Food and Agriculture
Organization of the
United Nations

# Synergies and trade-offs in climate-smart agriculture

## An approach to systematic assessment

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# Acronyms and abbreviations

| | |
|---|---|
| **APSIM** | Agricultural Production Systems sIMulator |
| **CA** | conservation agriculture |
| **CBA** | cost-benefit analysis |
| **CFT** | Cool Farm Tool |
| **CSA** | climate-smart agriculture |
| **CSA-PF** | Climate-Smart Agriculture Prioritization Framework |
| **CV** | coefficient of variation |
| **GHG** | greenhouse gas |
| **GWP** | global warming potential |
| **HDP** | human-digestible protein |
| **IBFS** | income-based food security |
| **IFSM** | Integrated Farm System Model |
| **IMPACT** | International Model for Policy Analysis of Agricultural Commodities and Trade |
| **IPCC** | Intergovernmental Panel on Climate Change |
| **IRR** | internal rate of return |
| **RCP** | representative concentration pathway |
| **REDD+** | Reducing Emissions from Deforestation and forest Degradation, plus the sustainable management of forests, and the conservation and enhancement of forest carbon stocks |
| **SDG** | Sustainable Development Goal |
| **SLM** | sustainable land management |
| **TOA-MD** | Trade-off Analysis for Multi-Dimensional Impact Assessment |
| **ZT** | zero tillage |

## Chemical formulae

| | |
|---|---|
| $CH_4$ | methane |
| $CO_2$ | carbon dioxide |
| $CO_2eq$ | carbon dioxide equivalent |
| $N_2O$ | nitrous oxide |

# Executive summary

Food security, food systems and climate change are closely intertwined issues that need to be urgently addressed to achieve sustainable development globally, and for all. Climate-smart agriculture (CSA) is an integrated approach that seeks to advance sustainable food production, climate change adaptation and mitigation in the agriculture sector – the three pillars of CSA – concomitantly. Given the multiple objectives of this approach, it is essential to identify and understand the interlinkages between these, as well as with CSA intervention options. Such insights can inform and support strategic decisions that enhance synergies and reduce trade-offs to achieve better results for investments in climate-smart agriculture.

This publication proposes an approach to categorize and identify potential synergies and trade-offs in CSA in a structured manner. For this purpose, it breaks down each CSA pillar into subsets of three objectives, in order to present a more nuanced picture of possible interlinkages between objectives within and across the three pillars. From the pairwise comparison of these objectives, a scheme for the categorization of synergies and trade-offs in CSA is developed. A review of CSA-related scientific literature identifies examples of synergies and trade-offs for the various categories of relationships between CSA objectives. This makes it possible to *characterize* each category and provide useful additional information, including relevant indicators and assessment methods. This information is presented as a set of characterization sheets, as well as a menu of methodologies and tools for the *ex-ante* assessment of synergies and trade-offs in CSA.

In addition, a simple five-step procedure is proposed to use the information presented as a tool for the systematic screening of CSA interventions for potential synergies and trade-offs and the selection of appropriate assessment methods and tools. The publication is intended as a resource for all actors engaged in the development of CSA strategies, plans and interventions, as well as for investors and financing institutions involved in CSA, and researchers working in this field.

The literature review finds examples of both synergies and trade-offs for many of the categories – i.e. relationships between CSA objectives – even within an agriculture subsector. This corroborates the notion that the realization of CSA objectives, and the synergies between them, is strongly context-specific. It also implies that findings on synergies and trade-offs should not be transferred between geographical areas or agro-ecological and socio-economic contexts, without contextualized testing or assessment.

The documented cases show the importance of assessing relationships between CSA objectives at multiple scales, as exemplified by the case of irrigation development in a catchment area with negative impacts on livelihood opportunities and ecosystem services in downstream areas of the river basin. They also display a variety of indicators that can be used for each CSA objective. The careful selection of indicators for each CSA objective is crucial, as it may result in opposing conclusions. For example, a reduction in greenhouse gas (GHG) emissions per litre of milk suggests a mitigation benefit. However, this may be associated with increased production volumes, resulting in higher GHG emissions per area and therefore a trade-off with climate change mitigation objectives.

Many of the *ex-ante* assessment methodologies and tools identified in the reviewed literature focus on specific aspects, such as GHG emissions or productivity. While these are indispensable, they need to be complemented by methodologies that enable an integrated assessment of multiple indicators, such as sustainability polygons, in order to account for the interconnectedness of objectives within and across the three CSA Pillars.

The compilation of synergies and trade-offs, indicators, methodologies and tools presented here draws in large part on scientific literature that explicitly refers to *climate-smart agriculture*. This results in a bias towards examples from the crop and livestock sectors. In order to obtain better representation of forestry, fisheries, aquaculture and integrated production systems, as well as to expand the menu of indicators and assessment methods, wider-ranging research, including grey literature, should be undertaken. The approach adopted in this publication provides a flexible framework that can be expanded with additional information.

In conclusion, this publication provides an overview of possible synergies and trade-offs within and between the three pillars of climate-smart agriculture. It can support a structured thinking process for the design of CSA interventions in terms of flagging possible risks and opportunities and identifying tools to further investigate and quantify these – following the proposed screening procedure. While it does not provide a stand-alone methodology for an all-inclusive assessment of synergies and trade-offs in CSA, it could represent a further step towards the development of a standardized framework for such assessments, and serve as a reference to determine basic requirements and principles for such a framework.

1

# Introduction

The current trends in food systems, food security and climate change expose substantial interlinked challenges lying ahead (Mbow *et al.*, 2019). The number of undernourished people is increasing,[1] as is the demand for food due to a growing global population, income growth and changing dietary habits – along with its associated social and environmental impacts and greenhouse gas emissions. Food systems contribute about 21 to 37 percent of anthropogenic GHG emissions, and absolute emissions from food systems are expected to increase by 30 to 40 percent by 2050, if food demand is satisfied by increasing food supply through business-as-usual food production and distribution methods. At the same time, the impacts of climate change on food production and food security – such as reduced crop and livestock productivity due to heat and drought stress, damage to agricultural assets and disruptions of food supply chains caused by extreme weather events – can already be observed and are expected to intensify.

Climate-smart agriculture is an approach that seeks to address this triple challenge of food security, climate change adaptation and climate change mitigation in an integrated way (FAO, 2013). It pursues three main objectives, the so-called CSA pillars:

- **CSA Pillar 1:** Sustainably increasing agricultural productivity and incomes
- **CSA Pillar 2:** Adapting and building resilience to climate change
- **CSA Pillar 3:** Reducing and/or removing greenhouse gas emissions, where possible

From the early stages of development of the CSA concept, it has been recognized that interventions in the food, agriculture and land-use sectors can create synergies between these three objectives,[2] but may also involve trade-offs (FAO, 2009, 2010, 2013; Lipper *et al.*, 2014). Interventions often focus on one specific objective, i.e. one of the CSA pillars, based on stakeholder interests and funding streams. However, it is important to analyse the impacts of such interventions on the other CSA pillars by means of measurable indicators, as this may reveal unintended negative effects (trade-offs), as well as opportunities to create synergies. Such assessments can support comparison of alternative intervention options and the selection of the option with the strongest outcomes for all three CSA pillars.

This publication aims to improve the understanding of synergies and trade-offs in climate-smart agriculture and promote their systematic assessment in support of evidence-based CSA planning processes. It breaks down each CSA pillar into subsets of objectives, in order to provide a more nuanced picture of possible interlinkages between objectives within and across the pillars. The resulting matrix of relationships – along with 'characterization sheets', or descriptions for each relationship – provides a tool for the systematic screening of CSA interventions for potential synergies and trade-offs. The characterization sheets present indicators and metrics, as well as methodologies and tools, which can be used for the assessment and evaluation of specific synergies and trade-offs at different scales, ranging from field to landscape to country scale. They also highlight enabling environment factors – such as the presence of social networks or the adoption of new governance approaches – that are critical for enhancing a specific synergy or reducing a given trade-off.[3] The publication is intended as a resource for all actors engaged in the development of CSA strategies, plans and interventions, as well as for investors and financing institutions involved in CSA, and researchers working in this field. The ultimate objective is to support strategic decisions that enhance synergies and reduce trade-offs, so as to achieve better results for investments in climate-smart agriculture.

Section 2 of this document describes the applied approach to the characterization of synergies and trade-offs in CSA. It further proposes a simple method to use the characterization as a screening tool for potential synergies and trade-offs. The section is complemented by a full set of characterization sheets in Annex 1. Section 3 provides a selection of methodologies and tools that can be used for synergy and trade-off assessments. It is complemented by Annex 2, which presents a brief description of each methodology/tool. Finally, Section 4 summarizes the results of the analysis and discusses the potential and limitations of the approach.

1 After a decline in numbers of undernourished people globally over several decades, there has been a consistent upward trend since 2014 (FAO *et al.*, 2020)

2 Throughout the publication, the term 'intervention' is used to describe any type of programme or action that aims to achieve agricultural development goals, be it at policy, institutional, community, farm, field or any other level.

3 The creation of an enabling environment for the transition to climate-smart food systems forms part of the CSA implementation approach. Therefore, the identification of enabling environment factors is of particular interest.

# 2

# Characterization of synergies and trade-offs in CSA

The dynamic relationships between food production, climate change adaptation and mitigation make the assessment of synergies and trade-offs a challenging task:

- It involves a multitude of different spatial and temporal scales, sectors, agro-ecological and socio-economic contexts. This may result in a wide range of possible synergies and trade-offs, difficult to identify and duly address in their entirety in the design of a climate-smart agriculture intervention.
- It involves different degrees of complexity, including synergies and trade-offs that are more evident or easily understood – such as the trade-off between crop production for human consumption or as a biofuel feedstock – than other more complex or indirect interlinkages.
- It is highly context-specific and results may not be transferable to other locations or contexts. For example, some practices may generate synergies between two objectives, such as productivity and adaptation to drought in one place, but present a trade-off in another place due to the specific agro-ecological, socio-economic or cultural conditions, and/or the effects on different spatial or temporal scales.

To help address such challenges, this publication proposes an approach to categorize and identify potential synergies and trade-offs in CSA (as defined in Box 1) in a structured manner. The categorization is based on the pairwise comparison of a set of CSA objectives. For each category, a characterization sheet is then presented, which provides examples of synergies and trade-offs along with suitable indicators, methodologies and tools for their assessment (see Section 2.1). While neither the categorization nor the characterization sheets replace context-specific assessments, they can serve as a tool for the systematic screening of CSA interventions for potential synergies and trade-offs and assist in the selection of appropriate assessment methods (see Section 2.2). The complete set of characterization sheets is presented in Annex 1.

## Box 1: Concept of synergy and trade-off in climate-smart agriculture

The terms 'synergy' and 'trade-off' are widely used, without any definition, in reports and scientific literature about climate-smart agriculture – or about the interlinkages between climate change adaptation and mitigation in the food and agriculture sector more generally (FAO, 2009, 2013; Harvey *et al.*, 2014; Smith and Olesen, 2010). For the purpose of this report, 'synergy' is defined as a positive relationship between two measurable objectives, i.e. when a positive impact on a given objective coincides with a positive impact on another objective. A 'trade-off' is defined as a negative relationship between two measurable objectives, i.e. when a positive impact on a given objective coincides with a detrimental effect on another objective. These definitions appear to be in line with use of the terms 'synergy' and 'trade-off' in most of the evaluated literature and follow the concept of trade-off analysis (Kanter *et al.*, 2018). It should be noted, however, that according to this definition, a synergy does not necessarily involve a mutually reinforcing relationship.

# 2.1 Approach

As mentioned in Box 1, synergies and trade-offs can be defined in terms of the relationship between coexisting objectives, where a positive relationship represents a synergy, and a negative relationship represents a trade-off. This is illustrated by the following two examples:

1) Efficient livestock feeding practices can enhance livestock productivity and contribute to increased farmers' incomes. At the same time, they can reduce methane emissions from enteric fermentation (Shikuku *et al*., 2017). Improved feeding practices thereby create a synergy between the improvement of farmers' incomes (an objective linked to CSA Pillar 1) and the reduction of GHG emissions per unit of product (an objective linked to CSA Pillar 3).

2) Shade trees in cocoa agroforestry systems can significantly contribute to carbon sequestration in above-ground biomass and also reduce heat stress for cocoa crops (Blaser *et al*., 2018). However, at high levels of shade-tree cover which maximize carbon sequestration and the cooling effect, water availability and cocoa yield decline dramatically, impacting both drought resilience and productivity. Therefore, a trade-off exists in agroforestry systems between carbon sequestration (linked to CSA Pillar 3), the resilience of the agro-ecosystem (linked to CSA Pillar 2) and its productivity (linked to CSA Pillar 1). In the specific case of cocoa agroforestry systems in Ghana, shade-tree cover of around 30 percent was found to minimize the trade-offs.

These examples also show that each CSA pillar, rather than being viewed as one single objective, can be subdivided into a combined set of objectives. Table 1 proposes sets of objectives for each CSA pillar, which enables a more differentiated assessment to be made of synergies and trade-offs between – and within – the CSA pillars.[4]

[4] The sets of objectives capture different aspects of the CSA pillars and do not represent indicators in themselves. Each objective can be measured and assessed with various indicators, as identified in the characterization sheets in Annex 1 and summarized in Annex 2.

**Table 1**: Set of CSA objectives used to categorize synergies and trade-offs in climate-smart agriculture

| CSA Pillar 1: Sustainably increasing agricultural productivity and incomes | | |
|---|---|---|
| **1.A** | **Increasing agricultural productivity**<br>Any improvements in the productivity or efficiency of food production systems; expressed as food production per unit area or per unit of a specific input. | **Productivity** |
| **1.B** | **Increasing food producers' incomes**<br>Any improvements in incomes or profitability at household, farm or product level; expressed as household income, net revenue per unit area, internal rate of return, etc., | **Income** |
| **1.C** | **Social and environmental sustainability**[5]<br>Based on the aim of CSA Pillar 1 to achieve increases in productivity and incomes 'sustainably'. While economic sustainability is represented in Objectives 1.A and 1.B, this objective captures relevant aspects of social and environmental sustainability, e.g. food security, social equality, biodiversity and ecosystem services. | **Soc./Env. sustainability** |

| CSA Pillar 2: Adapting and building resilience to climate change | | |
|---|---|---|
| **2.A** | **Improving climate risk mitigation strategies for food producers' livelihoods**<br>Any improvements in livelihood resilience to climate impacts derived from mitigation strategies such as diversification or microinsurance; expressed as income stability, change in unsustainable coping strategies, etc. | **Livelihood resilience** |
| **2.B** | **Adapting food production systems to current and expected future climate change**<br>Any technical or agronomic adaptation measures that aim to reduce exposure and sensitivity to physical impacts of climate change, as well as to exploit opportunities offered by changing climate conditions, e.g. use of improved varieties, adoption of irrigation, change of crop or livestock species or construction of dykes; expressed as yield stability, area under irrigation, etc.. | **Production system adaptation** |
| **2.C** | **Increasing the resilience of agro-ecosystems**<br>Any improvements in the resilience of food production systems to climate impacts derived from the enhancement of ecosystem functions and services, e.g. species diversification, increasing structural diversity and natural habitats or improving soil health; expressed as yield stability, damage from climate-related disasters, etc. | **Agro-ecosystem resilience** |

| CSA Pillar 3: Reducing and/or removing greenhouse gas emissions, where possible | | |
|---|---|---|
| **3.A** | **Increasing carbon stocks in soils and biomass**<br>Any measures to conserve or enhance terrestrial or marine carbon sinks at field, farm, landscape or seascape level; expressed as carbon stock per unit area, area reforested, area of carbon-rich ecosystems conserved, etc. | **Carbon stocks** |
| **3.B** | **Reducing emission intensities of agricultural products**<br>Any improvements in GHG emission per unit of product or unit area at product, field, farm, landscape or national level; expressed as emissions of individual GHGs per unit or emissions of carbon dioxide equivalent ($CO_2$eq), i.e. global warming potential (GWP) per unit. | **Emissions** |
| **3.C** | **Replacing fossil fuels with renewable energies**<br>Volume of renewable energy production, as far as related to agriculture. This includes, for example, renewables that are integrated in agricultural systems (e.g. solar-powered irrigation), or bioenergy and/or bioenergy feedstock that are derived from agriculture. It may also concern the production of renewable energy outside the agriculture sectors, where agriculture competes for the same resources (e.g. hydropower versus irrigated agriculture); expressed as energy production at river basin level, energy content of bioenergy feedstock, biomass yield, etc. | **Renewables** |

[5] For a more extensive and articulated mapping of synergies and trade-offs between CSA and the dimensions of sustainability, the reader is referred to the publication Climate-smart agriculture and the Sustainable Development Goals (FAO, 2019).

