# Descriptor Results and Calibrated Statements for crop pest and diseases, biological control, and yield losses

## Malawi

### Low climate risk / LT (ineffective agricultural policy) scenario

#### CS1: 20-40% loss due to pests and diseases (Yengoh 2012), ~25% (±5) mean reduced yield compared to (Kravchenko et al. 2017)

Under low climate risk and an ineffective agricultural policy (assuming that this is the situation at present), pests and diseases (CPD) inflict substantial annual crop losses. CPD-driven yield losses, on average, cause a ~25% reduction in yields (ranging from 20 to 40 %). Annual yield losses vary among crop species : 16-29% in beans and 12-35% reduction in maize yields.

**Robustness:** ***Medium robustness.*** Highly robust for the overall averaged impact of pest and diseases on food production, which combines the four major crops (maize, beans, cassava, and soya). However, there is uncertainty about the individual effects of specific CPDs, and crop-specific projections are less certain. This suggests medium robustness.

**Agreement:** ***Medium agreement.*** The effect of CPD on production is based on the assumptions that crop damage is negatively correlated with production. There is high agreement about the negative impact of CPD on food production and that CPD damage causes ~20-30% reduction in yields. However, there may be regional variations in the effect size. Also, there is likely to be compounding effects of pest and diseases (e.g. pest and disease both damaging the plants at the same time). Such compounding effects are not accounted for in the majority studies focusing on either pests or diseases. Therefore, we are downgrading the agreement to "medium" in the absence of more specific information.
***Medium Confidence (medium robustness and medium agreement).***

#### CS2: Increased impact of diseases on livestock production

The increasing incidence of livestock diseases is an important cause of livestock losses and declining household asset status. Loss of livestock due to diseases directly impacts food security in terms of food availability and access. Also, livestock loss results in a shortage of manure for crop fertilisation, which leads to lower crop production.
**Robustness:** Medium robustness. Negative impacts of livestock diseases are well established. However, how the impact on livestock due to diseases affects food production is not quantified. The impact of disease on livestock varies between diseases and livestock (Cattle, sheep, goats, poultry, pig) being considered.
**Agreement:** Medium agreement. Studies broadly agree on the impact of disease on livestock. However, the impact of livestock diseases is difficult to establish due to a lack of proper records by farmers and government authorities responsible for the livestock sector.
***Medium Confidence (medium robustness and medium agreement).***
References -(Mangisoni 1994; Freeman et al. 2008; Komarek and Msangi 2019)

#### Assumptions

Under this scenario, the yield losses due to CPD under present conditions are reflected. Also, we assumed that the dominant crops are maize, beans, and cassava. Farm-level CPD-driven annual yield losses are often determined by the composition of crops on the farm. Diverse crop systems are likely to experience lower mean yield losses compared to more homogenous production systems. It also assumes that the challenges from climate change and climate variability experienced now will not worsen in the future.

## High climate risk / LT (ineffective agricultural policy scenario)

**CS1: Increased pest and disease prevalence**

Pest pressures increase with rising temperature. The number of generations, population abundance, activity, and distribution of pests is known to increase when temperatures rise by 2˚C to 9˚C. An increase in the duration of the dry season (beyond 4 months) causes resurgence of some pests and the further establishment of what are typically considered minor pests (cassava mealybug, cassava green mite and grasshopper). Insect pests that are sensitive to temperatures will track suitable climate more optimal for their growth and survival, and migrate to colonise higher altitudes where they may not have been encountered before.

Elevated CO2 levels alter the type of diseases prevalent, and higher daily temperatures have been found to increase disease incidence. The effect of climate on disease prevalence is realised via two pathways – (i) increase in growth, fecundity, and activity of disease vectors (e.g., whitefly as a vector of cassava mosaic virus), and (ii) increase in occurrence, severity, and rate of spread in the distribution of crop diseases.

With increasing temperature, the effectiveness of pest natural enemies is likely to reduce, leading to lower levels os biological control. The decrease in effectiveness for biocontrol be due to mismatch between pests and enemies in space and time. Reduced natural biocontrol increases food production costs as farmers depend on external inputs, such as pesticides, for controlling pest and disease crop damage. Under low input agriculture, where farmers do not have access to external inputs, the CPD-driven crop damage will result in higher yield losses.

**Robustness:** In lowland areas, more complex interactions with rainfall and relative humidity make predictions of the impact of climate on the severity of pests and diseases difficult. Different crops and their pests may respond in diverse ways, which is poorly understood. While the majority (90%) of invertebrates exhibit changes in their geographic range, population dynamics, and life history, studies have revealed highly variable responses of CPDs to climate change. Therefore, the robustness of the predictions is low. Because of the diverse and often indirect effects of climate change on CPD and natural enemies, predictions are less robust and there is a need for local-scale studies evaluating the environmental and farm management effects on tritrophic interactions.

**Agreement:** There is greater agreement among studies on the overall increase in pest severity because of climate change, but there is high variability in effect sizes reported from different studies. Therefore, the agreement here is medium.

***Low Confidence (Low robustness, medium agreement)***

References: (Thornton and Cramer 2012; Bisimwa et al. 2019)

**CS2: Yield losses due to crop pests and diseases**

The increase in CPD prevalence and intensity, and the reduction in effectiveness of biological control, will result in higher crop damage and yield losses. The cost of food production will increase as farmers will have to use pesticides, if affordable and available, to control pests and disease vectors. Increased dependence on external inputs will increase the cost of food production.

*10 to 25% higher yield loss per degree of global mean surface warming, or ~32% (20-57) yield loss to CPD when average global surface temperatures increase by 2°C* (Deutsch et al. 2018).
*Maize 22.5 % (19-41), Beans (Soybean, Groundnut) 21.4% (11-32), Potato 17.2% (8-21)*

**Robustness:** Information about percentage change in yield losses is based on a global synthesis of pest damage on common crops in 19 regions across the world. The regional averages do not always reflect the spatio-temporal variability in pest populations and their impacts at local scales. Nor do they consider local-scale effects of climate, which may arise, for example, between low and high-altitude farming areas. Thus, we consider this to be of medium robustness.

**Agreement:** Low agreement: CPD responses to climate varies depending on the specifics of CPD, crops and regions, but an increase in pest severity is commonly observed. However, changes in pest populations and distributions, and the impact of these changes on food production, has uncertainties and there are considerable disagreements between studies e.g. (Deutsch et al. 2018) and (Lehmann et al. 2018)

***Low Confidence (medium robustness, low agreement)***

## Low climate risk / HT (effective agricultural policy scenario)

**CS1: Increased pest prevalence due to reduced biological control.**

Pest prevalence is often determined by the management practices in the field. If the effective agricultural policy scenario entails conversion of intercrops to monocrops of tolerant crop varieties, with expansion and intensification of agriculture, CPD prevalence and damage may increase due to loss of biological control. Biological control is often underpinned by the presence of natural enemies of invertebrate pests, which reside in the natural and semi-natural areas within and between the fields.

