and several Asian countries, including Bangladesh, China, Sri Lanka, Thailand and Viet Nam. More recently, FAW was reported in Australia, the Canary Islands and New Caledonia (Kenis *et al.*, 2022) (Figure 1).

Figure 1. Global map of fall armyworm invasion



Source: FAO. 2023. Global Action for Fall Armyworm Control. In: *FAO*. [Cited October 2023]. www.fao.org/fall-armyworm/monitoring-tools/faw-map/en/

2 Background

2.1 Drivers of the rapid fall armyworm invasion

Genomic studies indicate that FAW entered Africa via multiple routes, primarily through trade (Nagoshi *et al.*, 2022; Tay *et al.*, 2022), with Western Africa serving as a major entry point. FAW, a highly polyphagous pest, prefers maize but can infest over 350 plant species, including important crops like rice, sorghum, wheat, cotton, sugarcane and soybean. The rapid spread of FAW in Africa is driven by its ability to exploit diverse host plants year-round, favourable warm climates, abundance of maize, prolific egg-laying (up to 2 000 eggs per female) and the capacity of adult moths to fly long distances, up to 100 kilometres in a single night. Models suggest that suitable environmental conditions for FAW are widespread in Africa, warmer parts of Asia, and some areas in southern Europe (Early *et al.*, 2018).

2.2 Early estimates of direct and indirect economic losses due to fall armyworm

FAW causes significant economic losses by reducing harvest yields and increasing pest control expenses. For instance, in 2009, Brazil spent approximately USD 600 million on FAW control. In Africa, early estimates of FAW-related losses varied between countries; for example, Ghana and Zambia experienced maize yield losses estimated at USD 284 and USD 198 million, respectively. The Centre for Agriculture and Bioscience International (CABI) extrapolated losses to be between USD 2.5 billion and USD 6.3 billion in 2017 across 12 African countries (Day *et al.*, 2017). Abrahams *et al.* (2017) estimated annual losses of up to USD 13 billion in maize, rice, sorghum and sugarcane across sub-Saharan Africa. These early estimates underscore the potentially devastating impact of this new pest. Consequently, assessing the extent of FAW damage is crucial to formulate effective responses to its invasion. Traditionally, FAW has been controlled in the Americas through insecticides and transgenic maize, methods not easily accessible to resource-constrained farmers in affected regions. Therefore, understanding the damage caused by FAW is essential for developing relevant and sustainable pest management strategies, especially within the framework of disaster risk reduction (DDR).

The FAW invasion has continued to negatively affect productivity of smallholder farming systems, making millions of smallholder farmers in Africa and Asia even more vulnerable. In addition to the direct impacts on agricultural systems and livelihoods of farming communities, FAW also causes indirect impacts, including negative ones on human health, but these have not been measured in any systematic way. Impacts of the invasion include increased use of synthetic pesticides, increased cost of pest management, reduced crop yields and farm-level income, and aggravated negative impacts on the environment, all of which have negative implications for welfare. For example, studies have reported that FAW-affected households were more likely to experience hunger, suggesting that severe levels of infestation reduced per capita household income by up to 44 percent and increased a household's likelihood of experiencing hunger by 17 percent in Zimbabwe (Tambo *et al.*, 2020).

3 Methods

Attributing crop damage and loss to FAW is challenging due to the diversity of crop species, crop varieties, plant growth cycles and stages, pest life stages, and other confounding factors like weather, soil health and the ecological forces affecting FAW. For example, plants can often compensate if damage occurs during an early stage of development, and if resources, including soil nutrients and moisture, are adequate (Trumble *et al.*, 1993), resulting in reduced effect on crop yields.