The matrix in Table 3 shows all 36 possible combinations of objectives listed in Table 1. Each matrix cell represents a category or type of relationship between CSA objectives. These categories form the basis of the characterization of synergies and trade-offs in climate-smart agriculture.

The characterization of synergy and trade-off categories was based on a literature review. The review focused on scientific publications in peer reviewed journals. An initial list of literature was created through a search of the bibliographic database Web of Science[6] and was complemented by a screening of the *Special Report Climate Change and Land* of the Intergovernmental Panel on Climate Change (IPCC)[7] for additional relevant resources, resulting in a total of 92 evaluated studies. The choice to focus the literature search on articles explicitly referring to 'climate-smart' agriculture was made in order to obtain the most relevant results, ideally addressing all three CSA pillars. It is acknowledged, however, that this has resulted in a bias towards studies in the crop and livestock sectors, and specifically ones that compare productivity and GHG emissions, where the use of the term *climate-smart* is more common. In contrast, few or no studies on integrated production systems and fisheries were found, respectively.

The literature review identified all studies that present pairwise comparisons of indicators pertaining to two or more of the above-mentioned CSA objectives. All pairwise comparisons were documented as cases of synergies or trade-offs and assigned to the matching category(ies) in the matrix of relationships presented in Table 3.[8] The set of cases collected under each category was then used to elaborate a characterization sheet for the respective category of synergies and trade-offs. The features and structure of the characterization sheets are presented in Table 2. The complete set of characterization sheets is provided in Annex 1. The indicators and metrics referred to in each characterization sheet are limited to those used in the examples cited. They are outcome indicators throughout and comprise different scales of application, ranging from field, farm and household level, through community and watershed to national and river basin scale. A summary of indicators by objectives is presented in Annex 2, which also provides information about the scale of application, data sources and examples of related assessment methodologies and tools for each indicator.

6 Search term – Topic: 'climate smart' AND (agricultur* OR food OR crop OR livestock OR fisher* OR aquaculture OR forest*) AND (synerg* OR trade-off* OR co-benefit*); Results: 64.

7 www.ipcc.ch/srccl/

8 It should be noted that one single case may appear in several categories if the respective study presents a set of indicators that are relevant to more than two CSA objectives. Such cases are counted separately under each relevant category.

**Table 2**: Structure and features of the CSA synergy and trade-off characterization sheets

<table>
<tr><th colspan="4">[Objective A: short name] vs. [Objective B: short name]</th></tr>
<tr><td>Objective<br>[Code]</td><td>[Objective A: Full name]</td><td>[Objective B: Full name]</td><td>Objective<br>[Code]</td></tr>
<tr><td colspan="4">[Description of relationship, including typical synergies and trade-offs, most relevant spatial or temporal scales, etc.]</td></tr>
<tr><td colspan="4">Indicators & metrics<br>[Provides a list of examples of indicators and metrics suitable to assess Objective A against Objective B, based on the cases identified through reviewed literature]</td></tr>
<tr><td colspan="2">[Indicator(s)]<br>• [Metric(s)]</td><td colspan="2">[Indicator(s)]<br>• [Metric(s)]</td></tr>
<tr><td colspan="4">Examples<br>[Provides a list of examples of synergies and trade-offs for interventions in different agricultural subsectors.]</td></tr>
<tr><td>S</td><td colspan="3">[Example of a synergy or trade-off from agricultural subsector X]<br>The circles beneath the sector icon indicate if the example revealed a synergy ('S' on green circle), a trade-off ('T' on yellow circle) and/or no interaction ('N' on grey circle) between two objectives.</td></tr>
<tr><td>S T</td><td colspan="3">[Example of a synergy or trade-off from agricultural subsector Y]</td></tr>
<tr><td colspan="2">Sustainability</td><td colspan="2">Enabling environment</td></tr>
<tr><td colspan="2">[Description of relevant sustainability aspects that are highlighted in the reviewed literature in the context of a specific relationship between two CSA objectives - where available.]<br>This could include positive or negative effects on any of the three dimensions of sustainability – economic, social, environmental – or themes from across the Sustainable Development Goals.</td><td colspan="2">[Description of relevant enabling environment factors to reap synergies and reduce trade-offs, as highlighted in the reviewed literature in the context of a specific relationship between two CSA objectives - where available.]<br>This could include, for example, the redesign of policies or subsidies, social protection schemes, or the strengthening or creation of specific institutions.</td></tr>
<tr><td colspan="4">Methodologies & Tools<br>[Provides a list of methodologies and tools for the assessment of synergies and trade-offs in a given category, based on the cases identified through the literature review-where available]</td></tr>
<tr><td colspan="3">[Methodology/tool]: [Description]</td><td>[see page XX]</td></tr>
<tr><td colspan="3">[Methodology/tool]: [Description]</td><td>[see page XX]</td></tr>
</table>

## Sector icons:

Crop production | Livestock production | Fisheries & aquaculture | Forestry | Integrated systems | Renewable energy

**Table 3**: Matrix defining the categories of relationships between objectives within and across CSA pillars

For each of the 36 possible relationships, the number of cases identified in the reviewed literature is indicated, as well as the page number where the respective characterization sheet can be found. Each case can represent a synergy, a trade-off, or both, or even a neutral relationship. The percentages and colour shading in each matrix cell indicate the ratio between identified synergies (green), trade-offs (yellow) and neutral relationships (grey) for each category.

| | **CSA OBJECTIVES** | **CSA Pillar 1**<br>1.A Productivity | **CSA Pillar 1**<br>1.B Incomes | **CSA Pillar 1**<br>1.C Soc./Env. sustainability | **CSA Pillar 2**<br>2.A Livelihood resilience | **CSA Pillar 2**<br>2.B Production system adaptation | **CSA Pillar 2**<br>2.C Agro-ecosystem resilience | **CSA Pillar 3**<br>3.A Carbon stocks | **CSA Pillar 3**<br>3.B Emissions | **CSA Pillar 3**<br>3.C Renewables |
|---|---|---|---|---|---|---|---|---|---|---|
| CSA Pillar 1 | **1.A** Productivity | | | | | | | | | |
| CSA Pillar 1 | **1.B** Incomes | # cases: 4<br>See page: 57<br>100% | | | | | | | | |
| CSA Pillar 1 | **1.C** Soc./Env. sustainability | # cases: 6<br>See page: 59<br>40% 60% | # cases: 3<br>See page: 61<br>50% 50% | | | | | | | |
| CSA Pillar 2 | **2.A** Livelihood resilience | # cases: 1<br>See page: 28<br>100% | # cases: 1<br>See page: 32<br>100% | # cases: 2<br>See page: 37<br>75% 25% | | | | | | |
| CSA Pillar 2 | **2.B** Production system adaptation | # cases: 3<br>See page: 29<br>100% | # cases: 5<br>See page: 33<br>70% 30% | # cases: 2<br>See page: 38<br>100% | | | | | | |
| CSA Pillar 2 | **2.C** Agro-ecosystem resilience | # cases: 5<br>See page: 30<br>100% | # cases: 3<br>See page: 35<br>70% 30% | # cases: 1<br>See page: 40<br>50% 50% | | | | | | |
| CSA Pillar 3 | **3.A** Carbon stocks | # cases: 1<br>See page: 41<br>100% | # cases: 1<br>See page: 44<br>50% 50% | # cases: 4<br>See page: 47<br>50% 50% | | # cases: 2<br>See page: 52<br>50% 50% | # cases: 2<br>See page: 56<br>50% 50% | | | |
| CSA Pillar 3 | **3.B** Emissions | # cases: 11<br>See page: 42<br>70% 30% | # cases: 5<br>See page: 45<br>80% 20% | # cases: 3<br>See page: 49<br>30% 70% | # cases: 1<br>See page: 51<br>50% 50% | # cases: 3<br>See page: 53<br>70% 30% | | # cases: 1<br>See page: 63<br>100% | | |
| CSA Pillar 3 | **3.C** Renewables | | | | | # cases: 1<br>See page: 55<br>100% | | # cases: 1<br>See page: 64<br>100% | # cases: 1<br>See page: 65<br>100% | |

# 2.2 CSA synergy and trade-off screening

The categorization process, together with the characterization sheets – as described in the previous section – aim to inform decisions in the design of CSA strategies, programmes and projects by supporting planners in considering a broad range of potential synergies and trade-offs. A simple screening procedure is proposed, which uses the main objective of a given CSA intervention as an entry point into the matrix of CSA synergy and trade-off categories. The procedure consists of the following steps.

**STEP 1**: Identify main/prioritized objective of CSA intervention as an entry point to the matrix (see Figure 3).

**STEP 2**: Identify categories of potential synergies and trade-offs (see Figure 1) and – if necessary, e.g. due to limited resources – prioritization of categories to be assessed based on other CSA objectives that are either identified as objectives of the same CSA intervention, or prioritized by national/local development strategies.

**STEP 3**: Consult characterization sheet for each identified/prioritized category to identify appropriate indicators and methodologies/tools.

**STEP 4**: Perform assessment of synergies/trade-offs, using the indicators and methodologies/tools identified in STEP 3.

**STEP 5**: Compare indicator results across all selected CSA objectives/categories and for all evaluated alternative intervention options. Results can be visualized using methods such as sustainability polygons (see Section A3.2.2). Sustainability polygons can also be used for quantitative comparisons of baseline and alternative intervention options. It should be noted that such comparisons require weights to be assigned for each indicator, which should be determined through stakeholder consultation and in line with national and local development priorities.

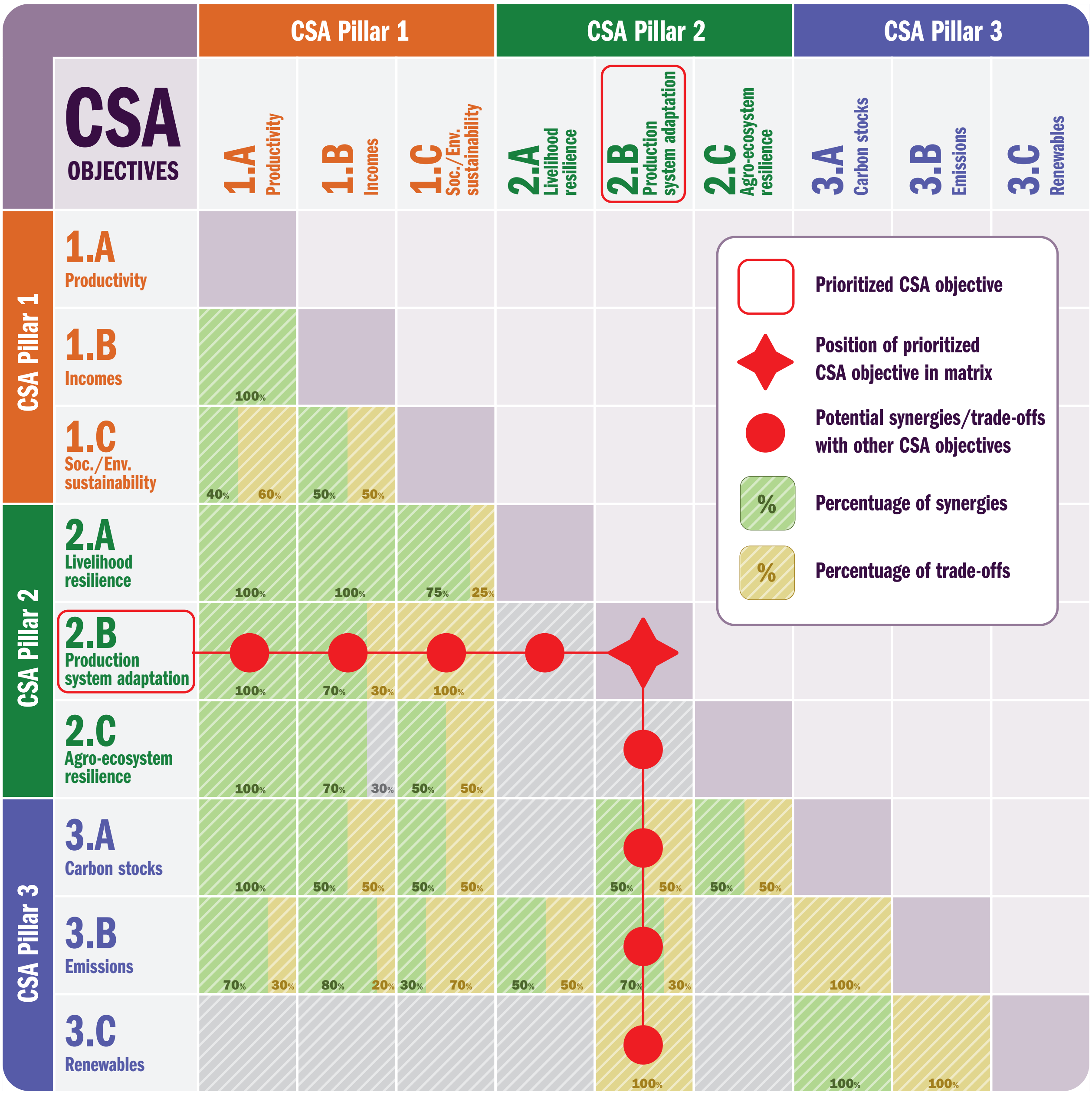


**Figure 1:** Diagram for the screening of CSA initiatives for potential synergies and trade-offs based on the matrix of categories of synergies and trade-offs

# 3

# Methodologies and tools

The literature review revealed a wide variety of methodologies and tools that can be applied in the assessment of synergies and trade-offs between CSA objectives. These methodologies and tools can be classified according to the point in time at which they are used – before or after a change in practices has been introduced.

*Ex-ante* assessments are conducted before a change in practices has been introduced. These assessments are used to gauge the comparative impacts of several possible changes on a given set of CSA objectives. The comparison is usually articulated around a business-as-usual scenario and one or more alternative scenarios. Generally, baseline surveys are used to characterise the 'initial conditions' for a set of CSA indicators of interest.[9] Most often, the assessment relies on dynamic or empirical models. Key model assumptions may refer to the behaviour of main actors in food systems, likely future climate conditions, and the probable development of food markets.

*Ex-post* evaluations are conducted after a change in practices has been introduced. These analyses increase our understanding as to the potential that certain practices, technologies and other measures to advance CSA objectives may have, and the extent to which their use creates synergies between them. *Ex-post* evaluations usually compare adopters of a specific technology or practice with non-adopters, drawing on data from field measurements, household surveys and/or earth observation. Statistical methods are applied to analyse the effects of practice/technology adoption on CSA objectives, determine the significance of these effects, and establish empirical relationships between practice changes and their effects. These relationships also provide the basis for empirical models which, in turn, can be applied in *ex-ante* assessments, or in the estimation of indicators that are complex and/or costly to measure in practice, such as GHG emissions. While *ex-post* evaluation methodologies cannot be applied in the design phase of CSA interventions – due to the absence of observable cases of implementation – they can form part of the monitoring and evaluation of ongoing interventions and enable an adaptive process with incremental improvements.