**CS2:** ***2-5 % yield loss if heterogeneous agriculture-natural landcover is converted to simplified homogenised production systems.***

Homogenised production is characterised by reduced crop diversity due to a reliance on a few dominant crop species, which could occur with agricultural expansion and intensification, leading to a transformation from heterogeneous small-scale agriculture to large-scale corporate agriculture. Increased uniformity of cultivars leads to greater vulnerability to CPD. When pests and pathogens evolve to overcome the genetic resistance of the crop, the result can be a severe crop failure with immediate detrimental effects on food availability and nutrition. The negative effects of crop homogenisation will interact and multiply with local habitat loss, landscape simplification, and invasive CPDs.

**Robustness: Medium robustness,** Several studies suggest that intercrops and heterogenous diverse crops may suppress pests through provisioning of biological control via natural enemies. However, the effect of natural enemies varies based on local context and landcover. For example, AFRICAP's empirical study from Tanzania shows that the characteristic of neighbouring fields influences natural enemy and pest populations in the focal field. Fallow and intercrop neighbours have higher diversity and population of natural enemies and contribute to pest reduction in the focal field.

**Agreement:** There is high variability among studies on how natural enemies respond to crp and landscape heterogeneity, and global syntheses have further indicated inconsistent responses of pests and natural enemies to heterogeneity, hence, **medium agreement**.

***Medium Confidence (medium robustness, medium agreement)***

**References:** (Perrin 1976; Oerke 2006; Karp et al. 2018)

## High climate risk / HT (effective agricultural policy scenario)

**CS1: exacerbated impacts of pests and diseases**

If the agricultural policy includes intensive cultivation of susceptible genotypes, the incidence and severity of pests and diseases are likely to be exacerbated. Intensive agriculture often leads to loss of biodiversity, which underpins agroecosystems stability and influences plant disease epidemiology. Hence, intensive cultivation in a homogenous environment increases CPD pressures. High climate risks will further exacerbate CPD-induced production losses.

With agricultural policies favouring intensive cultivation and a reduction in biological control, the vector populations increase leading to higher incidence and severity of crop diseases (e.g., increase in whitefly populations causing higher risks of cassava mosaic)

The yield losses in this scenario could be: *~32% (20-57) yield loss due to CPD as a result of climate + 2-5 % yield loss due to reduced pest suppression under homogenisation.*

**Robustness:** There are few studies quantifying yield losses because of crop or landscape homogenisation coupled with climate change. Thus, the **robustness is low.**
**Agreement:** Agreement between studies on increased impact of pests under climate is medium. Studies largely agree that there will be increased pest prevalence and vulnerability under homogenised agriculture. Therefore, we put this as **medium agreement.**
**Low confidence (low robustness, medium agreement)**

# 2. Tanzania

## Low climate risk and low technological development (present condition)

**CS1: Pest and diseases cause an average of ~25% (±5%) reduction in annual yields with estimates of crop-specific losses (maize, beans, cassava, and soya) ranging from 20-60%** (Savary et al. 2019)**.**

The parasitic weeds, *Striga hermonthica* and *S. forbesii*, cassava mealybug, green mite, spotted stem borer, Fall armyworm, African stalk borer, pink stem borer, and diseases such as cassava mosaic, maize leaf blight, maize rust, maize ear rot and stalk rots, are the most common CPD constraints to food production in Tanzania (Wortmann 1992; Pallangyo et al. 2019).

In the mountain production systems, mixed farming with cash and food crops is practiced. Farmers grow maize, beans, cassava, sweet potatoes, bananas, and various spices, such as clove, cardamom, and black pepper. CPD-induced yield losses are lower in the highlands compared to the lowlands.

In lowland farming areas, fall army worm, stalk borers, maize streak and cassava mosaic are major problems. In highland production systems, yam mosaic virus, parasitic weeds, black sigatoka on bananas and plantains, clove disease and casava root rot are commonly reported.

**Robustness:** Local-scale studies based on field trials provide a range of yield loss estimates, which vary between crops and CPD types. The global-scale syntheses provide regional estimates (e.g., sub-Saharan Africa), which may lack this local precision. Also, the importance of CPD varies based on regions and Tanzania has a diverse range of different agro-ecological zones, including mountains, coasts and forests. Hence, a general estimate may not provide a robust indicator of yield losses that are highly variable and contextual. Therefore, we place this statement under **medium robustness.**

**Agreement:** The estimates of yield losses overlap among studies and there is a general agreement of yield losses being between 20-30%. This is validated by AFRICAP's empirical study in the East Usambara Mountains. So, there is **High agreement** on average estimates of yield losses due to CPD.
**High Confidence (Medium robustness, high agreement)**

## High climate risk and low technological development

**CS1: Under high climate risk, median losses in yield due to CPD would increase by 10 to 25% per degree of global mean surface warming. Mean estimates of CPD-induced yield losses are estimated at ~32% (20-57) of annual crop yields, when average global surface temperatures increase by 2°C** (Deutsch et al. 2018)**.**

Rising temperature along with higher atmospheric CO2, may favour the growth and survival of many pests and diseases specific to agricultural crops. With increasing temperature, generation times, metabolic rates, food consumption, and growth rates of insect pests and disease vectors are expected to increase. Metabolic increases will alter food web dynamics which govern pest and natural enemy interactions in agricultural ecosystem and underpin biocontrol. Climate risks are likely to coincide with elevated rates of herbivory and predation, as well as changes in the spread of insect-borne tropical diseases. Some pests which are already present, but only occur in small areas or at low densities, may be able to exploit the changing conditions by spreading more widely and reaching damaging population densities (Dillon et al. 2010; Lobell and Gourdji 2012; Nazaries et al. 2015). Finally, the effects of changing climate and more variable weather suggest that pest and pathogen attacks are likely to be more unpredictable, but their impact larger.
**Robustness:** Information about percentage change in yield losses is based on a global synthesis of pest damage on common crops in 19 regions across the world. The regional averages do not always reflect the spatio-temporal variability in pest populations and their impacts at local scales. Thus, we consider this to be of **medium robustness**.
**Agreement: Low agreement:** CPD responses to climate varies depending on the specifics of CPD, crops and regions, but increased pest severity is commonly observed. However, changes in pest populations and distributions, and the impact of these changes on food production, has uncertainties, and there are disagreements between studies, e.g. (Deutsch et al. 2018) and (Lehmann et al. 2018)
**Low Confidence (medium robustness, low agreement)**

**CS2: The estimated CPD induced yield losses vary among major crops – e.g., 31% (±15%) for maize, 50% (±25%) for cassava, 40% (±20%) for wheat.**

**Robustness:** The effect on crops of high climate risk is mainly based on projections from models, and there is high variability among studies in the yield losses attributed to different crop pests and diseases. Thus, **medium robustness.**
**Agreement:** There is high agreement about the overall negative impact of CPD on crops.; however, the effect sizes differ between regional and local-scale studies. This is **medium agreement.**
**Medium confidence (medium robustness, medium agreement)**