The paper is based on FAW-induced losses to maize from a range of data sources; peer-reviewed journal publications, institutional and agency reports and national reports on FAW infestation. For the peer-reviewed publications, a literature search in Web of Science was conducted between August and September 2022 using specific search terms as described in Overton *et al.* (2021), which yielded a total of 1 863 articles. Additional searches included published literature and reports of experiments that examined FAW management approaches, particularly those that included a positive control that could be used to calculate yield loss (Overton *et al.*, 2021). To identify additional reports, Google searches were conducted. The titles and abstracts of all articles were screened manually to identify relevant ones, which were then scrutinized in detail. Because of reported disparities between experimental data on yield losses and those reported from farmer perceptions and survey studies (Overton *et al.*, 2021), only sources that reported experimental field data were selected. The yield loss proportion was determined by dividing the observed yield by the positive control (or non-infested plot) yield and subtracting from 1. Additionally, a regression analysis was conducted, and a linear regression line plotted to help visualize the relationship between yield loss and key parameters including pest pressure.

4 Results

4.1 Measuring fall armyworm infestation and crop damage

From a review of published literature, institutional reports and other sources of data, the number of reports on impact of FAW on agriculture is increasing in Africa and Asia, although fewer reports are available for Asia. These are mostly plot-level assessments, with synthetic reviews or models only starting to be conducted. Indeed, this is only the second assessment after Overton *et al.* (2021) that attempts to establish the impact of FAW on production losses from available evidence. The review shows that infestation of FAW and its impact on maize is measured in diverse ways (**Table 1**), indicating that there are no standardized tools and procedures for these assessments.

Table 1. Different ways through which FAW infestation, crop damage and yields have been assessed on maize

Parameter	Ways of measurement	Reference examples
FAW infestation	(i) Most reports measure incidence through estimation of proportions (%) of plants showing damage symptoms caused by the pest, including windowing and shot holes caused by young larvae, or a mass of holes on leaves and the whorl (funnel), ragged edges and larval frass from older larvae (Figure 2).	Aniwanou *et al.*, 2022; Tanyi *et al.*, 2020; Babendreier *et al.*, 2020; Roy *et al.*, 2021; Guera *et al.*, 2021; Bilbo *et al.*, 2020
	(ii) Others assess infestation through the number of FAW life stages (principally larvae) per unit area, including plant, plot, acre or hectare.	Cruz *et al.*, 1999; Deshmukh *et al.*, 2020; Pereira and Hellman, 1993
FAW-induced crop damage	Most studies use ordinal damage rating scales that include incidence and severity measures, with Davis' (Davis *et al.*, 1992) "0 to 9" whorl damage scale (where 0 means no foliar damage and 9 represents total foliar damage) being the most used, with modifications.	Burtet *et al.*, 2017; Koffi *et al.*, 2022; Teixeira Silva *et al.*, 2015; Agboyi *et al.*, 2021; Osae *et al.*, 2022
Grain yields	Assessments based on weight of grain (and cobs) sampled at different scales, from cob to plant, sample quadrat and plot.	Tanyi *et al.*, 2020; Deshmukh *et al.*, 2020; Koffi *et al.*, 2022

Source: Authors' own elaboration.

Figure 2. Symptoms of damage caused by young (left) and mature (right) FAW larvae feeding on maize

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4.2 Fall armyworm-induced yield losses