## Box 2: Participatory methods for ex-ante assessments

An alternative approach to *ex-ante* assessments involves using participatory methods, for example as part of rapid appraisal approaches such as the *Climate-Smart Agriculture Prioritization Framework (CSA-PF)* (Andrieu *et al.*, 2017). The assessment of synergies and trade-offs in the CSA-PF largely relies on the judgement of experts and local stakeholders about the expected effects of adopting new practices, technologies and services on productivity, adaptation and mitigation. Participants rate the effect of each CSA option being considered on the three CSA pillars, using a scale from -10 to 10. By comparing the average scores of any given CSA option across the pillars, the existence of synergies and trade-offs is determined. However, these methods do not provide quantitative data for pairwise comparisons of indicators – the rationale of the present approach – and are therefore not further discussed in this publication.

The methodologies and tools presented in this section focus on *ex-ante* assessments, since these are the ones needed to identify synergies and trade-offs in the early stages of CSA planning processes. Table 4 shows a selection of methodologies and tools that were used for *ex-ante* assessments of CSA synergies and trade-offs in the reviewed literature. It should be noted that this is not an exhaustive list. It is limited to examples from the reviewed literature, and many more relevant methodologies and tools could certainly be identified in scientific literature that is not labelled 'climate-smart', as well as in grey literature – for the types of assessment identified here, as well as for other types. The methodologies and tools identified in Table 4 fall into five different categories: cost-benefit analysis, trade-off analysis, nexus approaches, GHG emissions, natural resources and ecosystem services. A brief description of each methodology or tool is provided in Annex 3, including purpose and scope of application, data requirements, common issues or limitations, and references to literature where it is applied. Pointers to these descriptions are also included in the characterization sheets throughout Annex 1 in the context of examples of application.

[9] The baseline survey also includes other parameters that are needed to estimate the effects of the different scenarios on the selected CSA indicators.

**Table 4**: Methodologies and tools for ex-ante assessment identified in reviewed literature

| Category | Methodology/tool | CSA synergy/trade-off* | Description** |
|---|---|---|---|
| Cost-benefit analysis | Cost-benefit analysis | 1.B vs. 1.C | A3.1.1 |
| | Implementation cost approach (for leakage-free REDD+ projects) | 1.B vs. 3.A | A3.1.2 |
| Trade-off analysis | Trade-off Analysis Model for Multi-Dimensional Impact Assessment (TOA-MD) | 1.A vs. 3.B | A3.2.1 |
| | Sustainability polygons | 1.A vs. 2.B<br>1.B vs. 2.B<br>1.C vs. 2.B<br>2.B vs. 3.B | A3.2.2 |
| Nexus approaches | Nexus Webs | 1.C vs. 2.B<br>2.B vs. 3.C | A3.3.1 |
| Scenario analysis | Agricultural Production Systems sIMulation (APSIM) | 1.A vs. 2.B<br>1.B vs. 2.B<br>1.C vs. 2.B<br>2.B vs. 3.C | A3.4.1 |
| | Integrated Farm System Model (IFSM) | 1.A vs. 2.A<br>1.B vs. 2.A<br>1.C vs. 2.A<br>1.B vs. 3.B<br>1.C vs. 3.B<br>2.A vs. 3.B<br>1.A vs. 1.B<br>1.A vs. 1.C<br>1.B vs. 1.C | A3.4.2 |
| | International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) | 1.A vs. 3.B | A3.4.3 |
| GHG emissions | Cool Farm Tool | 1.A vs. 3.B<br>1.B vs. 3.B | A3.5.1 |
| | RUMINANT model | 1.A vs. 3.B<br>1.B vs. 3.B<br>1.C vs. 3.B<br>1.B vs. 1.C | A3.5.2 |
| Natural resources and ecosystem services | Thornthwaite-Mater water balance modeling approach. | 1.C vs. 3.A<br>2.B vs. 3.A<br>2.C vs. 3.A | A3.6.1 |

* The alphanumeric codes represent the pairwise comparison of CSA objectives as defined in Table 3.

** Indicates the corresponding section in Annex 2 which provides the brief description of the methodology/tool.

# 4

# Discussion and conclusion

The characterization of synergies and trade-offs in climate-smart agriculture presented in this document is an attempt to map the potential synergies and trade-offs that can occur between and within the three pillars of CSA in digestible units. It thereby aims to enable a structured approach to the identification of potential synergies and trade-offs in the design of CSA interventions. The categorization of cases of synergies and trade-offs reported in the reviewed literature by relationships among a set of CSA objectives – 36 categories overall – illustrates the breadth and complexity of the issue.

## LITERATURE REVIEW

In total, 92 studies were reviewed, out of which 37 provided cases in at least one of the 36 categories. A total of 73 cases were identified, distributed over 26 out of the 36 possible relationship categories. The distribution by CSA pillar is shown in Table 5 and, in more detail, in Table 3 (page 9). The distribution shows a clear bias towards relationships that involve CSA Pillar 1, which is attributed to the fact that most studies include data on productivity and/or income. A general limitation in identifying cases was that literature, in particular review articles, often compares indicators across studies from different locations and contexts. Such comparison can indicate possible synergies or trade-offs, but does not actually prove them. Therefore, many review articles were excluded as sources of cases.

**Table 5**: Distribution of cases by CSA pillar

| | CSA Pillar 1 | CSA Pillar 2 | CSA Pillar 3 |
|---|---|---|---|
| CSA Pillar 1 | 13 | | |
| CSA Pillar 2 | 23 | 0 | |
| CSA Pillar 3 | 25 | 9 | 3 |

Despite the extensive literature review, the characterization sheets can only provide an anecdotal reflection of the breadth of possible synergies and trade-offs in the different agricultural subsectors and across different scales. As mentioned in Section 2.1, the focus of literature research on 'climate-smart' agriculture identified mostly studies in the crop and livestock sectors, few studies on forestry and integrated farming systems, and none in the fisheries and aquaculture sectors. A better representation of the latter sectors would require a wider ranging literature research and possibly an expansion into grey literature, such as institutional reports.

## SYNERGIES AND TRADE-OFFS

Many categories present both synergies and trade-offs even within an agriculture subsector. This corroborates the notion that the realization of CSA objectives and synergies between them is strongly context-specific. It also implies that findings on synergies and trade-offs should not be transferred between geographical areas, or agro-ecological and socio-economic contexts, without contextualized testing or assessment.

The relationships between CSA Pillar 1 and CSA Pillar 2 generally show strong potential for synergies of different adaptation strategies – such as diversification, microinsurance or integrated production systems – with productivity, incomes and food security. CSA strategies or practices that rely on intensification principles may involve potential trade-offs with long-term resilience of the production system when they rely on high-performing crop varieties or animal breeds that are more susceptible to environmental stress and change. Such strategies and practices also often show an increase in the environmental cost of production,[10] while agro-ecosystem-based adaptation strategies tend to provide environmental benefits. Technical adaptation options, such as irrigation, may involve important trade-offs at the landscape scale, affecting natural systems, as well as livelihood opportunities and adaptation options for downstream populations.

In the relationships between CSA Pillar 1 and CSA Pillar 3, a recurring phenomenon is the reported synergy between productivity or income and reduction in GHG emission intensities which, however, is often associated with an increase in absolute GHG emissions and/or an increase in environmental costs. It is frequently argued that this potential trade-off should be offset by land-sparing strategies. However, these are challenging to implement in practice, and depend on factors such as the consistent implementation of conservation policies, strict and comprehensive GHG accounting, and changes in dietary preferences and food demand, which often lie beyond the scope of CSA interventions. Assessments of the relationship between productivity/profitability and GHG emissions, such as in the context of (sustainable) intensification strategies, should be combined with analyses of the indirect effects on land use and the environment and target the identification of possible measures to reduce these trade-offs and limit negative impacts. The protection and restoration of forest land in order to conserve and increase carbon stocks often involves trade-offs for the current land users. Compensations for forgone benefits from land use, for example those funded through carbon credits, are often insufficient or inequitably distributed. Compensation schemes therefore need to be based on assessments of the livelihood strategies and societal structures among the affected populations. They could also involve capacity-building for improved agricultural practices, which can lead to increased production and incomes from unrestricted land. Such interventions require equitable access for all affected food producers to the remaining land resources. Furthermore, it is imperative that the proposed production intensification does not offset the climate change mitigation benefits from forest conservation and restoration.

The relationships between CSA Pillar 2 and CSA Pillar 3 highlight the potential trade-offs between technical adaptation options that rely on the use of additional natural resources, such as irrigation, with both increasing carbon stocks, such as through re/afforestation, and increasing renewable energy production, for example hydroelectric power. On the other hand, agro-ecosystem-based adaptation strategies show potential synergies with increasing carbon stocks in the agro-ecosystem. Possible synergies and trade-offs with GHG emissions reduction were found for both technical adaptation strategies and livelihood resilience strategies, such as diversification of the production system.

The identified cases of relationships within CSA Pillar 1 showed frequent synergies between productivity, incomes and food security, as well as high risk for environmental trade-offs related to agricultural intensification strategies. No cases were identified for relationships within CSA Pillar 2. The few cases of relationships identified within CSA Pillar 3 indicate potential trade-offs between the reduction of GHG emissions from biomass production and the maximization of bioenergy feedstock yields. Reductions in GHG emissions from crop systems, including through reductions in external inputs and their associated GHG footprint, may in some cases also be associated with a decline in soil organic carbon. At a global scale, synergies between increasing the share of bioenergy in energy supply and increasing carbon stocks seem possible, at least under a long-term sustainable development pathway.

## INDICATORS

The collected cases of synergies and trade-offs in climate-smart agriculture expose a multitude of indicators that can be used to assess and describe these relationships. In CSA Pillar 1, indicators of productivity (Objective 1.A) mostly focus on yields and partial factor productivity, and for income (Objective 1.B), net revenue is the most common indicator, besides a few measures of profitability. In contrast, Objective 1.C shows a broad range of indicators across various aspects of social and environmental sustainability. Across the three objectives of CSA

[10] At least at farm level. Increased environmental cost may be compensated at landscape level if a comprehensive sustainable intensification plan ensures conservation and regeneration of substantive areas of natural habitats within the landscape.

Pillar 2 (2.A, 2.B, 2.C), yield stability and income stability turned out to be the most common indicators. Several indicators that quantify the resilience of agro-ecosystems could only be determined following extreme climate events and are therefore of limited value for *ex-ante* assessments of resilience. In CSA Pillar 3, indicators for GHG emissions (Objective 3.B) were mostly expressed as emissions of specific GHGs or the global warming potential – in carbon dioxide equivalent – per unit of product or unit area. These metrics sometimes included emissions from carbon stock changes and hence present an overlap with Objective 3.A. Besides carbon stock changes per unit area, carbon storage in soils and biomass (Objective 3.A) was also expressed through proxies, such as area of forest conserved or area re/afforested. Renewable energy production (Objective 3.C) was either quantified in units of energy produced, or yields of biomass for bioenergy production.

## METHODOLOGIES AND TOOLS

The selection of methodologies and tools presented in Section 3 and Annex 2 illustrates the variety of approaches that can be adopted to assess synergies and trade-offs in CSA at different scales, either focusing on a specific aspect or seeking to draw a comprehensive picture of effects on a multitude of indicators. Methods with a narrow technical focus are essential to quantify indicators such as GHG emissions. Several examples of negative externalities associated with synergies between two given objectives highlight the need to embed these specialized methods in more holistic assessment methods, such as sustainability polygons. These enable integrated assessments across all CSA pillars and additional aspects of social and environmental sustainability as relevant in a given context. The example of a cost-benefit analysis (CBA) that attempts to quantify and include environmental (and social) costs illustrates the related challenges (Sain *et al*., 2017). The selection of non-economic aspects (social/environmental costs and benefits) often depends on data availability and specific stakeholder interests. Also, the way that these aspects are quantified (price per unit) is subject to many assumptions, and is again often limited by availability of data. There is hence a wide range of possible results for CBAs that consider social and environmental factors. This should be taken into account in the design of CBA – and climate-smart agriculture assessment methods more generally – and when interpreting its results. Sensitivity analysis of changes in parameter values can facilitate the interpretation. Qualitative data on social and environmental aspects that are not considered in a given assessment should be made available to allow for better-informed decision-making processes based on quantitative results.

## CONCLUSION

This publication provides an overview of possible synergies and trade-offs within and between the three pillars of climate-smart agriculture. It can also support a structured thinking process for the design of CSA interventions in terms of flagging possible risks and opportunities and identifying tools to further investigate and quantify these – following the proposed screening procedure (see Section 2.2). Noting that the compilation of synergies and trade-offs, indicators and methods is not exhaustive, the approach presented provides a flexible framework that can be expanded with additional information.

While the publication does not provide a stand-alone methodology for an all-inclusive assessment of synergies and trade-offs in climate-smart agriculture, it may represent a further step towards the development of a standardized framework for such assessments, and serve as a reference to determine basic requirements and principles for such a framework.

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# Annex 1

## Characterization sheets of relationships between CSA objectives

# A1.1 Synergies and trade-offs between CSA Pillar 1 'Productivity' and CSA Pillar 2 'Adaptation'

## Productivity vs. Livelihood resilience

| Objective 1.A | Increasing agricultural productivity | Improving climate risk mitigation strategies for food producers' livelihoods | Objective 2.A |
|---|---|---|---|

The diversification of food production systems, for example from livestock to integrated crop-livestock production, holds potential for synergies between productivity and livelihood resilience. Farm simulation models provide a tool to assess which farm configurations are likely to realize this synergy across a range of different socio-economic and climatic scenarios. Such models can also provide estimates of environmental impact indicators, including GHG emissions, enabling the assessment of all three pillars of CSA, as well as environmental sustainability more broadly (see example below).

### Indicators & *metrics*

**Productivity**: e.g. expressed as amount of human-digestible protein (HDP) and food energy content produced per unit area.

- *Kilograms of HDP per hectare [kg HDP/ha]*
- *Megacalories of food energy per hectare [Mcal/ha]*

**Income stability**: expressed as farm income, i.e. net revenues from sale of agricultural produce, of alternative farm systems under different climate change scenarios.

- *Net revenue per hectare [USD/ha]*

### Examples

A farm simulation of medium and large beef cattle farms in the state of Mato Grosso, Brazil, shows higher productivity for integrated crop-livestock systems (soybean-beef cattle), compared with pure livestock systems (extensive or rotational grazing). The integrated system also shows the greatest economic resilience under both optimistic and pessimistic climate change scenarios up to the year 2050, corresponding to representative concentration pathway (RCP) 2.6 and RCP 8.5, respectively. This illustrates the potential of on-farm diversification to improve both productivity and climate resilience of a production system – in this specific case enabled by higher livestock stocking rates in the integrated system and lower sensitivity to fluctuations in market prices of beef and soybean. However, while the integrated system is also more profitable and has lower environmental impacts and GHG emissions per unit of human-digestible protein (HDP), the absolute emissions and environmental impacts of the system (per hectare) are greater. So there is a trade-off which depends on the development of land use, food production and related GHG emissions in the wider landscape context. Specific measures to reduce the environmental impact of the integrated system may contribute to reducing the trade-offs (Gil *et al.*, 2018).

Methodologies/tools applied (refer to list at bottom of this sheet): 1

### Methodologies & Tools

1. **Integrated Farm System Model (IFSM)**: Whole-farm simulation model to assess productivity, profitability and environmental impacts of different farm configurations. [see page 79]

# Productivity vs. Production system adaptation

| Objective 1.A | Increasing agricultural productivity | Adapting food production systems to current and expected future climate change | Objective 2.B |
|---|---|---|---|

Global long-term simulations of climate change impacts on crop yields and the effects of adaptation suggest that targeted adaptation measures can mitigate or even reverse the negative impacts on crop yields (Challinor *et al*., 2014). Localized simulations and field experiments on cropping system adaptation confirm this potential for synergies between productivity increases and stability of crop yields across variable climate conditions (see examples below).

## Indicators & *metrics*

**Yield:** crop yield per unit area:

- *Tonnes per hectare [t/ha]*

**Irrigation water productivity**: expressed as gross margin/net revenue per unit of irrigation water, e.g.:

- *Net revenue in Indian rupees (INR) per millilitre of irrigation water [INR/ml]*

**Yield stability:** expressed as coefficient of variation (CV), i.e. standard deviation divided by the mean, of a time series of observed or simulated crop yields. It can be expressed as a ratio or percentage, with low values indicating high stability.