**CS3: Increase in extreme events and crop pests and pathogens – e.g., locust outbreaks in east Africa.**

Extreme events may become more frequent in the future, increasing the risks to crop yields. Some pest species, such as locusts, exhibit potentially highly damaging outbreaks periodically in response to certain weather conditions. These species may survive the longer dry periods and extreme climate variability projected (Gregory et al. 2009), while outbreaks are projected to increase in frequency and severity (Salih et al. 2020).
Robustness: Low robustness, there are no studies which provide information on frequency of outbreaks with respect to climate change for locust outbreaks and for other potential insects which could create pest outbreaks.
Agreement: There is high agreement among research studies and syntheses that climate risks will influence large regional to global scale pest and disease outbreaks.
***Medium Confidence: Low robustness, high agreement***

**CS4: New pests in the highland farming system due to migration of pests from lowlands to highlands affecting cash crops like banana and yam.**
**5% increase in yield losses in highland farming systems (elevation above 1000 m above sea level).**
Crops that are grown in the Tanzanian highlands (banana, yams, spices) will experience significant yield losses increase due to the migration and spread of CPD from the lowlands if the temperature increases by 2°C. These crops are currently less exposed to nematode, weevil, and sigatoka problems. When major production areas in the highlands are infected by CPDs (weevils, nematodes, etc.) from the lowlands, the yield losses are expected to increase by 5% (in addition to the average losses).

**Robustness:** Some local studies and reports describe the impacts of CPD migration to higher altitudes on yield losses. However, these yield losses due to CPD resurgence is not quantified and yield response curves are not yet established. Thus, **low robustness.**

**Agreement:** There is high agreement among studies on CPD establishment to highlands with severe implications on food production. However, the yield losses are not quantified in most studies. Hence, **medium agreement.**
***Low Confidence (Low robustness, medium agreement)***

## High climate risk and high technological development

**CS1: Pest and disease-induced crop yield losses exacerbated by climate and homogenised agriculture.**

The yield losses in this scenario could be:
~32% (20-57) yield loss due to CPD because of climate
+ 2-5 % yield loss due to reduced pest suppression under homogenised agriculture

Climate change will affect the geographic range, incidence and severity of pests, weeds, and diseases, consequently impacting both crop and livestock production.

The stakeholder workshops indicate that there would be an expansion of agriculture and conversion of pasture to crop lands due to population growth and technological development. Technological development is often correlated with mechanisation, agricultural intensification (increased inputs) and homogenisation of agricultural systems. Under homogenised agriculture, risks of pest and disease outbreaks could be greater compared with heterogeneous mixed systems (Descheemaeker et al. 2016).

**Robustness:** *Low robustness:* Several studies suggest that intercrops and heterogenous crop and landscape diversity may suppress pests through provisioning of biological control via natural enemies. However, the effect of natural enemies varies based on local context and landcover. AFRICAP's empirical study from Tanzania shows that the characteristics of neighbouring fields (fallow or intercrop) influences the natural enemy and pest populations in the focal field. Thus, there may be large uncertainties due to the local landscape contexts and management practices. If climate change and technological development leads to homogenisation of agriculture, then the likelihood of negative impacts on food production is high. However, there is little empirical information and existing analyses focus mostly on single pathogens. Therefore, the uncertainty around the effects is large.

**Agreement:** There is high variability among studies on how natural enemies respond to heterogeneity, and global syntheses have indicated inconsistent responses of pests and natural enemies. Also, understanding of how climate will impact pathogens is from broad scale analyses of selected pathogens with a lack of agreement between studies (e.g. (Savary et al. 2019; Lehmann et al. 2020). Hence, *medium agreement.*
***Low Confidence (Low robustness, medium agreement)***

**CS2: An additional 2-5 % yield loss if heterogeneous agriculture-natural landcover mosaics are converted to simplified homogenised production systems.**

Homogenised production characterised by reduced crop diversity, due to the reliance on a few dominant species, could occur with agricultural expansion and intensification, and transformation of heterogeneous small-scale agriculture to large-scale corporate agriculture. Increased uniformity of cultivars leads to greater vulnerability to CPD.

For small-scale farmers, the cost of agriculture will increase as dependence on chemical inputs for controlling CPDs will increase. Large scale corporate farms with wealth and ability to generate more income will increase the use of chemical pesticides that may offset the crop losses. When pests and pathogens evolve to overcome the genetic resistance of the crop, the result can be a severe crop failure with immediate detrimental effects of food availability and nutrition. The negative effects of crop homogenisation will interact and multiply with local habitat loss, landscape simplification, and invasive CPD.

**Robustness:** There is limited local-scale evidence. Hence, **low robustness.**
**Agreement:** Evidence from other geographical regions, which have had global trade driven transformation of agriculture, suggest a high likelihood of landscape level homogenisation under technological development and globalised trade (Green et al. 2019). Thus, **high agreement.**
***Medium Confidence: Low robustness, high agreement***

**CS3: An additional 13% crop yield loss due to novel pest and diseases.**
Climate and increased trade and homogenisation of agricultural systems will facilitate introduction, establishment, dominance and spread of novel transboundary pests and diseases, and increase the likelihood of invasive species being introduced from abroad. While the number of invasive species would increase, some species, such as fall army warm, could have a devastating impact on production leading to 60-100% of yield losses. The likelihood of these acute invasive species being introduced will increase with increased trade.
**Robustness:** There is limited local-scale evidence. Hence, low robustness.
**Agreement:** Most studies indicate the negative impacts of novel pests and diseases on crop yields. Thus, high agreement.
***Medium Confidence: Low robustness, high agreement***

**CS4: Severe trade-offs among food production and resilience to CPD**
**Tanzania largely has heterogenous diversified and small-scale crop production systems where the** endemic pests are much more likely to have natural enemies in their local habitats. The spread and emergence of new CPDS in new areas (e.g. in the highlands) due to climate change, the introduction of novel CPDs due to trade, and landscape homogenisation due to technological development, will lead to existing biological control mechanisms becoming ineffective, which will impact on the resilience of food systems.
**Robustness:** Studies indicate inconsistent and occasionally, contrasting effects of landscape heterogeneity on CPDs (Karp et al. 2018). There is also limited local-scale empirical evidence of the roles of natural enemies and landscape heterogeneity on food system resilience. Thus, medium robustness.
**Agreement:** The majority of studies agree on the pest suppression effects of heterogenous production systems. However, there are some disagreements; occasionally intercrops and natural-habitat proximity have been reported to increase the CPD load and crop damage. Hence, medium agreement.
**Medium Confidence (Medium robustness, medium agreement)**

**CS5: Adaptation measures may involve greater pesticide use, at the cost of associated health and environmental damage and the elevated threat of pesticide resistance.**

Large scale commercial farming practices can afford pesticides that may offset CPD-induced losses, but still incur the negative health and environmental impacts

**Robustness:** Most studies report an increased use and dependence on pesticides with implications for human health, however studies do not provide effect sizes. Hence, medium robustness.
**Agreement:** There is high agreement among studies on pesticide use and health implications
***Medium Confidence (Medium robustness, high agreement)***

## Low climate risk and high technological development

**CS1: An additional 2-5 % yield loss if heterogeneous agriculture-natural landcover mosaics are converted to simplified homogenised production systems.**

An increase in globalised trade of economically desired plants and animals will reduce farm-level diversity, lead to landscape-level homogenisation, and negatively affect long-term resilience of food systems to crop pests and diseases.
Homogenised production is characterised by reduced crop diversity, due to the reliance on a few dominant species, could occur with agricultural expansion and intensification, and transformation of heterogeneous small-scale agriculture to large-scale corporate agriculture. Increased uniformity of cultivars leads to greater vulnerability to CPD. When pests and pathogens evolve to overcome the genetic resistance of the crop, the result can be a severe crop failure with immediate detrimental effects of food availability and nutrition. The negative effects of crop homogenisation will interact and multiply with local habitat loss, landscape simplification, and invasive CPD.