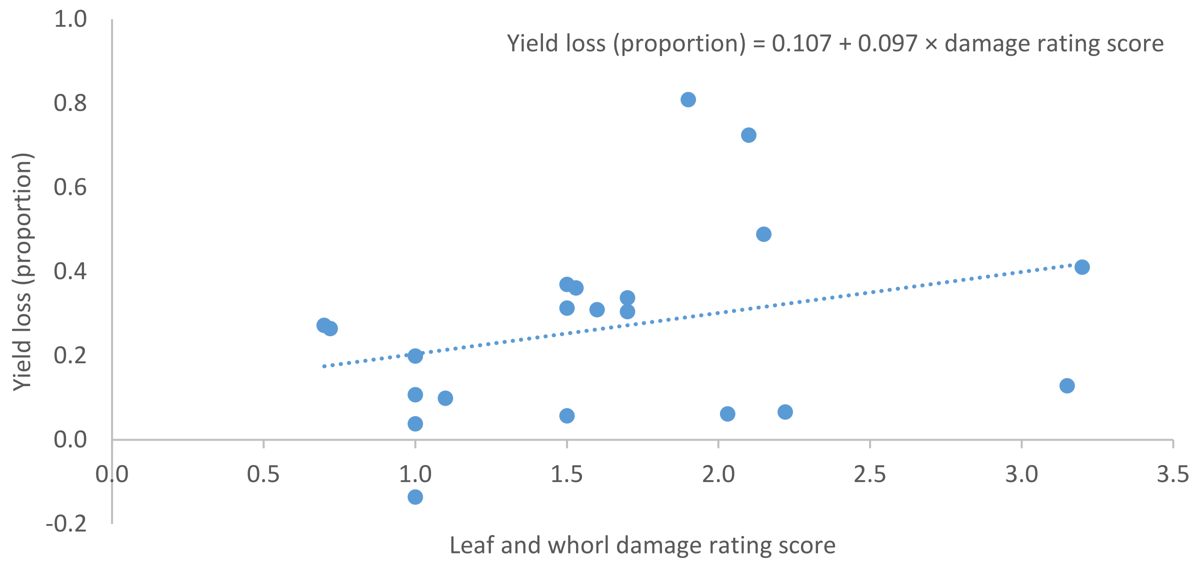
From farmer perception survey reports, FAW-induced yield losses to maize in sub-Saharan Africa have been estimated to be between 11 percent and 70 percent. These include yield reductions of up to 47 percent in Kenya and Ethiopia (Kumela *et al.*, 2019; De Groote *et al.*, 2020; Abro *et al.*, 2021), and 22–67 percent in Ghana and Zambia (Day *et al.*, 2017; Rwomushana *et al.*, 2018). However, lower estimates have also been reported for Malawi and Zambia (Harrison *et al.*, 2022). In Asia, yield losses have been estimated at 33 percent in India, and up to 32 and 40 percent in Bangladesh and Thailand, respectively (Balla *et al.*, 2019; Sagar *et al.*, 2020; Srikanth *et al.*, 2018). In the Americas, yield losses of up to 34 percent in Brazil (Lima *et al.*,2010), 40 percent in Honduras (Wyckhuys and O'Neil, 2006), and 72 percent in Argentina (Murúa *et al.*, 2006) have also been reported.

Analysis of experimental data herein indicates that FAW-induced direct yield loss in maize ranges from 0.4 percent to 94.8 percent. In terms of country-to-country variations, average yield loss in the analysis ranged between 15.7 percent in Ecuador and 45.7 percent in India, and included 37.3 percent, 37.2 percent, 36.5 percent, 26.7 percent and in Cameroon, Kenya, Ethiopia and Ghana, respectively. It should be noted that these losses do not include quality losses and are based on field/plot-level measurements at various scales (no standardized scales), and with variable numbers of observations in the different countries. This notwithstanding, some of the results corroborate recent findings, for example, by Abro *et al.* (2021) who estimated yield losses of 36 percent in Ethiopia through triangulation methods. Notably, different methods have yielded different yield loss estimates, for example, in Zimbabwe, yield loss to maize was estimated at 58 percent from farmer perceptions in 2017 (Chimweta *et al.* 2019), and 12 percent from rigorous analysis of field data in 2018 (Baudron *et al.* 2019), implying that farmers' perceptions might overestimate yield losses (Overton *et al.*, 2021).