- *CV of crop yields over a given period of time [%]*

## Examples

A scenario analysis, using a crop simulation model, was conducted to test the sustainability and climate-smartness of adaptation strategies for cotton and maize production in smallholder paddy rice-cotton and paddy rice-maize systems in south India under historic climate and moderate climate scenarios (2021–2040; representative concentration pathway (RCP) 6). Adaptation options included new criteria to determine the sowing date and adoption of supplemental irrigation for maize/cotton combined with reducing paddy rice area to source water for supplemental irrigation. Year-to-year climate variability was greater than variability between scenarios. Adaptation options were assessed and compared with current practice using the following set of indicators: yield, yield stability, gross margin, stability of gross margin, global warming potential and GHG emission intensity (as CSA indicators); as well as water use, water productivity, ground water recharge and nitrogen leaching (as sustainability indicators). While supplemental irrigation presented some trade-offs related to groundwater recharge and nitrogen leaching, most combinations of adaptation options improved the CSA indicators and showed greater overall sustainability compared with current practice – determined through sustainability polygons. The performance of adaptation options was influenced by agro-ecological conditions in the three assessed locations, as well as by farm size. The study enabled the identification of location- and farm-specific adaptation options that increase climate resilience – in terms of yield and gross margin stability – and also overall productivity of the cropping system (Hochman *et al*., 2017).

Methodologies/tools applied (refer to list at bottom of this sheet): 1, 2

On-farm experiments across southern and East Africa (Kenya, Mozambique, Tanzania) showed that the strategic application of small amounts of fertilizer increased the productivity, profitability and yield stability of maize-pigeon pea intercropping, compared with unfertilized systems. Intercropping also had a positive effect on nutrient-use efficiency, compared with fertilized sole maize crops. The effect on GHG emissions was not assessed (Kiwia *et al*., 2019).

## Methodologies & Tools

1. **Agricultural Production Systems sIMulator (APSIM):** Crop simulation model. [see page 79]
2. **Sustainability polygons:** Visualization and comparison of multiple indicators across alternative options. [see page 77]

# Productivity vs. Agro-ecosystem resilience

| Objective 1.A | Increasing agricultural productivity | Increasing the resilience of agro-ecosystems | Objective 2.C |
|---|---|---|---|

The integration of agro-ecological principles in food production systems holds strong potential for synergies between increased productivity and greater resilience to extreme climate events. In the example of Cuban smallholder farms, the multilayer design of these systems was found to be an important factor that enhances resilience. While strong winds during a hurricane damaged trees and high plants such as bananas, crops in the lowest vegetative layer remained largely unaffected (Rosset *et al.*, 2011).

## Indicators & *metrics*

**Land productivity/crop yield, e.g.:**

- *Total revenues from agricultural produce per hectare of cultivated land [USD/ha]*
- *Tonnes of wheat grain per hectare [t/ha]*

**Labour productivity, e.g.:**

- *Total revenues from agricultural produce per farm worker [USD/worker]*

**Initial damage/yield penalty** (after extreme event), e.g.:

- *Percentage of production value lost [%]*
- *Yield reduction compared with normal year [%]*

**Recovery of productive potential** (60/120/180 days after extreme event):

- *Percentage of productive potential [%]*

**Stability index**, expressed as the ratio of mean value of a series of yield measurements (over a range of environmental variation in space and/or time) over the standard deviation of yields (inverse of the coefficient of variation).

## Examples

The adoption of conservation agriculture (CA)-based wheat production in wheat-rice systems in northern India led to higher average yields and also reduced yield penalty in the case of extreme climate events (in this case, untimely excessive rainfall), compared with conventional tillage-based systems (Aryal *et al.*, 2016).

Experiments of biomass productivity of intensively managed rainfed grassland systems in Ireland and Switzerland have found consistently higher yields in four-species grassland plots, compared with single- or two-species grassland, under both normal and (simulated) drought conditions. Four-species grassland plots also showed greater yield stability across varying climatic conditions, demonstrating that higher species diversity in grassland agro-ecosystems can increase both productivity and drought resilience (Haughey *et al.*, 2018; Hofer *et al.*, 2016).

Smallholder farms in Cuba with a higher degree of agro-ecological integration showed greater land and labour productivity and were also less affected by Hurricane Ike (2008) and recovered their productive potential more quickly (Rosset *et al.*, 2011). The study was conducted among farms of a cooperative with initial, medium or high agro-ecological integration, according to a classification scheme based on a range of criteria, including farmers' attitude, knowledge of agro-ecological concepts, farm diversification, dependence on external inputs, productivity, income and social well-being, integration in local markets, and gender equality

## Sustainability

The adoption of CA at scale – especially on large farms which contribute the main share of marketable surplus production – could not only increase farm resilience to climate extremes, but could also play a critical role in improving food security at regional scale.

## Enabling environment

In the case of smallholder farms in Cuba, the success of the large-scale adoption of agro-ecological practices – besides the limited access to agrochemicals – is attributed to the strong networks among farmers and farmer-to-farmer extension.

| | |
|---|---|
| The existence of compensation schemes for farmers affected by extreme climate events, for example, in some states of India, causes a heavy financial burden for the state government in the event of large-scale climate-related damage to crops. Therefore, large-scale adoption of climate-resilient and climate-adapted cropping systems would have a positive economic effect on public budgets at state or national level. | In the case of CA in northern India, slow adoption of the practice is observed. It is argued that improved availability of direct seeding technology and farmers' confidence in using it would be key enabling factors for adoption. Demonstrations, training and direct exchange between farmers and researchers are needed to increase farmers' knowledge and confidence in new technologies. Local farmers' clubs can play a key role in initiating such programmes. |

# Income vs. Livelihood resilience

| Objective 1.B | Increasing food producers' incomes | Improving climate risk mitigation strategies for food producers' livelihoods | Objective 2.A |
|---|---|---|---|

The diversification of food production systems, for example from livestock to integrated crop-livestock production, holds potential for synergies between incomes and livelihood resilience. Farm simulation models provide a tool to assess which farm configurations are likely to realize this synergy across a range of different socio-economic and climatic scenarios. Such models can also provide estimates of environmental impact indicators, including GHG emissions, enabling the assessment of all three pillars of CSA, as well as environmental sustainability more broadly (see example below).

## Indicators & *metrics*

**Farm income:** expressed as net revenue, e.g.:

- *Net revenue per hectare [USD/ha]*

**Income stability:** expressed as farm income, i.e. net revenues from sale of agricultural produce, of alternative farm systems under different climate change scenarios.

- *Net revenue per hectare [USD/ha]*

## Examples

A farm simulation of medium and large beef cattle farms in the state of Mato Grosso, Brazil, shows higher incomes for integrated crop-livestock systems (soybean-beef cattle), compared with pure livestock systems (extensive or rotational grazing) or pure soybean cropping systems. The integrated system also shows the greatest economic resilience under both optimistic and pessimistic climate change scenarios up to the year 2050, corresponding to representative concentration pathway (RCP) 2.6 and RCP 8.5, respectively. This shows the potential of on-farm diversification to improve both incomes and climate resilience of a production system – in this specific case enabled by higher livestock stocking rates in the integrated system and lower sensitivity to fluctuations in market prices of beef and soybean. While the integrated system is also more productive than pure livestock systems – in terms of human-digestible proteins per hectare – it also presents higher environmental costs per hectare in terms of energy use, water use and nitrogen losses. If calculated per HDP, the environmental burden is similar between all livestock systems, but increases considerably for pure livestock systems under extreme climate change (RCP 8.5). GHG emissions per HDP are lower for the integrated system in all climate scenarios, but still one order of magnitude greater compared with the pure soybean cropping system, while emissions per hectare in the integrated system – which is also the most intensive – are highest in all climate scenarios (Gil *et al.*, 2018).

Methodologies/tools applied (refer to list at bottom of this sheet): 1

## Methodologies & Tools

1. **Integrated Farm System Model (IFSM):** Whole-farm simulation model to assess productivity, profitability and environmental impacts of different farm configurations. [see page 79]

## Income vs. Production system adaptation

| Objective 1.B | Increasing food producers' incomes | Adapting food production systems to current and expected future climate change | Objective 2.B |
|---|---|---|---|

Both synergies and trade-offs can be observed between the objectives of increased farmer incomes and production system adaptation. Some strategies aim to increase incomes through production intensification or adoption of a cash crop. Although this may raise incomes under current normal conditions, these strategies may turn out to rely, for example, on more productive cattle breeds, which are also more sensitive to climate stress and hence lead to reduced income and production stability in the long term (see examples below; Paul *et al*., 2018; Tuong *et al*., 2018). It is therefore important to assess the profitability of new technologies and practices under current, as well as expected future climatic conditions (see example below; Hochman *et al*., 2017).

### Indicators & *metrics*

**Gross margin/net income:** expressed as net revenue, i.e. income from sale of produce minus production costs, e.g.:

- *Net revenue in Indian rupees (INR) per hectare [INR/ha]*
- *Net income per farm [USD/farm]*

**Returns on family labour:** expressed as net income per unit of family labour, e.g.:

- *Net revenue per person-day [USD/person-day]*

**Benefit-cost ratio:** i.e. the ratio of gross income and total production cost.

**Marginal rate of return:** expressed as the ratio of differences in marginal net returns and marginal costs between two alternative systems.

**Net present value**

**Yield stability:** expressed as coefficient of variation (CV), i.e. standard deviation divided by the mean, of a time series of observed or simulated crop yields. It can be expressed as a ratio or percentage, with low values indicating high stability.

- *CV of crop yields over a given period of time [%]*

**Income stability:** expressed as percent deviation from yields in a normal year.

**Annual farm nitrogen balance:** net balance of nitrogen imports and exports (cf. Paul *et al*., 2019).

- *Nitrogen (N) balance per farm [kg N/farm]*

### Examples

T

Scenario analysis of smallholder farm systems in the mountainous region of northern Viet Nam has evaluated the adoption of tea as a climate-smart option in conventional mixed maize-rice-livestock enterprises. While the inclusion of tea increased overall farm income and profitability across a range of climatic conditions, it showed reduced income stability in locations with high rainfall and/or temperature variability. It thus presents a trade-off between increasing household incomes – which may also contribute to the economic resilience of the farm system (CSA Objective 2.A) – and climate change adaptation of the production system in locations with potentially increasing climate variability. The analysis also found potential co-benefits of tea to enhance soil carbon sequestration (Tuong *et al*., 2018).

S

A scenario analysis, using a crop simulation model, was conducted to test the sustainability and climate-smartness of adaptation strategies for cotton and maize production in smallholder paddy rice-cotton and paddy rice-maize systems in south India under historic climate and moderate climate scenarios (2021–2040; RCP 6). Adaptation options included new criteria to determine the sowing date and adoption of supplemental irrigation for maize/cotton combined with reducing paddy rice area to source water for supplemental irrigation. Year-to-tear climate variability was greater than variability between scenarios. Adaptation options were assessed and compared with current practice using the following set of indicators: yield, yield stability, gross margin, stability of gross margin, global warming potential and GHG emission intensity (as CSA indicators); and water use, water productivity, groundwater recharge and nitrogen leaching (as sustainability indicators). While supplemental irrigation presented some trade-offs related to groundwater recharge and nitrogen leaching, most combinations of adaptation options improved the CSA indicators and showed reater overall sustainability compared with current practice – determined through sustainability polygons. The performance of adaptation options was influenced by agro-ecological conditions in the three locations assessed, as well as by farm size. The study enabled the identification of location- and farm-specific adaptation options that increase climate resilience (in terms of yield and gross margin stability) and also the income derived from crop production of the cropping system (Hochman *et al*., 2017).

Methodologies/tools applied (refer to list at bottom of this sheet): 1, 2

S T

A bio-economic simulation of smallholder mixed crop-livestock farms in northern Tanzania was performed to identify farm configurations with the least trade-offs. Choosing from a predefined set of possible farm adaptations (presumably improvements), the farm model was applied to four representative farm types optimizing the trade-offs between increasing income, increasing the nitrogen (N) balance and reducing GHG emissions at farm level. While N balance was used as an approximation of adaptive capacity – representing increased farm and soil resources and thus enhanced buffer capacity to shocks in the context of smallholder farms that do not use any mineral fertilizers – it should be noted that high farm N balances are actually an environmental concern in industrialized countries. The simulations identified possible triple-wins for three of the four farm types, with modifications differing by type. Common modifications across most types were reduction of livestock units, replacement of local livestock breeds with improved dairy cattle breeds, reduction of on-farm pasture, increase of on-farm feed production (Napier grass) and oilseed cake feeding, reduction of crop residue feeding and increased residue retention in fields. In each farm type, configurations were identified that increased farm income as well as N balance. Although this was interpreted to increase farm resilience to shocks (including climate shocks), it should be noted that the improved dairy breeds are more susceptible to heat stress and diseases, and hence increase the climate risk of the livestock farm component (Paul *et al*., 2019).

S

A household survey in Odisha, India, showed that beneficiaries of a rural livelihoods support programme who had adopted drought adaptation measures in their farm systems achieved higher net revenues and value of production. Adaptation measures included creation of field contour dams, use of drought-tolerant seeds, and diversification of the agricultural system (Patnaik, Das and Bahinipati, 2019).

S

On-farm experiments across southern and East Africa (Kenya, Mozambique and Tanzania) showed that the strategic application of small amounts of fertilizer increased the productivity, profitability and yield stability of maize-pigeon pea intercropping, compared with unfertilized systems. Intercropping also had a positive effect on nutrient-use efficiency, compared with fertilized sole maize crops. The effect on GHG emissions was not assessed (Kiwia *et al*., 2019).

## Sustainability

Despite the economic advantages and increased efficiency of sustainable livestock intensification, reducing herd sizes and replacing local with improved breeds may have negative implications. For example, large herd size may be an expression of social status. Improved cattle, being more expensive, may also be more difficult to sell at local markets, and they are not suitable as draught power for crop cultivation. Another frequent challenge is the lack of services and infrastructure to support rearing of improved breeds, including artificial insemination and cooling facilities. Livestock intensification also increases farm labour requirements and may be problematic where labour availability is limited, although labour productivity is likely to increase.

## Methodologies & Tools

1. **Agricultural Production Systems sIMulator (APSIM):** Crop simulation model. [see page 79]
2. **Sustainability polygons:** Visualization and comparison of multiple indicators across alternative options. [see page 77]

# Income vs. Agroecosystem resilience

| Objective 1.B | Increasing food producers' incomes | Increasing the resilience of agro-ecosystems | Objective 2.C |
|---|---|---|---|

The integration of agro-ecological principles in food production systems, including soil and land management practices, holds strong potential for synergies between increased incomes and greater resilience to extreme climate events. It seems, however, that these synergies – and advantages over conventional systems – cannot always be realized. This may, in part, depend on thresholds of severity of the extreme climate event at which agro-ecological systems also collapse. It may also depend on the original purpose of agro-ecological practices. For example, measures to enhance resilience to drought may be of limited effectiveness in mitigating the impacts of a hurricane. Lack of maintenance of physical structures, such as terraces, may also reduce their effectiveness over time.

## Indicators & *metrics*

**Impact of extreme climate events on farm income:** e.g. expressed as share of harvest lost or as net revenue (profit or loss) derived from crops, calculated based on pre-impact market prices of the extreme event (e.g. hurricane).

- *Net revenue per hectare [USD/ha]*
- *Share of harvest lost [%]*

**Additional crop value:** income advantage of an agro-ecological production system over a conventional system, derived from yield difference and market price.