**Robustness**
There are few studies quantifying yield losses because of homogenisation and climate change. Thus, the robustness is low.
**Agreement**
Agreement between studies on the increased impact of CPDs due to climate change is medium. Studies largely agree on the increased pest prevalence and vulnerability under homogenised agriculture. Therefore, we put this as medium agreement.
***Low Confidence (Low robustness, medium agreement)***

**CS2: An additional 13% crop yield loss due to novel pest and diseases.**
Increased trade and homogenisation of agricultural systems will facilitate the introduction, establishment, dominance and spread of novel transboundary pest and diseases and increase the likelihood of invasive species being introduced from abroad. Acute invasive species – such as fall army warm – could have a devastating impact on production leading to 60-100% of yield losses.
**Robustness:** There is limited local-scale evidence. Hence, **low robustness.**
**Agreement:** Most studies indicate the negative impacts of novel pests and diseases on crop yields. Thus, **high agreement.**
***Medium Confidence: Low robustness, high agreement***

**CS3: Trade-offs among food production and resilience to CPD**
**Tanzania has heterogenous diversified and small-scale production systems where the** endemic pests are much more likely to have natural enemies in their local habitats. Introduction of CPDs due to trade, and landscape homogenisation due to technological development, will lead to existing biological control mechanisms becoming ineffective, which will impact on the resilience of food systems.

**Robustness:** Studies indicate inconsistent, and occasionally, contrasting effects of landscape heterogeneity (Karp et al. 2018). There is also limited local-scale empirical evidence of the roles of natural enemies and landscape heterogeneity on food system resilience. Thus, **medium robustness.**
**Agreement:** The majority of studies agree on the pest suppression effects of heterogenous production systems. However, there are some disagreements. For example, intercrops and natural-habitat proximity have been reported to increase the CPD load and crop damage. Hence, **medium agreement.**
***Medium Confidence (Medium robustness, medium agreement)***

# Zambia

## Low climate risk and low market connectivity (present condition)

**CS1: Pest and diseases cause on average a ~25% (±5) reduction in annual yields with estimates of crop-specific losses (maize, beans, cassava, and soya) ranging from 20-60%** (Savary et al. 2019)**.**

Zambian agriculture primarily consists of maize and cassava production by small-scale farmers (~85% of farmers with ~1.5 ha land) (Kimhi 2006). A majority of these farmers lose about 20–40% of crop yield pre-harvest due to crop pests and diseases, and additionally attribute about 10-20% yield loss due to poor quality soil and climatic conditions (Mwase and Kapooria 2001; Sileshi et al. 2008). Major CPDs in Zambia include fall armyworm (FAW), larger grain borer (LGB), cotton bollworm, grey leafspot (GLS), maize streak virus, bacterial leaf blight, and several species of stalk and pod borers, grasshoppers and aphids. CPDs like LGB, FAW, and GLS are introduced CPDs and are mainly prevalent in the low-land agriculture areas of Zambia. Farmers generally do not use control measures for the very common and less devastating beetles, aphids, caterpillars and grasshoppers. Under severe disease infections or infestations by large numbers of armyworms or grasshoppers they often handpick and destroy insects, spray ash or chilly powders, or destroy the infected plants. Farmers usually practice farm diversification through agroforestry, regular rotations, and intercropping to reduce crop vulnerability to pest damage (Sileshi et al. 2008).

**Robustness:** Local-scale studies based on field trials provide a range of yield loss estimates, which vary between crops and CPD types. The global-scale syntheses provide regional estimates (e.g., sub-Saharan Africa), which may lack local precision. Hence, a general estimate may not provide a robust indicator of yield losses that are highly variable and contextual. Therefore, we place this statement under **medium robustness.**

**Agreement:** The estimates of yield losses overlap among studies and there is a general agreement of yield losses of 20-30%. So, there is **High agreement** on average estimates of yield losses due to CPD.
***High Confidence (Medium robustness, high agreement)***

## High climate risk and low market connectivity

**CS1: Under high climate risk, median losses in yield due to CPD would be increase by 10 to 25% per degree of increase in global mean surface warming. Mean estimates of CPD-induced yield losses are estimated at ~32% (range 20-57%) of annual crop yields, when average global surface temperatures increase by 2°C** (Deutsch et al. 2018)**.**

Rising temperature along with higher atmospheric CO2, may favour the growth and survival of many pests and diseases specific to agricultural crops. With temperature, generation times, metabolic rates, food consumption, and growth rates of insect pests and disease vectors are expected to increase. Metabolic increases will alter food web dynamics, leading to elevated rates of herbivory and predation, as well as changes in the spread of insect-borne tropical diseases. Some pests which are already present, but only occur in small areas or at low densities, may be able to exploit the changing conditions by spreading more widely and reaching damaging population densities (Dillon et al. 2010; Lobell and Gourdji 2012; Nazaries et al. 2015).
**Robustness:** Information about percentage change in yield losses is based on a global synthesis of pest damage on common crops in 19 regions across the world. The regional averages do not always reflect the spatio-temporal variability in pest populations and their impacts at local scales. Thus, we consider this to be of medium robustness.
**Agreement:** Low agreement: CPD responses to climate varies depending on the specifics of CPD, crops and regions, but an increase in pest severity is commonly observed. However, changes in pest populations and distributions, and the impact of these changes on food production, has considerable uncertainties and there are disagreements between studies e.g. (Deutsch et al. 2018) and (Lehmann et al. 2018)
***Low Confidence (medium robustness, low agreement)***

**CS2: large-scale farmers lose up to 45-50% of crop yield due to CPD after investing in high chemical inputs. Small-scale farmers lose up to 60% of yield if unable to use pesticides.**

Small-scale farmers can mitigate the effects of CPDs on yield loss by adopting improved seed varieties, diverse crop rotations and intercropping, and agroforestry.

**Robustness:** Crop losses due to CPD are temporally and spatially variable depending on climatic conditions and management practices, which highlights the need for context and region-specific monitoring and mitigation measures. Thus, low robustness.