4.3 Pest pressure, severity of crop damage and yield loss

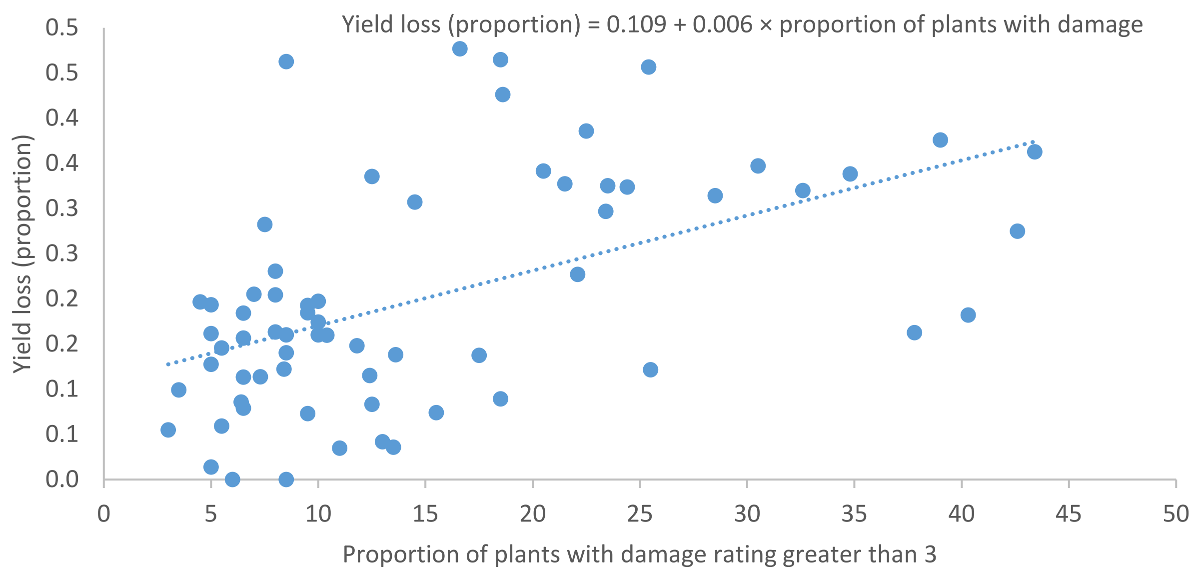
Results of the analysis showed that maize grain yield loss tended to increase with the increase in plant damage severity, measured through a damage rating scale (although this was not statistically significant, with a p value greater than 0.05), with one unit increase in damage rating score being associated with approximately 10 percent increase in yield loss (proportion) (Figure 3). A much stronger and statistically significant relationship ($p<0.05$) was observed with studies that reported damage as a proportion of plants with a damage rating greater than 3, i.e. plants showing damage ranging from small elongated and a few mid-sized elongated lesions on a whorl to those with a whorl almost totally destroyed (Davis *et al.*, 1992; Figure 4). This implies that once damage to a plant reaches a certain level, the impact on yields is likely to be significant. Additionally, yield losses seemed to be influenced by pest infestation level, measured as the number of FAW larvae per plant, although the relationship was not statistically significant (data not shown).

Figure 3. Line of best fit when total yield loss (proportion) is regressed on plant damage rating



Source: Authors' own elaboration based on FAO data.

Figure 4. Line of best fit for maize crop when yield loss (proportion) is regressed on plants with damage rating greater than three



Source: Authors' own elaboration based on FAO data.

4.4 Climate change and fall armyworm

Climate change models, including versions of climatic niche modelling in future climate scenarios in CLIMEX and MaxEnt, predict that under the current climate, there is an increased risk of global FAW invasion and establishment, with climatic suitability occurring in many parts of Africa, South and Southeast Asia, southeastern parts of China, the north coast of Australia, and a few pockets in Europe (Zacarias, 2020; Timilsena *et al.*, 2022; Ramasamy *et al.*, 2022). Further projections (up to the year 2080) suggest that the FAW invasive range will retract towards the equator from the northern and southern regions mainly due to climatic factors, particularly temperature. However, large parts of eastern and central Africa will remain conducive for the pest, thus serving as 'hotspots' from where FAW might migrate to areas projected to be unsuitable for its establishment. Furthermore, projections suggest that places such as southern Mediterranean Europe with large areas where FAW host plants are cultivated, together with parts of southern Italy, Spain and Portugal, are at risk of invasion and establishment of FAW. Indeed, FAW was reported in the Canary Islands in April 2021.