- *Economic value (currency) per hectare [USD/ha]*

**Impact of extreme climate events on agro-ecosystem:** e.g. impact of a hurricane on soil resources on conventional farms vs. adopters of agro-ecological practices:

- *Depth of topsoil [cm]*
- *Depth to moist soil [cm]*
- *Vegetation cover [%]*
- *Area affected by rill erosion [m²/ha]*
- *Volume of gully erosion [m³/ha]*
- *Area affected by landslides [m²/ha]*

**Yield penalty following extreme climate events:** change in crop yield compared with normal year (baseline), e.g. caused by untimely excessive rainfall:

- *Yield reduction compared with normal year [%]*

## Examples

| | |
|---|---|
| S | Farms on hillsides in Nicaragua applying agro-ecological practices – in particular, sustainable land management (SLM) practices – on average showed reduced net economic losses and even high profits in some cases, as well as reduced impacts on soil resources (erosion) after being hit by an extreme rainfall event (Hurricane Mitch, 1998), compared with neighbouring conventional farms (Holt-Giménez, 2002). However, this synergy – and comparative advantage over conventional farms – seems to have a threshold defined by steepness of the slope and rainfall intensity, beyond which it vanished. This threshold also depends on the specific combination of SLM practices and the level of maintenance of physical structures such as terraces, contour bunds and contour ditches. |
| N | Among Mexican hillside coffee farms of varying degrees of vegetative complexity, those with greater complexity were less affected by landslides (frequency and severity) when hit by Hurricane Stan in 2005. However, no significant effect on reducing economic losses at farm scale could be detected (Philpott *et al.*, 2008). |
| S | The adoption of conservation agriculture-based wheat production in wheat-rice systems in northern India led to higher average incomes and also reduced the yield penalty in the event of an extreme climate event – in this case, untimely excessive rainfall – compared with conventional tillage-based systems (Aryal *et al.*, 2016). |

| Sustainability | Enabling environment |
|---|---|
| The adoption of CA at scale – especially on large farms which contribute the main share of marketable surplus production – could not only increase farm resilience to climate extremes, but could also play a critical role in improving food security at regional scale.<br><br>The existence of compensation schemes for farmers affected by extreme climate events, for example, in some states of India, causes a heavy financial burden for the state government in the event of large-scale climate-related damage to crops. Therefore, large-scale adoption of climate-resilient and climate-adapted cropping systems would have a positive economic effect on public budgets at state or national level. | In the case of CA in northern India, slow adoption of the practice is observed. It is argued that improved availability of direct seeding technology and farmers' confidence in using it would be key enabling factors for adoption. Demonstrations, training and direct exchange between farmers and researchers are needed to increase farmers' knowledge and confidence in new technologies. Local farmers' clubs can play a key role in initiating such programmes. |

# Social/environmental sustainability vs. Livelihood resilience

| Objective 1.C | Social and environmental sustainability | Improving climate risk mitigation strategies for food producers' livelihoods | Objective 2.A |
|---|---|---|---|

For adaptation strategies that are based on production intensification, a potential risk observed is that with increasing economic resilience, the environmental burden will also grow (see example below; Gil *et al*., 2018).

Financial risk mitigation strategies, such as index-based microinsurance, hold potential for synergies between food security and economic resilience, as they can reduce negative coping strategies related to both food consumption and productive assets (see example below; Janzen and Carter, 2019).

## Indicators & *metrics*

**Loss of reactive nitrogen:** unit area or per unit of product, e.g.:

- *Kilograms of nitrogen (N) per hectare [kg N/ha]*
- *Kilograms of nitrogen per human digestible-protein (HDP) [kg N/kg HDP]*

**Water use:** unit area or per unit of product, e.g.:

- *Tonnes of water per hectare [t/ha]*
- *Tonnes of water per human digestible-protein [t/kg HDP]*

**Energy use:** per unit area or per unit of product, e.g.:

- *Terajoule per hectare [TJ/ha]*
- *Terajoule per human-digestible protein [TJ/kg HDP]*

**Food security:** expressed as probability of reducing meals (following livelihood impacts)..

**Income stability:** expressed as farm income, i.e. net revenues from sale of agricultural produce, of alternative farm systems under different climate change scenarios.

- *Net revenue per hectare [USD/ha]*

**Probability of selling productive assets** (following livelihood impacts).

## Examples

S T

A farm simulation of medium and large beef cattle farms in the state of Mato Grosso, Brazil, shows greater economic resilience for integrated crop-livestock systems (soybean-beef cattle), compared with pure livestock systems (extensive or rotational grazing), under both optimistic and pessimistic climate change scenarios up to the year 2050, corresponding to representative concentration pathway (RCP) 2.6 and RCP 8.5, respectively. However, while this system has comparable environmental costs per unit of product, the absolute environmental costs per hectare are considerably higher. A similar pattern is observed for GHG emissions (Gil *et al*., 2018).

Methodologies/tools applied (refer to list at bottom of this sheet): 1

S

The evaluation of an index-based livestock insurance scheme among pastoralist households in northern Kenya showed that insurance holders are less likely to reduce their food consumption following drought impacts on their livelihoods, and are also less likely to sell productive assets, mostly livestock. The microinsurance scheme thereby presented a synergy between food security and the resilience to drought of pastoralists' livelihoods (Janzen and Carter, 2019).

## Enabling environment

For the development of index-based livestock insurance products in Kenya, Matsaert et al. (2011) have identified several enabling factors, including legislation that enables microfinance institutions becoming banks and allows phone cash-transfer services; effective regulation of the insurance sector through a dedicated institution; and integration with existing social protection and rural development programmes which can support wide adoption of insurance by providing pastoralists with information about/access to insurance as well as cash to purchase insurance premiums.

## Methodologies & Tools

1. **Integrated Farm System Model (IFSM):** Whole-farm simulation model to assess productivity, profitability and environmental impacts of different farm configurations. [see page 79]

# Social/environmental sustainability vs. Production system adaptation

| Objective 1.C | Social and environmental sustainability | Adapting food production systems to current and expected future climate change | Objective 2.B |
|---|---|---|---|

Uses of natural resources for adaptation purposes in food systems and for ensuring (or restoring) ecosystem services may compete with each other and hence present trade-offs. This is illustrated by the example of expanding water use for irrigation in the upper part of a semi-arid river basin in Tanzania, at the cost of ecosystem health and livelihoods dependent on intact riverine ecosystems in the lower basin (see below).

## Indicators & *metrics*

**Economic security:** expressed as average household income at the river basin scale.

- *Annual household income [USD/y]*

**Natural food, fuel and materials:** economic value of foods, fuels and materials collected from natural habitats at the river basin scale.

- *Economic value [USD]*

**Environmental security:** dimensionless score representing ecosystem services and river health at the river basin scale (see Colloff *et al.*, 2019).

**Water use:** expressed as cumulative irrigation depth over the cropping season.

- *Irrigation water depth in millimetres [mm]*

**Groundwater recharge:** expressed as cumulative amount of deep percolation over the cropping season.

- *Percolation water depth [mm]*

**Nitrate leaching:** expressed as amount of total nitrogen (N) leached beyond the root zone per hectare during the cropping season.

- *Kilograms of N leached per hectare [kg N/ha]*

**Irrigated area:** depending on water allocation for climate change adaption at the river basin scale.

- *Hectares of crop land under irrigation [ha]*

**Water available for irrigation:** depending on water allocation for climate change adaption at the river basin scale.

- *Cubic metres of water allocated to irrigation [m³]*

**Yield stability:** expressed as coefficient of variation (CV), i.e. standard deviation divided by the mean, of a time series of observed or simulated crop yields. It can be expressed as a ratio or percentage, with low values indicating high stability.

- *CV of crop yields over a given period of time [%]*

## Examples

The allocation of greater amounts of water for the expansion of irrigated crop production – as an adaptation measure – in Northern Tanzania's upper Pangani river basin leads to a reduction of the environmental flows in the lower river basin, impacting the riverine ecosystem and livelihood activities that depend on it, such as fishing and the collection of wild foods and reed materials for housing. While average household incomes in the upper basin increase, they decline in the lower basin. The water allocation in favour of agriculture also reduces the renewable energy potential from hydropower and carbon storage in natural vegetation (Colloff *et al.*, 2019).

Methodologies/tools applied (refer to list at bottom of this sheet): 1

A scenario analysis, using a crop simulation model, was conducted to test the sustainability and climate-smartness of adaptation strategies for cotton and maize production in smallholder paddy rice-cotton and paddy rice-maize systems in south India under historic climate and moderate climate scenarios (2021–2040; RCP 6). Adaptation options included new criteria to determine the sowing date and adoption of supplemental irrigation for maize/cotton combined with reducing paddy rice area to source water for supplemental irrigation. Year-to-tear climate variability was greater than variability between scenarios. Adaptation options were assessed and compared with current practice using the following set of indicators: yield, yield stability, gross margin, stability of gross margin, global warming potential and GHG emission intensity (as CSA indicators); and water use, water productivity, ground water recharge and nitrogen leaching (as sustainability indicators). While most combinations of adaptation options show improvements across all CSA indicators (including climate resilience), the adoption of supplemental irrigation involves trade-offs

| | |
|---|---|
| | related to water use, groundwater recharge and nitrogen leaching. In all adaptation scenarios, water use and nitrogen leaching increase, while groundwater recharge declines. Considering the value range and local context, this presents a seemingly acceptable trade-off for the majority of stakeholders. But it also shows the importance of multistakeholder participation and weighting of indicators based on local context in the evaluation of results (Hochman *et al*., 2017).<br>Methodologies/tools applied (refer to list at bottom of this sheet): 2, 3 |

## Enabling environment

In the case of water management at the river basin scale, the development of polycentric governance arrangements, including water user associations and multistakeholder platforms, is instrumental in achieving equitable water allocation that minimizes trade-offs.

## Methodologies & Tools

1. **Nexus Webs:** A knowledge framework designed to promote collaborative exploration of synergies and trade-offs and enable changes in decision contexts for water use. [see page 79]
2. **Agricultural Production Systems sIMulator (APSIM):** Crop simulation model. [see page 79]
3. **Sustainability polygons:** Visualization and comparison of multiple indicators across alternative options. [see page 77]

## Social/environmental sustainability vs. Agro-ecosystem resilience

| Objective 1.C | Social and environmental sustainability | Increasing the resilience of agro-ecosystems | Objective 2.C |
|---|---|---|---|

The diversification of agro-ecosystems to increase their resilience to climate risks offers clear synergies with enhancing biodiversity. This is illustrated in the example of cocoa agroforestry systems in Ghana, which improve the microclimate in the production system and, at the same time increase species richness of trees and birds (see below).

### Indicators & *metrics*

**Biodiversity:** relative difference in biodiversity indicators between agro-ecological practices and conventional practices, e.g.:

- *Relative difference in tree richness [%]*
- *Relative difference in bird richness [%]*

**Dry season maximum temperature:** relative difference between agro-ecological practices and conventional practices.

- *Relative difference in dry season maximum temperature [%]*

**Dry season soil moisture:** Relative difference between agro-ecological practices and conventional practices.

- *Relative difference in dry season soil moisture [%]*

### Examples


Moderate levels of shade-tree cover (30 percent) in cocoa agroforestry systems in Ghana were found to have a positive effect on biodiversity (tree and bird richness), as well as a heat mitigating effect, compared with full-sun monocultures. The effect on soil moisture, soil fertility and cocoa yields was neutral (slightly negative, but insignificant for yield). An increase in shade-tree cover (up to 80 percent) further enhanced biodiversity, as well as the microclimate, albeit at the cost of drastically reducing water availability and cocoa yield. The effect of shade-tree cover on soil fertility was neutral across the whole gradient (Blaser *et al*., 2018).

# A1.2 Synergies and trade-offs between CSA Pillar 1 ‘Productivity’ and CSA Pillar 3 ‘Mitigation’

## Productivity vs. Carbon stocks

| Objective 1.A | Increasing agricultural productivity | Increasing carbon stocks in soils and biomass | Objective 3.A |
|---|---|---|---|

Ambitious land-based climate change mitigation goals may result in competition for land between food production and reforestation and afforestation, presenting a potential trade-off between food productivity at landscape/regional level and carbon stocks. Production intensification on a steadily decreasing arable land area can help to reduce this trade-off. However, generating synergies between two objectives will require radical changes in dietary preferences (see example below).

### Indicators & *metrics*

**Daily dietary energy production:** food energy that can be provisioned by agriculture per capita and day for a given geographical region.

- *Kilocalories per capita per day [kcal/capita/day]*

**Forest area size:** area covered by forest in a given geographical region:

- *Hectares of forested land [ha]*

### Examples

Scenario analysis for Europe indicates possible synergies between increasing dietary energy production and freeing up sufficient areas for reforestation and afforestation by the year 2050, in line with European countries' commitments to limiting global warming to 1.5 °C. However, these synergies could only be realized in scenarios that foresee a radical change in dietary preferences and either reduce both ruminant and non-ruminant meat consumption, or completely eliminate meat consumption (Lee *et al.*, 2019).

### Enabling environment

A shift in dietary preferences towards less meat-intensive diets is crucial to reducing or even avoiding the trade-off between increased food production and strengthened forest carbon stocks.

## Productivity vs. Emissions

| Objective 1.A | Increasing agricultural productivity | Reducing emission intensities of agricultural products | Objective 3.B |
|---|---|---|---|

Improved farming practices and technologies that achieve greater resource-use efficiency can create synergies between increasing the productivity of production systems and reducing the GHG emission intensities of agricultural production (e.g. Sapkota *et al*., 2014, 2017; Shikuku *et al*., 2017). This principle applies to all subsectors, but the realization of synergies depends on the proper use of these technologies.

Intensification of systems to increase productivity, such as increased fertilization rates in crop or biomass cultivation, may also result in higher emission intensities and thus present a trade-off (e.g. Balmford *et al*., 2018), particularly when compared with low-input systems where no fertilizers are applied, such as biomass production on marginal land (Carlsson *et al*., 2017). It is important to note that increased productivity – albeit at lower emission intensities – may increase absolute GHG emissions from a given unit of land due to the increase in overall production (see e.g. Gil *et al*., 2018). For example, a global ex-ante assessment of the adoption of a set of practices commonly promoted as CSA in cereal production systems found that the adoption based on the sole criterion of increased productivity might lead to significant increases of absolute emissions in several countries – compared with a business-as-usual scenario in projections up to the year 2050 (de Pinto *et al*., 2020). On the other hand, using a combined criterion of increased productivity and reduced emission intensity would result in a reduction of absolute emissions in most countries, and to slight increases in a very limited number of countries.

Under the premise that increased productivity leads to a reduction in land required for agricultural production, the concept of sustainable intensification argues that absolute increases of GHG emissions in intensified systems are offset by carbon sequestration through the conservation or restoration of carbon-rich ecosystems on spared land – resulting in a net reduction of greenhouse gas emissions at landscape scale. Indeed, when accounting for the carbon sequestration potential of spared land, some observed trade-offs between productivity and GHG emission intensity appear as synergies (Balmford *et al*., 2018). However, the benefits of land sparing can only be realized if areas set aside for conservation and restoration are protected by targeted policies, laws and regulations, such as strict land-use zoning, conditional access to markets and restricted rural subsidies. Otherwise, the profitability of higher-yielding systems is likely to result in increased conversion of natural to agricultural land..

### Indicators & *metrics*

**Yield:** product per unit of land area/livestock/etc. in a given time period, e.g.:

- *Tonnes of grain per hectare and year [t/ha]*
- *Tonnes of biomass dry matter (DM) per hectare and year [t DM/ha]*
- *Litres of milk per cow and day [L/d]*

**Land cost:** the inverse of crop yield, i.e. units of land required during one year for production of one product unit, e.g.:

- *Hectare-years per tonne of grain [ha-years/t]*
- *Hectare-years per tonne of carcass weight [ha-years/t]*

**Partial factor productivity:** product per unit of one specific input factor, such as fertilizer, e.g.:

- *Kilograms of grain per kg of nitrogen (N) [kg/kg N]*
- *Kilograms of grain per kg of phosphorous [kg/kg $P_2O_5$]*

**GHG emission intensity:** GHG emissions per unit of production, e.g.:

- *Kilograms of carbon dioxide equivalent ($CO_2$eq) per tonne of grain yield [kg $CO_2$eq/t]*
- *Litres of methane ($CH_4$) per litre of milk [L $CH_4$/L]*
- *Kilograms of carbon dioxide equivalent per energy unit of biogas vehicle fuel (megajoule) [kg $CO_2$eq/MJ]*

## Examples

Improved cattle feeding practices lead to higher dairy cattle productivity (milk yield) and to lower methane emission intensity (enteric fermentation) (Shikuku *et al.*, 2017).