**Agreement:** CPD responses to climate varies depending on the specifics of CPD, crops and regions, but an increase in pest severity is commonly observed. However, changes in pest populations and distributions, and the impact of these changes on food production has considerable uncertainties and there are disagreements between studies e.g. (Deutsch et al. 2018) and (Lehmann et al. 2018), hence, **low agreement.**
***Low confidence (low robustness, low agreement)***

**CS3: The estimated CPD-induced yield losses vary among major crops – e.g., 31% (±15%) for maize, 50% (±25%) for cassava, 40% (±20%) for wheat.**

**Robustness:** Effect on crops is mainly based on projections from models and there is high variability among studies in the yield losses attributed to different crop pests and diseases. Thus, **medium robustness.**

**Agreement:** There is high agreement about the overall negative impact of CPD on crops., however the effect sizes differ between regional and local-scale studies vary, thus **medium agreement.**
***Medim confidence (medium robustness, medium agreement)***

**CS4: An increase in extreme events and crop pests and pathogens – e.g., locust outbreaks in east Africa.**

Extreme events may become more frequent in the future, increasing the risks to crop yields. Species which do not cause outbreaks in present may start to create outbreaks trying to survive the longer dry periods and extreme climate variability (Gregory et al. 2009).
Robustness: **Low robustness,** there are no studies which provide information on frequency of outbreaks with respect to climate change.
Agreement: There is h**igh agreement** among research studies and syntheses that climate risks will influence large regional to global scale pest and disease outbreaks.
***Medium Confidence: Low robustness, high agreement***

## High climate risk and high market connectivity

**CS1: Pest- and disease-induced crop yield losses exacerbated by climate change and homogenised agriculture.**

The yield losses in this scenario could be:
~32% (range 20-57%) yield loss due to CPD because of climate
+ 2-5 % yield loss due to reduced pest suppression under homogenised agriculture

Climate change will affect the geographic range, incidence and severity of pests, weeds, and diseases, consequently impacting both crop and livestock production.

The stakeholder workshops indicated an expansion of land for crop as well as livestock production, which may involve conversion of natural and semi-natural areas to crop or pasture lands. Market connectivity is often correlated with mechanisation, agricultural intensification (increased inputs) and homogenisation of agricultural systems. Under homogenised agriculture, te risks of pest and disease outbreaks could be greater compared with heterogeneous mixed systems (Descheemaeker et al. 2016).

**Robustness:** *Low robustness:* Several studies suggest that intercrops and heterogenous diverse production systems may suppress pests through provisioning of biological control via natural enemies. However, the effect of natural enemies varies based on local context and landcover. AFRICAP's empirical study from Tanzania shows that the characteristics of neighbouring fields (fallow or intercrop) influences the natural enemy and pest populations in the focal field. Thus, there may be large uncertainties due to the local landscape contexts and management practices. If climate change and technological development leads to homogenisation of agriculture, then the likelihood of negative impacts on food production is high. However, there is little empirical information and existing analyses focus mostly on single pathogens. Therefore, the uncertainty around the likely effects is large.

**Agreement:** There is high variability among studies on how natural enemies respond to heterogeneity, and global syntheses have indicated inconsistent responses of pests and natural enemies due to heterogeneity. Also, the understanding of how climate will impact pathogens is from broad scale analyses of a selected pathogens with a lack of agreement between studies (e.g. (Savary et al. 2019; Lehmann et al. 2020). Hence, *medium agreement.*
***Low Confidence (Low robustness, medium agreement)***

**CS2: An additional 2-5 % yield loss if heterogeneous agriculture-natural landcover mosaics are converted to simplified homogenised production systems.**

Increase in globalised trade of economically desired plants and animals will reduce farm-level diversity, lead to landscape-level homogenisation, and negatively affect long-term resilience of food systems to crop pests and diseases.

Homogenised production characterised by reduced crop diversity - due to reliance on a few dominant species, could occur with agricultural expansion and intensification, and transformation of heterogeneous small-scale agriculture to large-scale corporate agriculture. Increased uniformity of cultivars leads to greater vulnerability to CPD. When pests and pathogens evolve to overcome the genetic resistance of the crop, the result can be a severe crop failure with immediate detrimental effects of food availability and nutrition. The negative effects of crop homogenisation will interact and multiply with local habitat loss, landscape simplification, and invasive CPD.

**Robustness:** There is limited local-scale evidence. Hence, low robustness.

**Agreement:** Evidence from other geographies which have had global trade driven transformation of agriculture suggest high likelihood of landscape level homogenisation under technological development and globalised trade (Green et al. 2019). Most studies indicate towards the negative impacts of novel pest and diseases on crop yields. However, there is lack of understanding for local scale drivers. Thus, medium agreement.

***Low Confidence (Low robustness, medium agreement)***

**CS3: An additional 13% crop yield loss due to novel pest and diseases.**

Climate and increased trade and homogenisation of agricultural systems will facilitate introduction, establishment, dominance and spread of novel transboundary pest and diseases and invasive species. Acute invasive species – such as fall army warm – could have a devastating impact on production leading to 60-100% of yield losses.

**Robustness:** There is limited local-scale evidence. Hence, low robustness.

**Agreement:** most studies indicate towards the negative impacts of novel pest and diseases on crop yields. Thus, high agreement.

***Medium Confidence (low robustness, High agreement)***

**CS4: Adaptation measures may involve greater pesticide use, at the cost of associated health and environmental damage and the elevated threat of pesticide resistance.**

**Robustness:** Most studies report increased use and dependence on pesticides with implications for human health, however studies do not provide effect sizes. Hence, medium robustness.

**Agreement:** There is high agreement among studies on pesticide use and health implications

***High Confidence (Medium robustness, high agreement)***

## Low climate risk and high market connectivity

**CS1: An additional 2-5 % yield loss if heterogeneous agriculture-natural landcover mosaics are converted to simplified homogenised production systems.**

Increase in globalised trade of economically desired plants and animals will reduce farm-level diversity, lead to landscape-level homogenisation, and negatively affect long-term resilience of food systems to crop pests and diseases.

Homogenised production characterised by reduced crop diversity - due to reliance on a few dominant species, could occur with agricultural expansion and intensification, and transformation of heterogeneous small-scale agriculture to large-scale corporate agriculture. Increased uniformity of cultivars leads to greater vulnerability to CPD. When pests and pathogens evolve to overcome the genetic resistance of the crop, the result can be a severe crop failure with immediate detrimental effects of food availability and nutrition. The negative effects of crop homogenisation will interact and multiply with local habitat loss, landscape simplification, and invasive CPD.