4.5 Proposed model

There are only a few studies on economic losses due to FAW in Africa and Asia. Additionally, the analyses have mostly been on single crops (mainly maize), and only on quantity losses. There is a need to consider all key crops attacked by FAW and to include quality losses as well as lost trade opportunities (Murray *et al.*, 2013; Day *et al.*, 2017), for example those brought about by stringent phytosanitary requirements for exporting farm products to Europe (Jeger *et al.*, 2018). This is needed for understanding the real economic impact of the pest. Below is a proposed modelling framework that could be applied to estimate the direct economic yield loss potential of FAW in the field in the absence of management (Overton *et al.*, 2021), with yield loss, FAW control and quality losses as the key measurement variables:

$$ELP_{(FAW)} = YL_{\sum(Cr1,\ Cr2,\dots Crn)} + FC_{\sum Cr1 + \sum Cr2 \dots + \sum Crn} + QL_{\sum(Cr1,\ Cr2,\dots Crn)}$$

where *ELP* is the economic loss potential resulting from FAW invasion; *YL* is the monetary value of yield loss attributed to FAW for crops 1, 2 …n; *FC* is the cost of FAW control in crops 1, 2…n, taking into account costs of various control options applied on each crop; *QL* is the quality loss attributed to FAW for crops 1, 2…n, taking into account the economic value of the produce whose quality is either reduced or lost due to FAW for each crop.

This accounting framework can be escalated to larger scales by adding variables such as production risk indices and product values at the various scales. The model does not include lost trade opportunities due to FAW. It also does not take into consideration the other value chain actors that are affected by reduced yields, for example livestock farmers who might be affected by FAW-induced reductions in maize stover quality and quantity.

5 Conclusions towards sustainable management of fall armyworm

FAO, CABI and other partners have established global monitoring, risk assessment and early warning systems that include national and regional subsystems. The frameworks include scouting as a basis for deploying FAW management tactics, and promotion of regional and global cooperation and information sharing. This is buttressed by the Fall Armyworm Monitoring and Early Warning System (FAMEWS) package that supports pest prevention and control, and surveillance and diagnosis efforts. To improve the performance of these efforts, and to make them more focused and effective, there is a need to (i) develop standardized tools (quantitative and qualitative) for subnational, national and global data collection as described above; (ii) enhance use of the information to create risk models and maps (e.g. Lowry *et al.*, 2022), as well as information briefs to guide action at the various levels; (iii) build capacity of stakeholders on the various aspects of the framework, including application of the standardized tools, data collation and interpretation to guide actions; and (iv) ensure an effective policy environment and coordination at the various levels, as well as phytosanitary measures to prevent further introduction and spread of FAW and other invasive pests.

The assessment shows that FAW is a serious threat to agriculture globally, and with projections that it will make the economies of countries, particularly in Africa and Asia, increasingly vulnerable to poverty as climate change-driven stressors become more severe. To date, FAW's impact on agriculture has been measured in diverse ways, making the collation of evidence across studies and scales, as well as extrapolations, impossible. Moreover, pest infestation has typically been measured using the proportion of plants with FAW-induced foliar damage symptoms, a measure that does not seem to correlate with the extent of yield loss in maize. Although derived from plot-based data, the analysis has shown that plant damage, especially for those at a rating score of 3 and above, is a good measure of the impact of FAW on maize as it corelates with the extent of yield loss. There is also a need to build capacity at the various levels supported by an effective coordination mechanism as proposed above.

Finally, the invasion of Africa, Asia, Australia and Europe by FAW provides insights into global movements of invasive pests and pathogens of plants, animals and humans, with trade as a possible route of entry of such species into new areas. Therefore, as global trade expands to increase economic growth, the threat of invasive species needs to be kept in mind. The system described above should encompass improved biosecurity preparedness and strategies that include effective monitoring, surveillance and response systems, not only for FAW but for detecting and managing other such pests at the national, regional, continental and global level, together with an effective coordination system.

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