Methodologies/tools applied (refer to list at bottom of this sheet): 2, 3

Depending on individual household status, cereal crop yields can be increased (from low/medium levels) or maintained (at high levels), while reducing GHG emission intensities through adoption of improved agronomic and fertilizer management practices, including zero tillage, precision nitrogen use, farm manure and crop residue management (Sapkota *et al.*, 2014, 2017).

In a meta-analysis looking exclusively at the effects of zero tillage on GHG emissions in cereal production, Huang *et al.* (2018) found highly variable results, indicating that both synergies and trade-offs can occur between yields and GHG emissions. Across the assessed cereal crops (barley, maize, rice, wheat) there was no clear pattern that showed an advantage of zero tillage over conventional tillage. Most positive effects of zero tillage were observed in rice and barley on reducing GHG emissions and increasing yield, respectively. Important factors influencing the effect were climate – with a tendency for positive effects in dry climates – soil pH, fertilization rate and placement.

Methodologies/tools applied (refer to list at bottom of this sheet): 1

The cultivation of perennial grasses and species-rich legume-grass mixtures as a feedstock for biogas production on marginal soils in Sweden showed that biogas vehicle fuel produced from unfertilized fields had consistently lower GHG emission intensity per energy unit than that from fields with fertilized treatments. However, the overall yield of biomass – and hence biogas – per hectare was also lower. While species diversity in seed mixtures showed neither a positive nor negative effect, it is argued that it brings many other benefits, such as enhanced pollination, soil fertility, carbon sequestration, resilience to climate variability, yield stability and reduced economic risk (Carlsson *et al.*, 2017).

The large-scale adoption of CSA practices – related to soil fertility, nutrient and water management – in maize, wheat and rice production systems is estimated to result in a significant increase in global production, as well as a significant reduction in global GHG emissions by 2050. The increased production would also lead to a significant decline in maize, wheat and rice prices, with positive effects on food security. However, GHG emission reductions, although significant, would be limited to maximum 7 to 10 percent of the baseline emissions. This suggests that switching to alternative production systems with higher mitigation potential and mitigation options across the entire food system should be explored in order to enable greater reductions, in line with international agreements. Also, the underlying scenario analysis did not consider indirect effects on land-use changes and related changes in emissions (de Pinto *et al.*, 2020).

Methodologies/tools applied (refer to list at bottom of this sheet): 4

## Sustainability

The adoption of improved practices depends in part on the educational status of producers. This shows the important links between agricultural development and the achievement of higher literacy rates.

Limiting the cultivation of bioenergy feedstock to species-rich systems on marginal soils, e.g. on set-aside areas dedicated to 'greening' measures under the European Union's Common Agricultural Policy, reduces competition for land with food and feed production and can also create synergies with biodiversity and other ecosystem services.

## Enabling environment

Level of education, economic status and access to information/agro-advisory services are important factors enabling the adoption of improved practices.

The success of sustainable intensification and land-sparing for GHG emission reductions depends on the existence and enforcement of conducive land-use policies, subsidy schemes and environmental laws. These are ideally complemented by demand-side measures to reduce the demand for resource-intensive products.

## Methodologies & Tools

1. **Cool Farm Tool:** Farm-level decision support tool for the assessment of GHG emissions of crop and livestock activities. [see page 80]
2. **RUMINANT model:** Dynamic estimation of methane emissions based on livestock diet. Static estimation of livestock growth and milk yield. [see page 80]
3. **Trade-off Analysis for Multi-Dimensional Impact Assessment (TOA-MD) model:** Parsimonious model (minimal input data) that predicts adoption rate of alternative options (compared with baseline) based on greatest expected economic benefit. [see page 76]
4. **International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT):** System of models to simulate agricultural commodity markets and their impacts on various socio-economic and environmental aspects under different agricultural and climate change scenarios. [see page 80]

# Income vs. Carbon stocks

| Objective 1.B | Increasing food producers' incomes | Increasing carbon stocks in soils and biomass | Objective 3.A |
|---|---|---|---|

Potential trade-offs can be observed between the promotion of food producers' incomes and the conservation of carbon stocks. The restriction of access to forest land and its conversion to agricultural land in order to conserve carbon in forest ecosystems is associated with opportunity costs for the local population. In areas with strong development potential in the food sector, these opportunity costs can be compensated by measures to increase productivity and production from existing agricultural land. However, such measures increase the implementation cost of carbon conservation projects and therefore depend on the achievement of higher carbon prices in international carbon markets.

## Indicators & *metrics*

**Opportunity cost of carbon conservation and/or sequestration:** value of forgone income opportunities, e.g. agricultural and charcoal production, expressed as net present value:

- *Net present value per hectare [USD/ha]*

**Carbon conservation and/or sequestration potential:** net amount of avoided carbon emissions from avoided deforestation or forest degradation, or carbon sequestered through re/afforestation and ecosystem restoration, e.g.:

- *Tonnes of carbon (C) per hectare [t C/ha]*

## Examples

S T

An assessment of the net carbon conservation potential of one hectare of average forest land in the context of a REDD+ project in Eastern Tanzania, and the economic benefits of converting this land for agricultural use and charcoal production, concluded that there is a high opportunity cost of REDD+ projects for the local population. This would be likely to lead to 'leakages', i.e. the local population would seek to compensate its demand for food and income sources in areas outside the REDD+ area, and simply displace carbon emissions. However, the study also identifies potential to compensate the forgone income from crop and charcoal production through targeted intensification of crop production – increasing crop yields on the existing cropland – and the introduction of fuel-efficient cooking stoves to reduce charcoal demand. The increased cost of implementation to include these measures in a REDD+ project could be economically viable, assuming a competitive carbon price of USD 12 per tonne of carbon – double of the price of compensating the opportunity cost (Fisher *et al*., 2011).

Methodologies/tools applied (refer to list at bottom of this sheet): 1

## Sustainability

The successful implementation of compensatory measures in REDD+ projects may avoid reinforcing social inequalities, while increasing productivity and overall food production and benefiting the conservation of ecosystems and biodiversity in the protected forest land.

## Methodologies & Tools

1. **Implementation cost approach:** Type of cost-benefit analysis that quantifies and compares the carbon conservation potential of forest land, the associated opportunity cost for local communities, and the cost of implementing complementary development interventions to compensate unmet demands sustainably. [see page 76]

# Income vs. Emissions

| Objective 1.B | Increasing food producers' incomes | Reducing emission intensities of agricultural products | Objective 3.B |
|---|---|---|---|

Practices and technologies targeting a reduction of GHG emission intensities through improved resource-use efficiency can, at the same time, increase household incomes. They therefore hold potential for synergies between the reduction of agricultural GHG emissions and improved food producers' livelihoods. However, this potential strongly depends on current practices on a given farm. Introducing new agricultural activities on a farm, for example livestock in a crop-based system, may also result in a steep increase in GHG emission intensities, despite positive effects on household income. Also, when calculating GHG emissions per unit area, the synergy may turn into a trade-off, at least at the field level; at the landscape level, this could be compensated by land-sparing strategies. In some cases, the synergy between incomes and emission intensities was found to be associated with an increase in environmental costs.

## Indicators & *metrics*

**Farm income,** e.g.:

- *Annual income [USD/year]*

**Net return/revenue,** e.g.:

- *Value of net return per hectare of cropland [USD/ha]*

**Benefit-cost ratio:** dimensionless measure representing the ratio of returns obtained from the sale of agricultural produce (e.g. one hectare cultivated for wheat) over the associated costs.

**GHG emission intensity:** GHG emissions per unit of production/land, e.g.:

- *Litres of methane ($CH_4$) per litre of milk [L $CH_4$/L]*
- *Kilograms of carbon dioxide equivalent ($CO_2$eq) per tonne of grain yield [kg $CO_2$eq/t]*
- *Kilograms of carbon dioxide equivalent per hectare [kg $CO_2$eq/ha]*
- *Kilograms of $CO_2$eq per farm [kg $CO_2$eq/farm]*
- *Kilograms of $CO_2$eq per kg of human-digestible protein (HDP) [kg $CO_2$eq/kg HDP]*

## Examples

S T

The adoption of improved cattle feeding practices in smallholder livestock systems in Lushoto district, Tanzania, is expected to be economically viable for the majority of households in the study area and lead to higher household incomes, as well as to a reduction in methane emission intensity from enteric fermentation. However, there is a potential trade-off for farms that do not currently own cattle: the acquisition of one head of improved-breed dairy cattle could substantially increase their incomes, but it would also increase the farms' net methane emissions manifold (Shikuku *et al.*, 2017).

Methodologies/tools applied (refer to list at bottom of this sheet): 1, 2

S

Adoption of zero tillage in highly mechanized, irrigated wheat production systems in Haryana state, northern India, resulted in increased farm incomes – from both reduced production cost and increased net revenues – and also reduced GHG emission intensities, in part due to soil carbon sequestration. There were, however, significant changes in wheat yields during the three-year trial (Aryal *et al.*, 2015).

Methodologies/tools applied (refer to list at bottom of this sheet): 3

S

Adoption of site-specific nutrient management – supported by a nutrient management decision support system – in wheat production systems in Haryana state, northern India, resulted in increased incomes (net returns), as well as reduced GHG emission intensities (Sapkota *et al.*, 2014). The study also tested different combinations of nutrient management strategies with zero tillage and conventional tillage. Increased yields under ZT were only observed in a year with above-normal climatic stress, pointing towards synergies with climate-resilience objectives. However, this aspect was not assessed quantitatively.

Methodologies/tools applied (refer to list at bottom of this sheet): 3

S T

In a farm simulation of medium and large beef cattle farms in the state of Mato Grosso, Brazil, integrated crop-livestock systems (soybean-beef cattle) show higher productivity and incomes, compared with pure livestock systems (extensive or rotational grazing), as well as lower GHG emission intensities. Productivity and GHG emission intensities refer to human-digestible protein in order to allow comparability across beef and soybean production. However, when considered per hectare, there is a clear trade-off between productivity/income and GHG emissions, with the integrated system – which is also the most intensive system with the highest cattle stocking rates – presenting the highest emissions, followed by the rotational pasture system. The same pattern was found in other environmental indicators (energy use, water use and nitrogen losses), pointing to a trade-off with environmental sustainability (Gil *et al*., 2018).

Methodologies/tools applied (refer to list at bottom of this sheet): 4

S

A bio-economic simulation of smallholder mixed crop-livestock farms in northern Tanzania was performed to identify farm configurations with the least trade-offs. Choosing from a predefined set of possible farm adaptations (presumably improvements), the farm model was applied to four representative farm types optimizing the trade-offs between increasing income, increasing the nitrogen (N) balance and reducing GHG emissions at farm level. While the N balance was used as an approximation of adaptive capacity – representing increased farm and soil resources and thus enhanced buffer capacity to shocks in the context of smallholder farms that do not use any mineral fertilizers – it should be noted that high farm N balances are actually an environmental concern in industrialized countries. The simulations identified possible triple-wins for three of the four farm types, with modifications differing by type. Common modifications across most types were reduction of livestock units, replacement of local livestock breeds with improved dairy cattle breeds, reduction of on-farm pasture, increased on-farm feed production (Napier grass) and oilseed cake feeding, reduction of crop residue feeding and increased residue retention in fields. Farm income showed a positive correlation with farm GHG emissions across the simulated alternative farm configurations at various target income levels. However, in each farm type there were configurations that increased farm income and reduced farm emissions, compared with the baseline (current practice) (Paul *et al*., 2019).

## Sustainability

In the case of livestock farms in Tanzania, the income gains were consistently associated with (predicted) reductions in poverty and improved food security (Shikuku *et al*., 2017).

Despite the economic advantages and increased efficiency of sustainable livestock intensification, reducing herd sizes and replacing local with improved breeds may have negative implications. For example, large herd size may be an expression of social status. Improved cattle, being more expensive, may also be more difficult to sell at local markets and are not suitable as draught power for crop cultivation. Often, another challenge is lack of services and infrastructure to support rearing of improved breeds, including artificial insemination and cooling facilities. Livestock intensification also increases farm labour requirements, and may be problematic where labour availability is limited, although labour productivity is likely to increase (Paul *et al*., 2019).

## Methodologies & Tools

1. **RUMINANT model:** Dynamic estimation of methane ($CH_4$) emissions based on livestock diet. Static estimation of livestock growth and milk yield. [see page 80]
2. **Trade-off Analysis for Multi-Dimensional Impact Assessment (TOA-MD) model:** Parsimonious model (minimal input data) that predicts adoption rate of alternative options (compared with baseline) based on greatest expected economic benefit. [see page 76]
3. **Cool Farm Tool:** Farm-level decision support tool for the assessment of GHG emissions of crop and livestock activities. [see page 80]
4. **Integrated Farm System Model (IFSM):** Whole-farm simulation model to assess productivity, profitability and environmental impacts of different farm configurations. [see page 79]

# Social/environmental sustainability vs. Carbon stocks

| Objective 1.C | Social and environmental sustainability | Increasing carbon stocks in soils and biomass | Objective 3.A |
|---|---|---|---|

Depending on the type of intervention to increase and/or conserve carbon stocks in agro-ecosystems, the modalities of implementation and the social and environmental aspects considered, there can be both synergies and trade-offs (see examples below). Agroforestry systems, for example hold strong potential to increase biodiversity. Afforestation and reforestation projects may have both negative and positive effects on soil and water resources at different spatial scales – for example, on-site vs. downstream effects. Forest conservation projects may have negative effects on equality if customary rights of current land users are not fully taken into consideration.

## Indicators & *metrics*

**Change in surface runoff,** e.g.:

- *Absolute change in runoff expressed as water depth [mm]*
- *Relative change in runoff [%]*

**Biodiversity:** relative difference in biodiversity indicators between agro-ecological practices and conventional practices, e.g.:

- *Relative difference in tree richness [%]*
- *Relative difference in bird richness [%]*

**Food security:** expressed as provision of basic calorie needs per person per day in a given geographical area, e.g. a community.

- *Kilocalories available per person per day [kcal/person/day]*

**Area afforested/reforested:** to enhance carbon sequestration, e.g.:

- *Hectares of land afforested/reforested [ha]*

**Carbon stock:** relative difference in carbon stocks in above-ground biomass and soil between agro-ecological practices and conventional practices, e.g.:

- *Relative difference in above-ground tree biomass carbon stock [%]*
- *Relative difference in carbon stock [%]*

**Carbon dioxide emissions avoided/GHG mitigation potential:** amount of carbon dioxide ($CO_2$) emission avoided through conservation of forest land and prevention of forest degradation or conversion to agricultural land, for example under REDD+ projects, e.g.:

- *Tonnes of $CO_2$ per hectare [t $CO_2$/ha]*

## Examples

S T

Moderate levels of shade-tree cover (30 percent) in cocoa agroforestry systems in Ghana were found to have a positive effect on biodiversity (tree and bird richness), and also to increase carbon sequestration in above-ground biomass, compared with full-sun monocultures. The effect on cocoa yields was neutral (slightly negative, but insignificant). An increase in shade-tree cover (up to 80 percent) further enhanced biodiversity, as well as above-ground carbon stocks, albeit at the cost of drastically reducing cocoa yield. The effect of shade-tree cover on soil fertility and carbon sequestration in soils was neutral across the whole gradient (Blaser *et al*., 2018).

S T

Afforestation and reforestation projects have the potential to sequester large quantities of carbon. A hydrological assessment of potential areas for afforestation or reforestation under the Kyoto Protocol's Clean Development Mechanism (CDM-A/R) globally found a sharp increase in actual evapotranspiration and, in many cases, a significant reduction in soil moisture and water runoff from afforested areas (Trabucco *et al*., 2008; Zomer *et al*., 2008). Case studies of project sites in Bolivia and Ecuador showed that outcomes of afforestation and reforestation are strongly context-dependent, with local conditions dictating whether the result is a synergy or a trade-off. On the one hand, reduced runoff may temper erosion on-site and the risk of downstream flooding. On the other, it may reduce stream flow in rivers, with impacts on downstream ecosystem health and water availability – including for agricultural use and, specifically, for purposes of climate change adaptation.