**Robustness**
There are only few studies quantifying yield losses because of homogenisation and climate change. This the robustness is low.
**Agreement**
Agreement between studies on increased impact of pests under climate is medium. Studies largely agree on the increased pest prevalence and vulnerability under homogenised agriculture. Therefore, we put this as medium agreement.
***Low Confidence (Low robustness, medium agreement)***

**CS2: additional 13% crop yield loss due to novel pest and diseases.**
Increased trade and homogenisation of agricultural systems will facilitate introduction, establishment, dominance and spread of novel transboundary pest and diseases and invasive species. Acute invasive species – such as fall army warm – could have a devastating impact on production leading to 60-100% of yield losses.
**Robustness:** There is limited local-scale evidence. Hence, low robustness.
**Agreement:** most studies indicate towards the negative impacts of novel pest and diseases on crop yields. Thus, high agreement.
**Medium Confidence (Low robustness, high agreement)**

# South Africa

## Low climate risk and low land reform (present condition)

**CS1: Pest and diseases induce on average a ~30% (±5%) reduction in annual yields with estimates of crop-specific losses (maize, beans, cassava, and soya) ranging from 20-60%** (Popp et al. 2013; Savary et al. 2019)**.**

South African agriculture primarily consists of three types of production models: Small-scale (<10ha), emerging (10-250ha) and large-scale commercial (>250ha). Pests and diseases are among the major constraints limiting maize productivity in small-scale farm systems. Commercial farmers and most emerging farmers use chemicals for controlling CPDs, whereas mall-scale farmers mainly use everyday household remedies (e.g., wood ash, plant extracts). Cob rots, grey leaf spot, maize streak virus, northern leaf blight, and common rust were the common diseases identified by farmers. In South Africa, yield losses due to crop pest and disease are usually 30 to 40%.

**Robustness:** Local-scale studies based on field trials provide a range of yield loss estimates, which vary between crops and CPD types. The global-scale syntheses provide regional estimates (e.g., sub-Saharan Africa) which may lack local precision. Also, the importance of CPD varies based on regions and Tanzania has a diverse range of different farming systems – from mountains, coasts to forests. Hence, a general estimate may not provide a robust indicator of yield losses that are highly variable and contextual. Therefore, we place this statement under **Medium robustness.**

**Agreement:** The estimates of yield losses overlap among studies and there is a general agreement of yield losses being between 20-30%. So, there is high agreement on average estimates of yield losses due to CPD.
***High Confidence (Medium robustness, high agreement)***

**CS2: Commercial farms using pesticides have, on average, ~5% higher crop damage and yield losses (Kravchenko et al. 2017) than small-scale heterogenous systems.**

Commercial farms, and some of the emerging farms, have higher crop productivity due to the planting of high-yielding varieties, irrigation, and the application of chemical fertilizers and pesticides. However, an increased yield potential of crops is often also associated with higher vulnerability to pest attack, leading to increasing absolute losses and loss rates. Despite a clear increase in pesticide use, crop losses have not significantly decreased during the last 40 years. In South Africa, field trials indicate that on average, 25-35 % of potential crop yield is lost to pre-harvest pests.

**Robustness:** Studies comparing crop pest and disease pressures in the same landscape in South Africa are rare. We used average yield losses mentioned in separate studies from commercial farms and small-scale farms. Hence, low robustness.
**Agreement:** The estimates of difference in CPD-induced yield losses among small and commercial farms are based on regional estimates. There is a general agreement among studies about the range of yield losses in different production systems. Hence, medium agreement.
***Low Confidence (Low robustness, medium agreement)***

## High climate risk and little land reform

**CS1: Under high climate risk, median losses in yield due to CPD would increase by 10 to 25% per degree of global mean surface warming. Mean estimates of CPD-induced yield losses are estimated at ~32% (range 20-57%) of annual crop yields, when average global surface temperatures increase by 2°C** (Deutsch et al. 2018)**.**

Rising temperature along with higher atmospheric CO2, may favour the growth and survival of many pests and diseases specific to agricultural crops. With temperature, generation times, metabolic rates, food consumption, and growth rates of insect pests and disease vectors are expected to increase. Metabolic increases will alter food web dynamics, leading to elevated rates of herbivory and predation, as well as changes in the spread of insect-borne tropical diseases. Some pests which are already present, but only occur in small areas or at low densities, may be able to exploit the changing conditions by spreading more widely and reaching damaging population densities (Dillon et al. 2010; Lobell and Gourdji 2012; Nazaries et al. 2015).
**Robustness:** Information about percentage change in yield losses is based on a global synthesis of pest damage on common crops in 19 regions across the world. The regional averages do not always reflect the spatio-temporal variability in pest populations and their impacts at local scales. Thus, we consider this to be of medium robustness.
**Agreement:** Low agreement: CPD responses to climate is varies depending on the specifics of CPD, crops and regions. Increase Pest severity is commonly observed. However, changes in pest populations and distributions, and the impact of these changes on food production has uncertainties and there are disagreements between studies e.g. (Deutsch et al. 2018) and (Lehmann et al. 2018)
**Low Confidence (medium robustness, low agreement)**

**CS2: Large-scale farmers lose up to 45-50% of crop yield due to CPD after investing in high chemical inputs. Small-scale farmers lose up to 60% of yield.**

Small-scale farmers can mitigate the effects of CPDs by adopting improved seed varieties, diverse crop rotations and intercropping, and agroforestry.

**Robustness:** Crop losses due to CPD are temporally and spatially variable depending on climatic conditions and management practices, which highlights the need for context and region-specific monitoring and mitigation measures. Thus, low robustness.

**Agreement:** CPD responses to climate varies depending on the specifics of CPD, crops and regions. Increase Pest severity is commonly observed. However, changes in pest populations and distributions, and the impact of these changes on food production has uncertainties and there are disagreements between studies e.g. (Deutsch et al. 2018) and (Lehmann et al. 2018)
***Low confidence (low robustness, low agreement)***

**CS3: The estimated CPD-induced yield losses vary among major crops e.g., 31% (±15%) for maize, 50% (±25%) for cassava, 40% (±20%) for wheat.**

**Robustness:** Effect on crops is mainly based on projections from models, and there is high variability among studies in the yield losses attributed to different crop pests and diseases. Thus, medium robustness.
**Agreement:** There is high agreement about the overall negative impact of CPD on crops, however the effect sizes different between regional and local-scale studies vary, this medium agreement.
***Medium Confidence (medium robustness, medium agreement)***

**CS4: Increase in extreme events and crop pests and pathogens e.g., droughts**

Extreme events may become more frequent in the future, increasing the CPD risks to crop yields. In central South Africa, farmers in the region have been facing longer dry spells and drought at the start of the planting season, and early onset (mid-March) and late cessation (mid-October) of frost for the last 4-5 years (Myeni et al. 2019). As a result, the growing season has shortened and standing crops are more vulnerable to winter stress and hailstorms in June, in addition to increased pest pressures from grasshoppers and birds. Climate shocks are expected to occur more frequently under high climate risks (Gregory et al. 2009).
**Robustness:** Low robustness, there are no studies which provide information on frequency of CPD outbreaks with respect to climate change.
Agreement: There is high agreement among research studies and syntheses that climate risks will influence large regional to global scale pest and disease outbreaks.
***Medium Confidence (Low robustness, high agreement)***

## High climate risk and significant land reform

Pest and disease impact under land reform depends on which direction the land reform programme takes:
(i) Land reform along with additional support to the emerging farmers in terms of mechanisation and market connectivity provided by the Department of Agriculture, Forestry and Fisheries (DAFF)
(ii) Land reform with little additional support from the government

**LR1 -** In the first situation land reform will most likely lead to an increase in crop land area, mechanisation, and homogenisation (loss of crop diversity) as farmers may focus on selected market commodities.
**LR2 -** In the second situation, land reform may lead to an increase in livestock pasture and crop diversity.

**CS1a: Pest and disease-induced crop yield losses exacerbated by climate and homogenised agriculture under LR1.**

The yield losses in this scenario could be:
~32% (20-57) yield loss due to CPD because of climate
+ 1-2 % yield loss due to reduced pest suppression under homogenised agriculture
CS1b: Under LR2 - The CPD driven yield losses may only be due to climate at ~32% (range 20-57%)

**Robustness:** *Low robustness:* Several studies suggest that intercrops and heterogenous diverse landscapes may suppress pests through provisioning of biological control via natural enemies. However, effect of natural enemies varies based on local context and landcover. AFRICAP's empirical study from Tanzania points out that characteristics of neighbouring field (fallow or intercrop) influences natural enemy and pest populations in the focal field. Thus, there may large uncertainties due to the local landscape contexts and management practices. If climate change and technological development leads to homogenisation of agriculture, then the likelihood of negative impacts on food production is high. Further, there is little empirical information and existing analyses focus mostly on single pathogens. Therefore, the uncertainty around the likely effects is large.

**Agreement:** There is high variability among studies on how natural enemies respond to heterogeneity, and global syntheses have indicated inconsistent responses of pests and natural enemies to heterogeneity. Also, the understating of how climate will impact pathogens is from broad scale analyses of a selected pathogens with lack of agreement between studies (e.g. (Savary et al. 2019; Lehmann et al. 2020). Hence, *medium agreement.*

***Low confidence (low robustness, medium agreement)***

**CS2: An additional 2-5 % yield loss if heterogeneous agriculture-natural landcover mosaics are converted to simplified homogenised production systems**

An increase in mechanisation and international trade of economically desired plants and animals will reduce farm-level diversity, lead to landscape-level homogenisation, and negatively affect long-term resilience of food systems to crop pests and diseases.

Homogenised production characterised by reduced crop diversity - due to reliance on a few dominant species, could occur with agricultural expansion and intensification, and transformation of heterogeneous small-scale agriculture to large-scale corporate agriculture. Increased uniformity of cultivars leads to greater vulnerability to CPD. When pests and pathogens evolve to overcome the genetic resistance of the crop, the result can be a severe crop failure with immediate detrimental effects of food availability and nutrition. The negative effects of crop homogenisation will interact and multiply with local habitat loss, landscape simplification, and invasive CPD.

**Robustness:** There is limited local-scale evidence. Hence, low robustness.

**Agreement:** Evidence from other geographies which have had global trade driven transformation of agriculture suggest high likelihood of landscape level homogenisation under technological development and globalised trade (Green et al. 2019). Thus, high agreement.

**Medium Confidence (low robustness, high agreement)**

**CS3: An additional 13% crop yield loss due to novel pest and diseases.**

Climate and increased trade and homogenisation of agricultural systems will facilitate introduction, establishment, dominance and spread of novel transboundary pest and diseases and invasive species.  Acute invasive species – such as fall army warm – could have a devastating impact on production leading to 60-100% of yield losses.

**Robustness:** There is limited local-scale evidence. Hence, low robustness.

**Agreement:** most studies indicate towards the negative impacts of novel pest and diseases on crop yields. Thus, high agreement.

**Medium confidence (Low robustness, high agreement)**

**CS4: Adaptation measures may involve greater pesticide use, at the cost of associated health and environmental damage and the elevated threat of pesticide resistance.**

**Robustness:** Most studies report increased use and dependence on pesticides have strong implications for human health, however studies do not provide effect sizes. Hence, medium robustness.

**Agreement:** There is high agreement among studies on pesticide use and health implications

**High Confidence (Medium robustness, high agreement)**

## Low climate risk and significant land reform

**CS1: An additional 2-5 % yield loss if heterogeneous agriculture-natural landcover mosaics are converted to simplified homogenised production systems. (LR)**

Increase in globalised trade of economically desired plants and animals will reduce farm-level diversity, lead to landscape-level homogenisation, and negatively affect long-term resilience of food systems to crop pests and diseases.

Homogenised production characterised by reduced crop diversity - due to reliance on a few dominant species, could occur with agricultural expansion and intensification, and transformation of heterogeneous small-scale agriculture to large-scale corporate agriculture. Increased uniformity of cultivars leads to greater vulnerability to CPD. When pests and pathogens evolve to overcome the genetic resistance of the crop, the result can be a severe crop failure with immediate detrimental effects of food availability and nutrition. The negative effects of crop homogenisation will interact and multiply with local habitat loss, landscape simplification, and invasive CPD.

**Robustness**

There are only few studies quantifying yield losses because of homogenisation and climate change. This the robustness is low.

**Agreement**

Agreement between studies on increased impact of pests under climate is medium. Studies largely agree on the increased pest prevalence and vulnerability under homogenised agriculture. Therefore, we put this as medium agreement.

***Low Confidence (low robustness, medium agreement)***

**CS2: An additional 13% crop yield loss due to novel pest and diseases.**

Increased trade and homogenisation of agricultural systems will facilitate introduction, establishment, dominance and spread of novel transboundary pest and diseases and invasive species. Acute invasive species – such as fall army warm – could have a devastating impact on production leading to 60-100% of yield losses.

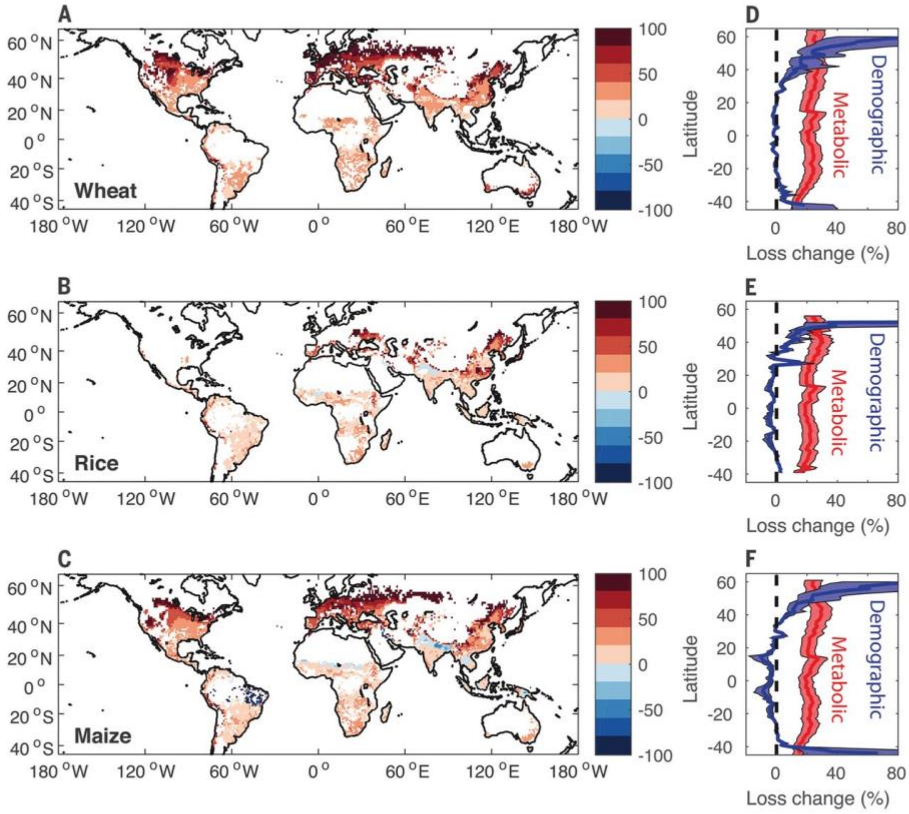
**Robustness:** There is limited local-scale evidence. Hence, low robustness.