Methodologies/tools applied (refer to list at bottom of this sheet): 1

T

The Kasigau Corridor REDD+ project in Kenya conserves and sequesters substantial amounts of carbon in forest biomass and generates benefits from the sale of carbon credits. However, while attempts were made to take equality issues into consideration in the distribution of benefits, the greatest shares flow to the recovery of project implementation costs and to the holders of official land titles. The minimal shares of benefits allocated to community members without land titles – too small to disburse individually – are collectively invested in communal projects. This leaves community members with no benefits in the form of individual incomes and high opportunity costs for the forgone benefits from crop cultivation, hunting, charcoal production and firewood collection. As a result, the project reinforced pre-existing inequalities between ordinary members of the local population and the elites (Chomba *et al.*, 2016).

S

An assessment of different crop production scenarios (extensification, intensification based on mineral fertilizers, green manure or agroforestry) found potential synergies between ensuring basic caloric needs and increasing the GHG mitigation potential for two villages in sub-Saharan Africa, one with low population density (Tanzania) and one with high population density (Kenya). While all scenarios would result in available land for reforestation and net carbon sequestration in the Tanzanian village, only two scenarios resulted in net mitigation of GHG emissions in the densely populated village in Kenya. The mineral fertilizer intensification scenario was projected to free up sufficient land for reforestation, which also offset the increasing nitrous oxide ($N_2O$) emissions from crop production. The agroforestry scenario was projected to have the highest net mitigation potential, sequestering large amounts of carbon in above-ground biomass, which also offset the slightly increased $N_2O$ emissions from the fertilization effect of legume trees (Palm *et al.*, 2010).

## Sustainability

Another possible trade-off that may arise in afforestation/reforestation projects is competition for land between carbon sequestration/bioenergy production and agriculture/food security. This particularly affects the livelihoods of smallholder farmers, many of whom rely on cultivating land identified as suitable for such projects.

## Methodologies & Tools

1. **Thornthwaite-Mather water balance modeling approach:** Hydrological model to assess the impact of land-use change on hydrological parameters. [see page 81]

# Social/environmental sustainability vs. Emissions

| Objective 1.C | Social and environmental sustainability | Reducing emission intensities of agricultural products | Objective 3.B |
|---|---|---|---|

Practices and technologies targeting a reduction of GHG emission intensities through improved resource-use efficiency can increase household incomes and, consequently, improve food security and reduce poverty. They therefore hold potential for synergies between reducing agricultural GHG emissions and improving social outcomes for farm households. However, this potential strongly depends on current practices on a given farm. Introducing new agricultural activities on a farm, for example livestock in a crop-based system, may also result in a steep increase in GHG emission intensities, despite positive social outcomes (Paul *et al*., 2018; Shikuku *et al*., 2017). Trade-offs may also occur with environmental costs, where reductions in GHG emission intensities are in part achieved through intensification of the farm systems and, hence, higher productivity levels (Gil *et al*., 2018).

## Indicators & *metrics*

**Poverty rate:** proportion of the population living under USD 1.25 per person per day, e.g.:

- *Proportion of population beneath poverty [%]*

**Income-based food security (IBFS):** proportion of the population with sufficient income available to purchase a representative food basket, e.g.:

- *Proportion of population food-secure according to IBFS threshold [%]*

**Food availability:** expressed as the calories available per family member, where household size is quantified in terms of male adult equivalents, based on the energy requirements of each household member by gender and age.

- *Kilocalories per person per day [kcal/person/day]*

**Loss of reactive nitrogen:** per unit area or per unit of product, e.g.:

- *Kilograms of nitrogen (N) per hectare [kg N/ha]*
- *Kilograms of nitrogen (N) per human-digestible protein (HDP) [kg N/kg HDP]*

**Water use:** per unit area or per unit of product, e.g.:

- *Tonnes of water per hectare [t/ha]*
- *Tonnes of water per human-digestible protein (HDP) [t/kg HDP]*

**Energy use:** per unit area or per unit of product, e.g.:

- *Terajoule per hectare [TJ/ha]*
- *Terajoule per human-digestible protein (HDP) [TJ/kg HDP]*

**GHG emission intensity:** GHG emissions per unit of production/land, e.g.:

- *Litres of methane ($CH_4$) per litre of milk [L $CH_4$/L]*
- *Kilograms of carbon dioxide equivalent ($CO_2$eq) per unit of human-digestible protein (HDP) [kg $CO_2$eq /kg HDP]*
- *Kilograms of $CO_2$eq per ha [kg $CO_2$eq/ha]*
- *Kilograms of $CO_2$eq per household [kg $CO_2$eq/household]*

## Examples

The adoption of improved cattle feeding practices in smallholder livestock systems in Lushoto district, Tanzania, is expected to lead to higher food security and reduced poverty rates among farms in the district, as well as a reduction in methane emission intensity from enteric fermentation (Shikuku *et al*., 2017).

Methodologies/tools applied (refer to list at bottom of this sheet): 1, 2

A farm simulation of medium and large beef cattle farms in the state of Mato Grosso, Brazil, shows the lowest GHG emission intensity for integrated crop-livestock systems (soybean-beef cattle), compared with pure livestock systems (extensive or rotational grazing) under both optimistic and pessimistic climate change scenarios up to the year 2050, corresponding to representative concentration pathways (RCP) 2.6 and RCP 8.5, respectively. However, environmental costs per area – water use, energy use and loss of reactive nitrogen – are considerably higher. Also, the GHG emissions per area are inversely proportional to the GHG emission intensities. Therefore, the achievement of overall emission reductions depends on successful land-sparing and carbon conservation and/or sequestration within the landscape, while the containment of environmental burden requires targeted measures to increase the resource-use efficiency and sustainable sourcing of inputs in the production system (Gil *et al.*, 2018).

Methodologies/tools applied (refer to list at bottom of this sheet): 3

A rapid ex-ante impact assessment was conducted to evaluate the effects of three national agricultural policies on the food security and GHG emissions of smallholder farm households in Rwanda. The three policies – (1) provisioning of households with one head of cross-bred dairy cattle each; (2) introducing improved livestock feeding practices; (3) mineral fertilizer subsidies – reached different types and numbers of households with different impacts. The subsidized dairy cattle considerably improved the food security of those households below the threshold of food availability of 2 500 kcal per person per day (the average energy requirement of a male adult), but also led to a steep increase in household GHG emissions, as these families formerly did not have any livestock. Improved feeding practices led to a moderate increase in food availability and a low increase in GHG emissions, but only reached better-off households that already owned livestock; this therefore represents the least equitable policy. Fertilizer subsidies were the most equitable policy, reaching most households and resulting in a low increase in both food availability and household GHG emissions. Overall, a clear trade-off between food availability and household GHG emissions was evident. Only in the case of improved feeding practices could a synergy be observed, if GHG emissions are expressed as emission intensity per unit of product. Most households with food availability above the threshold had substantial income contributions from livestock and/or off-farm employment, illustrating the benefits of livestock integration and off-farm income sources for the food security of crop-based smallholder farm households (Paul *et al.*, 2018).

## Methodologies & Tools

1. **RUMINANT model:** Dynamic estimation of methane ($CH_4$) emissions based on livestock diet. Static estimation of livestock growth and milk yield. [see page 80]
2. **Trade-off Analysis for Multi-Dimensional Impact Assessment (TOA-MD) model:** Parsimonious model (minimal input data) that predicts adoption rate of alternative options (compared with baseline) based on greatest expected economic benefit. [see page 76]
3. **Integrated Farm System Model (IFSM):** Whole-farm simulation model to assess productivity, profitability and environmental impacts of different farm configurations. [see page 79]

# A1.3 Synergies and trade-offs between CSA Pillar 2 'Adaptation' and CSA Pillar 3 'Mitigation'

## Livelihood resilience vs. Emissions

| Objective 2.A | Improving climate risk mitigation strategies for food producers' livelihoods | Reducing emission intensities of agricultural products | Objective 3.B |
|---|---|---|---|

Diversification of production systems can generate synergies between increased economic resilience under a range of future climate scenarios and reduced GHG emission intensities per product unit. Where reduced emission intensities derive mainly from intensification of the production system and a related increase in productivity, there is, however, a risk that emissions per unit area increase and consequently, so do absolute emissions at landscape level – unless effective land-sparing strategies are applied.

### Indicators & *metrics*

**Income stability:** expressed as farm income, i.e. net revenues from sale of agricultural produce, of alternative farm systems under different climate change scenarios.

- *Net revenue per hectare [USD/ha]*

**GHG emission intensity:** GHG emissions per unit of production/land, e.g.:

- *Kilograms of carbon dioxide equivalent ($CO_2eq$) per unit of human-digestible protein (HDP) [kg $CO_2eq$ /kg HDP]*
- *Kilograms of $CO_2eq$ per hectare [kg $CO_2eq$/ha]*

### Examples

S T

In a farm simulation of medium and large beef cattle farms in the state of Mato Grosso, Brazil, integrated crop-livestock systems (soybean-beef cattle) present stronger economic resilience, as well as lower GHG emission intensities, compared with pure livestock systems (extensive or rotational grazing) under different climate change scenarios. Productivity and incomes are also higher under the integrated system, showing potential synergies between all three CSA pillars. However, the crop-livestock system – being the most intensive – has the highest GHG emissions per hectare, so a real climate change mitigation benefit will only be achieved if the increased productivity leads to a substantial reduction in agricultural area and reforestation of abandoned land (Gil *et al.*, 2018).

Methodologies/tools applied (refer to list at bottom of this sheet): 1

### Sustainability

Intensification of the production system may result in additional environmental costs including, for example, resource use and nitrogen emissions.

### Methodologies & Tools

1. **Integrated Farm System Model (IFSM):** Whole-farm simulation model to assess productivity, profitability and environmental impacts of different farm configurations. [see page 79]

# Production system adaptation vs. Carbon stocks

| Objective 2.B | Adapting food production systems to current and expected future climate change | Increasing carbon stocks in soils and biomass | Objective 3.A |
|---|---|---|---|

Potential trade-offs may arise between the sequestration of carbon in ecosystems and adaptation options available to food production systems downstream, within a catchment area or river basin. This is illustrated by the example of afforestation and reforestation projects that reduce surface runoff and, consequently, river flow and downstream water availability for agricultural activities such as irrigation (see below; Trabucco *et al*., 2008). A possible trade-off was also found between drought adaptation strategies in irrigated cropping systems and soil carbon storage (see below; Weller *et al*., 2016).

## Indicators & *metrics*

**Change in surface runoff,** e.g.:

- *Absolute change in runoff expressed as water depth [mm]*
- *Relative change in runoff [%]*

**Irrigation water use,** e.g.:

- *Irrigation water depth applied per year [mm/year]*

**Area afforested/reforested:** to enhance carbon sequestration, e.g.:

- *Hectares of land afforested/reforested [ha]*

**Soil organic carbon stock change,** e.g.:

- *Megagrams (= tonnes) of carbon (C) per hectare [Mt C/ha]*

## Examples

S T — Field experiments comparing the traditional double paddy rice cropping system with diversified cropping systems (wet season: paddy rice; dry season: maize or aerobic rice) in the Philippines found a significant reduction in irrigation water usage in the diversified systems, with no significant effects on overall grain yield, qualifying these systems as possible drought adaptation strategies. However, while the overall global warming potential of the rotation systems was lower, the soil carbon stocks in the paddy rice-maize system diminished over the course of three years. In the medium to long term, this may present a trade-off with carbon storage, but also with soil fertility, possibly affecting yields and incomes (Weller *et al*., 2016).

S T — Afforestation and reforestation projects have the potential to sequester large quantities of carbon. A hydrological assessment of potential areas for afforestation or reforestation under the Kyoto Protocol's Clean Development Mechanism (CDM-A/R) globally found a sharp increase in actual evapotranspiration and, in many cases, significant reduction in soil moisture and water runoff from afforested areas (Trabucco *et al*., 2008; Zomer *et al*., 2008). Case studies of project sites in Bolivia and Ecuador showed that outcomes of afforestation and reforestation are strongly context-dependent, with local conditions dictating whether the result is a synergy or a trade-off. On the one hand reduced runoff may temper erosion on-site and the risk of downstream flooding. On the other, it may reduce stream flow in rivers, with impacts on downstream ecosystem health and water availability. In the latter case, afforestation and reforestation projects compromise the climate change adaptation options, such as irrigation, of downstream water users.

Methodologies/tools applied (refer to list at bottom of this sheet): 1

## Sustainability

Another possible trade-off that may arise in afforestation/reforestation projects is competition for land between carbon sequestration/bioenergy production and agriculture/food security. This particularly affects the livelihoods of smallholder farmers, many of whom rely on cultivating land identified as suitable for such projects.

## Methodologies & Tools

1. **Thornthwaite-Mather water balance modeling approach:** Hydrological model to assess the impact of land use change on hydrological parameters. [see page 81]

## Production system adaptation vs. Emissions

| Objective 2.B | Adapting food production systems to current and expected future climate change | Reducing emission intensities of agricultural products | Objective 3.B |
|---|---|---|---|

The relationship between production system adaptation and reducing GHG emissions can involve both synergies and trade-offs. Examples of synergies were observed in adaptations of irrigation systems, where emission reductions were associated with increased yield and income stability and/or a reduction in irrigation water use (see examples below; Hochman *et al*., 2017; Weller *et al*., 2016). An example of a trade-off was observed in livestock intensification on smallholder farms, where emission reductions were associated with increased farm and agro-ecosystem resilience on the one hand, but increased production risk on the other, due to the lower resilience of improved high-yielding livestock breeds to variable and extreme climatic conditions and diseases (see example below; Paul *et al*., 2018).

### Indicators & *metrics*

**Yield stability:** expressed as coefficient of variation (CV), i.e. standard deviation divided by the mean, of a time series of observed or simulated crop yields. It can be expressed as a ratio or percentage, with low values indicating high stability.

- *CV of crop yields over a given period of time [%]*

**Irrigation water use,** e.g.:

- *Irrigation water depth applied per year [mm/year]*

**Annual nitrogen balance,** i.e. the annual balance of imports and exports of nitrogen (N) at farm level:

- *Kilograms of N per farm [kg N/farm]*

**Global warming potential:** expressed as emissions of carbon dioxide equivalent ($CO_2$eq) e.g. per unit area, per farm or per unit of economic return:

- *Kilograms of $CO_2$eq per hectare [kg $CO_2$eq/ha]*
- *Kilograms of $CO_2$eq per Indian rupee (INR) of gross margin [kg $CO_2$eq/INR]*
- *Kilograms of $CO_2$eq per farm [kg $CO_2$eq/farm]*

### Examples

S

A scenario analysis, using a crop simulation model, was conducted to test the sustainability and climate-smartness of adaptation strategies for cotton and maize production in smallholder paddy rice-cotton and paddy rice-maize systems in south India, under historic climate and moderate climate change scenarios (2021–2040; RCP 6). Adaptation options included new criteria to determine the sowing date and adoption of supplemental irrigation for maize/cotton combined with reducing paddy rice area to source water for supplemental irrigation. Year-to-tear climate variability was greater than variability between scenarios. Adaptation options were assessed and compared with current practice, using the following set of indicators: yield, yield stability, gross margin, stability of gross margin, global warming potential and GHG emission intensity (as CSA indicators); and water use, water productivity, groundwater recharge and nitrogen leaching (as sustainability indicators). While supplemental irrigation presented some trade-offs related to groundwater recharge and nitrogen leaching, most combinations of adaptation options improved the CSA indicators and showed greater overall sustainability, compared with current practice – determined through sustainability polygons. The performance of adaptation options was influenced by agro-ecological conditions in the three assessed locations, as well as by farm size. The study enabled the identification of location- and farm-specific adaptation options that increase climate resilience (in terms of yield and gross margin stability) and also reduce GHG emissions (Hochman *et al*., 2017).