**Agreement:** most studies indicate towards the negative impacts of novel pest and diseases on crop yields. Thus, high agreement.

**Medium Confidence (Low robustness, high agreement)**

# Appendix

1. **Projected yield losses under due to climate** (Savary et al. 2019)




2. “Many pests and pathogens exhibit considerable capacity for generating, recombining, and selecting fit combinations of variants in key pathogenicity, fitness, and aggressiveness traits that there is little doubt that any new opportunities resulting from climate change will be exploited by them.” (Gregory et al. 2009)
3. (Lehmann et al. 2018) *41% showed responses expected to lead to increased pest damage, whereas only 4% exhibited responses consistent with reduced effects; notably, most of these species (55%) demonstrated mixed responses.*
4. “Globally, an average of 35 % of potential crop yield is lost to pre-harvest pests (Oerke 2005). In addition to the pre-harvest losses, food chain losses are also relatively high (IWMI 2007).”

# References

Bisimwa EB, Birindwa DR, Yomeni MO, et al (2019) Multiple Cassava Viruses’ Co-Infections and Resurgence of Pests Are Leading to Severe Symptoms and Yield Losses on Cassava in the South-Kivu Region, Democratic Republic of Congo. Am J Plant Sci. https://doi.org/10.4236/ajps.2019.1011138

Descheemaeker K, Oosting SJ, Homann-Kee Tui S, et al (2016) Climate change adaptation and mitigation in smallholder crop–livestock systems in sub-Saharan Africa: a call for integrated impact assessments. Reg Environ Chang 16:2331–2343. https://doi.org/10.1007/s10113-016-0957-8

Deutsch CA, Tewksbury JJ, Tigchelaar M, et al (2018) Increase in crop losses to insect pests in a warming climate. Science (80- ) 361:916–919. https://doi.org/10.1126/science.aat3466

Dillon ME, Wang G, Huey RB (2010) Global metabolic impacts of recent climate warming. Nature. https://doi.org/10.1038/nature09407

Freeman HA, Kaitibie S, Moyo S, et al (2008) Livestock, livelihoods and vulnerability in Lesotho, Malawi and Zambia: designing livestock interventions for emergency situations [Language: en]. ILRI Res Rep

Green JMH, Croft SA, Durán AP, et al (2019) Linking global drivers of agricultural trade to on-the-

ground impacts on biodiversity. Proc Natl Acad Sci U S A 116:23202–23208. https://doi.org/10.1073/pnas.1905618116
Gregory PJ, Johnson SN, Newton AC, Ingram JSI (2009) Integrating pests and pathogens into the climate change/food security debate. In: Journal of Experimental Botany
Karp DS, Chaplin-Kramer R, Meehan TD, et al (2018) Crop pests and predators exhibit inconsistent responses to surrounding landscape composition. Proc Natl Acad Sci U S A 115:E7863–E7870. https://doi.org/10.1073/pnas.1800042115
Kimhi A (2006) Plot size and maize productivity in Zambia: Is there an inverse relationship? Agric Econ 35:1–9. https://doi.org/10.1111/j.1574-0862.2006.00133.x
Komarek AM, Msangi S (2019) Effect of changes in population density and crop productivity on farm households in Malawi. Agric Econ (United Kingdom). https://doi.org/10.1111/agec.12513
Kravchenko AN, Snapp SS, Robertson GP (2017) Field-scale experiments reveal persistent yield gaps in low-input and organic cropping systems. Proc Natl Acad Sci U S A 114:926–931. https://doi.org/10.1073/pnas.1612311114
Lehmann P, Ammunét T, Barton M, et al (2018) Complex responses of global insect pests to climate change. bioRxiv [Preprint] 425–488. https://doi.org/10.1101/425488
Lehmann P, Ammunét T, Barton M, et al (2020) Complex responses of global insect pests to climate warming. Front. Ecol. Environ.
Lobell DB, Gourdji SM (2012) The influence of climate change on global crop productivity. Plant Physiol. https://doi.org/10.1104/pp.112.208298
Mangisoni JH (1994) Effectiveness of livestock production and marketing policies in Malawi. Agric Econ Anal Rural Dev
Mwase WF, Kapooria RG (2001) Incidence and severity of frogeye leaf spot and associated yield losses in soybeans in agroecological zone II of Zambia. Mycopathologia 149:73–78. https://doi.org/10.1023/A:1007126225457
Myeni L, Moeletsi M, Thavhana M, et al (2019) Barriers affecting sustainable agricultural productivity of smallholder farmers in the eastern free state of South Africa. Sustain 11:1–18. https://doi.org/10.3390/su11113003
Nazaries L, Tottey W, Robinson L, et al (2015) Shifts in the microbial community structure explain the response of soil respiration to land-use change but not to climate warming. Soil Biol Biochem. https://doi.org/10.1016/j.soilbio.2015.06.027
Oerke EC (2006) Crop losses to pests. J. Agric. Sci.
Pallangyo B, Mdily K, Mkondo C, Kibola A (2019) Crop pests, control measures and potential impacts in Kihansi catchment area. Tanzania J Sci
Perrin RM (1976) Pest management in multiple cropping systems. Agro-Ecosystems 3:93–118. https://doi.org/10.1016/0304-3746(76)90110-4
Popp J, Pető K, Nagy J (2013) Pesticide productivity and food security. A review. Agron. Sustain. Dev.
Salih AAM, Baraibar M, Mwangi KK, Artan G (2020) Climate change and locust outbreak in East Africa. Nat. Clim. Chang.
Savary S, Willocquet L, Pethybridge SJ, et al (2019) The global burden of pathogens and pests on major food crops. Nat Ecol Evol 3:430–439. https://doi.org/10.1038/s41559-018-0793-y
Sileshi GW, Kuntashula E, Matakala P, Nkunika PO (2008) Farmers' perceptions of tree mortality, pests and pest management practices in agroforestry in Malawi, Mozambique and Zambia. Agrofor Syst 72:87–101. https://doi.org/10.1007/s10457-007-9082-5
Thornton P, Cramer L (2012) Impacts of climate change on the agricultural and aquatic systems and natural resources within the CGIAR's mandate
Wortmann CS (1992) Assessment of yield loss caused by biotic stress on beans in africa. CIAT
Yengoh GT (2012) Determinants of yield differences in small-scale food crop farming systems in Cameroon. Agric Food Secur 1:1–17. https://doi.org/10.1186/2048-7010-1-19