Methodologies/tools applied (refer to list at bottom of this sheet): 1, 2

S T

Field experiments comparing the traditional double paddy rice cropping system with diversified cropping systems (wet season: paddy rice; dry season maize or aerobic rice) in the Philippines found a significant reduction in irrigation water usage, as well as lower overall global warming potential in the diversified systems, with no significant effect on grain yields. This qualifies the rotation systems as possible drought adaptation, as well as climate change mitigation strategies. However, the soil carbon stocks in the paddy rice-maize system diminished over the course of three years. In the medium to long term, this may present a trade-off with carbon storage, but also with soil fertility, possibly affecting yields and incomes (Weller *et al*., 2016).

A bio-economic simulation of smallholder mixed crop-livestock farms in northern Tanzania was performed to identify farm configurations with the least trade-offs. Choosing from a predefined set of possible farm adaptations (presumably improvements), the farm model was applied to four representative farm types optimizing the trade-offs between increasing income, increasing the nitrogen (N) balance and reducing GHG emissions at farm level. While the N balance was used as an approximation of adaptive capacity – representing increased farm and soil resources and thus enhanced buffer capacity to shocks in the context of smallholder farms that do not use any mineral fertilizers – it should be noted that high farm N balances are actually an environmental concern in industrialized countries. The simulations identified possible triple-wins for three of the four farm types, with modifications differing by type. Common modifications across most types were reduction of livestock units, replacement of local livestock breeds with improved dairy cattle breeds, reduction of on-farm pasture, increase of on-farm feed production (Napier grass) and oilseed cake feeding, reduction of crop residue feeding and increased residue retention in fields. In each farm type, configurations were identified that increased the N balance and at the same time reduced farm GHG emissions. Although the N balance was interpreted to increase farm resilience to shocks (including climate shocks), it should be noted that the improved dairy breeds are more susceptible to heat stress and diseases and hence increase the climate risk of the livestock farm component (Paul *et al.*, 2018).

## Sustainability

Despite the economic advantages and increased efficiency of sustainable livestock intensification, reducing herd sizes and replacing local with improved breeds may have negative implications. For example, large herd size may be an expression of social status. Improved cattle, being more expensive, may also be more difficult to sell at local markets and they are not suitable as draught power for crop cultivation. Often, another challenge is lack of services and infrastructure to support rearing of improved breeds, including artificial insemination and cooling facilities. Livestock intensification also increases farm labour requirements and may be problematic where labour availability is limited, although labour productivity is likely to increase.

## Methodologies & Tools

1. **Agricultural Production Systems sIMulator (APSIM):** Crop simulation model. [see page 79]
2. **Sustainability polygons:** Visualization and comparison of multiple indicators across alternative options. [see page 76]

# Production system adaptation vs. Renewables

| Objective 2.B | Adapting food production systems to current and expected future climate change | Replacing fossil fuels with renewable energies | Objective 3.C |
|---|---|---|---|

Uses of natural resources for adaptation purposes in food systems and for renewable energy generation may compete with each other and hence present trade-offs. This is illustrated by the example of expanding water use for irrigation in the upper part of a semi-arid river basin in Tanzania, at the cost of energy production at a hydroelectric power plant downstream (see below).

## Indicators & *metrics*

**Irrigated area:** depending on water allocation for climate change adaption at the river basin scale.

- *Hectares of cropland under irrigation [ha]*

**Water available for irrigation:** depending on water allocation for climate change adaption at the river basin scale.

- *Cubic metres of water allocated to irrigation [m³]*

**Hydroelecric power production:** production of renewable energy form hydroelectric power plants aggregated over the river basin, e.g.:

- *Total amount of energy production in gigawatt-hours [GWh]*

## Examples

The allocation of greater amounts of water for the expansion of irrigated crop production – as an adaptation measure – in Northern Tanzania's upper Pangani river basin leads to lower levels of hydroelectric power, and therefore presents a trade-off with renewable energy production. While it supports increased crop productivity, incomes and food security, it also impacts natural vegetation and its carbon storage capacity in the upper basin. In addition, it reduces environmental flows in the lower river basin, impacting the riverine ecosystem and livelihood activities that depend on it, such as fishing and the collection of wild foods and reed materials for housing (Colloff *et al.*, 2019).

Methodologies/tools applied (refer to list at bottom of this sheet): 1

## Enabling environment

In the case of water management at the river basin scale, the development of polycentric governance arrangements, including water user associations and multistakeholder platforms, is instrumental in achieving equitable water allocation that minimizes trade-offs.

## Methodologies & Tools

1. **Nexus Webs:** A knowledge framework designed to promote collaborative exploration of synergies and trade-offs and enable changes in decision contexts for water use. [see page 79]

# Agro-ecosystem resilience vs. Carbon stocks

| Objective 2.C | Increasing the resilience of agro-ecosystems | Increasing carbon stocks in soils and biomass | Objective 3.A |
|---|---|---|---|

There is strong potential for synergies between the resilience of agro-ecosystems to climate stresses and increased carbon stocks in the landscape. Increasing tree cover in agro-ecosystems sequesters carbon and, at the same time, regulates the microclimate and protects soil resources. However, in agroforestry, particular care needs to be taken to find the most beneficial degree of tree cover, as too much shade compromises crop yields.

## Indicators & *metrics*

**Change in surface runoff** e.g.:

- *Absolute change in runoff expressed as water depth [mm]*
- *Relative change in runoff [%]*

**Dry season maximum temperature:** relative difference between agro-ecological practices and conventional practices.

- *Relative difference in dry season maximum temperature [%]*

**Dry season soil moisture:** relative difference between agro-ecological practices and conventional practices.

- *Relative difference in dry season soil moisture [%]*

**Area afforested/reforested:** to enhance carbon sequestration, e.g.:

- *Hectares of land afforested/reforested [ha]*

**Carbon stock:** relative difference in carbon stocks in above-ground biomass and soil between agro-ecological practices and conventional practices, e.g.:

- *Relative difference in above-ground tree biomass carbon stock [%]*
- *Relative difference in carbon stock [%]*

## Examples


Afforestation and reforestation projects have the potential to sequester large quantities of carbon. A hydrological assessment of potential areas for afforestation or reforestation under the Kyoto Protocol's Clean Development Mechanism (CDM-A/R) globally found a sharp increase in actual evapotranspiration and, in many cases, significant reduction in soil moisture and water runoff from afforested areas (Trabucco *et al*., 2008; Zomer *et al*., 2008). Case studies of project sites in Bolivia and Ecuador showed that outcomes of afforestation and reforestation are strongly context-dependent, with local conditions dictating whether the result is a synergy or a trade-off. On the one hand, reduced runoff may temper erosion on-site and the risk of downstream flooding. On the other, it may reduce stream flow in rivers, with impacts on downstream ecosystem health and water availability. In the former case, afforestation and reforestation projects enable synergies with enhancing the climate resilience of agro-ecosystems.

Methodologies/tools applied (refer to list at bottom of this sheet): 1


Moderate levels of shade-tree cover (30 percent) in cocoa agroforestry systems in Ghana were found to have a heat mitigating effect, and also increase carbon sequestration in above-ground biomass, compared with full-sun monocultures. The effect on cocoa yields and soil moisture was neutral (slightly negative, but insignificant). However, a trade-off with water availability for cocoa plants was observed at higher levels of shade-tree cover. With increasing shade-tree cover (up to 80 percent), the heat mitigating effect and above-ground carbon sequestration increase further, albeit at the cost of drastically reducing water availability and cocoa yield. The effect of shade-tree cover on soil fertility and carbon sequestration in soils was neutral across the whole gradient (Blaser *et al*., 2018).

## Sustainability

Another possible trade-off that may arise in afforestation/reforestation projects is competition for land between carbon sequestration/bioenergy production and agriculture/food security. This particularly affects the livelihoods of smallholder farmers, many of whom rely on cultivating land identified as suitable for such projects.

## Methodologies & Tools

1. **Thornthwaite-Mather water balance modeling approach:** Hydrological model to assess the impact of land use change on hydrological parameters. [see page 81]

# A1.4 Synergies and trade-offs within CSA Pillar 1 'Productivity'

## Productivity vs. Income

| Objective 1.A | Increasing agricultural productivity | Increasing food producers' incomes | Objective 1.B |
|---|---|---|---|

Generally, increased productivity, and incomes are in synergy, as shown in examples of conservation agriculture and in intensification of intercropping systems and livestock systems (see below). This synergy may only be achieved over the longer term in some production systems, i.e. several years after the adoption of a new system (see example below; Jat *et al*., 2020).

### Indicators & *metrics*

**Productivity:** e.g. expressed as amount of human-digestible protein (HDP) and food energy content produced per unit area.

- *Kilograms of HDP per hectare [kg HDP/ha]*
- *Megacalories of food energy per ha [Mcal/ha]*

**Yield:** : expressed as crop yield per unit area:

- *Tonnes per hectare [t/ha]*

**Farm income:** expressed as net revenue, e.g.:

- *Net revenue per hectare [USD/ha]*

**Gross margin/net revenue,** i.e. gross receipts for grain yield minus variable production costs, e.g.:

- *Gross margin per hectare [USD/ha]*

**Returns on labour,** expressed as the ratio of gross margin to labour cost.

**Returns on investment,** expressed as ratio of gross margin to variable production costs.

### Examples

In a farm simulation of medium and large beef cattle farms in the state of Mato Grosso, Brazil, integrated crop-livestock systems (soybean-beef cattle) show higher productivity, as well as incomes, compared with pure livestock systems (extensive or rotational grazing), both under current climate conditions and climate change scenarios up to 2050. For comparability across farm activities, soybean and beef productivity are expressed as human-digestible proteins per hectare. A comparison with soybean monocropping shows that HDP productivity in the pure cropping system is greater throughout all climate scenarios, whereas income is higher in the integrated system or, under the most extreme climate scenario (RCP 8.5), equal to soybean monocropping. This, on the one hand, points to the income opportunities of high-value products, in this case beef cattle. On the other, it presents a potential trade-off between food security at national to global scale – in terms of food availability – and profitability for individual food producers (Gil *et al*., 2018).

Methodologies/tools applied (refer to list at bottom of this sheet): 1

On-farm experiments comparing maize production under conventional and conservation agriculture on smallholder farms in Zimbabwe over a period of nine years found that the CA systems were on average both more productive and more profitable. The productivity advantage derives mainly from increased water infiltration and soil moisture. However, the effect of CA on drought resilience was not systematically assessed; nor was the carbon sequestration or global warming potential, although in years for which data were available, significantly higher soil carbon stocks were found under CA, while the stocks under conventional tillage declined slightly over time (Thierfelder *et al*., 2015)

On-farm experiments across southern and East Africa (Kenya, Mozambique and Tanzania) showed that the strategic application of small amounts of fertilizer increased the productivity, profitability and yield stability of maize-pigeon pea intercropping, compared with unfertilized systems. Intercropping also had a positive effect on nutrient-use efficiency, compared with fertilized sole maize crops. The effect on GHG emissions was not assessed (Kiwia *et al*., 2019).

A long-term experiment comparing conventional and conservation agriculture-based rice-wheat rotation production systems in the Gangetic plain of northeast India found higher productivity and higher profitability for the CA-based systems. While wheat yields showed higher yields from the second year of CA adoption, rice yields increased above levels of conventional production from the fourth year. This illustrates the often-observed yield depression immediately after adoption of sustainable farming practices, which, however, is often offset and inverted in the long term (Jat *et al*., 2020).

## Enabling environment

In the case of Zimbabwe, it has been noted that a lack of technical information and farmers' financial capacity limit the adoption of conservation agriculture.

## Methodologies & Tools

1. **Integrated Farm System Model (IFSM):** Whole-farm simulation model to assess productivity, profitability and environmental impacts of different farm configurations. [see page 79]

## Productivity vs. Social/environmental sustainability

| Objective 1.A | Increasing agricultural productivity | Social and environmental sustainability | Objective 1.C |
|---|---|---|---|

Productivity gains derived from intensification of production systems show synergies with the reduction of environmental cost, such as nitrogen leaching and water use in many examples, if these costs are calculated per unit of product. When calculated per area, they mostly present trade-offs. Under the premise that increased productivity leads to a reduction in land required for agricultural production, and more land available for nature conservation, the concept of sustainable intensification argues that a possible increase of environmental cost in intensified systems is compensated by avoidance of environmental impacts elsewhere (land sparing). In line with this reasoning, some of the trade-offs appear as synergies, if environmental cost is considered per unit of product rather than land area.

Practices with a focus on sustainability, such as agroforestry, were found to provide numerous environmental benefits in several cases. These benefits were either associated with similar or lower yield levels, compared with conventional practices, and therefore present potential trade-offs with productivity.

### Indicators & *metrics*

**Land cost:** i.e. the inverse of yield, expressed as the area required – during one year – to produce one product unit, e.g.:

- *Hectare-years per tonne of grain [ha-years/t]*
- *Hectare-years per tonne of energy-corrected milk (ECM) [ha-years/t]*

**Yield/productivity:**

- *Tonne of grain per hectare [t/ha]*
- *Relative yield difference between new and baseline practice [%]*
- *Human-digestible protein (HDP) per ha [kg HDP/ha]*
- *Food energy content (megacalories) produced per ha [mcal/ha]*

**Nitrogen and phosphorous leaching:** expressed as amount of nitrogen (N) or phosphorous (P) leached per unit of product, e.g.:

- *Kilograms of N leached per tonne of wheat [kg N/kg]*
- *Kilograms of P leached per tonne of energy-corrected milk (ECM) [kg P/kg]*

**Water use:** amount of water used per unit area, product unit or food nutrient unit, e.g.:

- *Tonnes of water per hectare [t/ha]*
- *Tonnes of water per kg of human-digestible protein [t/kg HDP]*

**Water cost:** expressed as the amount of water used per unit of product, i.e. the inverse of water productivity, e.g.:

- *Cubic metres of water per tonne of rice [m³/t]*

**Energy use:** amount of energy used per unit area, product unit or food nutrient unit, e.g.:

- *Terajoule per hectare [TJ/ha]*
- *Megajoule per kg of human-digestible protein [MJ/kg HDP]*

**Soil loss:** expressed as the amount of soil eroded per unit of product, e.g.:

- *Kilograms of soil per per tonne of energy-corrected milk (ECM) [kg/t]*

**Biodiversity:** Relative difference in biodiversity indicators between agro-ecological practices and conventional practices, e.g.:

- *Relative difference in tree richness [%]*
- *Relative difference in bird richness [%]*

### Examples

S T

In European wheat production systems (United Kingdom), increased application of inorganic nitrogen (N) fertilizer resulted in reduced land cost (i.e. high yields), as well as low nitrogen leaching per tonne of wheat. However, above a threshold of 96 kg of N applied per hectare, additional yield gains were minimal and N leaching increased (Balmford *et al.*, 2018).

| | |
|---|---|
| S | In monoculture and rotational paddy rice systems in China, higher fertilization levels with inorganic nitrogen resulted in lower land cost (i.e. higher yields), as well as lower water cost (i.e. water used per tonne of rice) (Balmford *et al.*, 2018). |
| S | Intensified dairy production systems in the United Kingdom – using a higher share of concentrate feed and less grazing than other conventional and organic systems – presented lower land cost (i.e. higher yields), as well as lower losses of nitrate, phosphorous and soil per tonne of energy-corrected milk (Balmford *et al.*, 2018). |
| T | In a farm simulation of medium and large beef cattle farms in the state of Mato Grosso, Brazil, integrated crop-livestock systems (soybean-beef cattle) show higher productivity and incomes compared with pure livestock systems (extensive or rotational grazing). However, this scenario also presents the highest environmental cost per hectare (energy use, water use and nitrogen losses), which is mainly attributed to the higher cattle stocking rate. Only if calculated per unit of production (human-digestible protein) and under extreme climate change (RCP 8.5) – which disproportionately impacts productivity in the two less intensive systems – do the integrated systems present the lower environmental cost (Gil *et al.*, 2018).<br>Methodologies/tools applied (refer to list at bottom of this sheet): 1 |
| T | Moderate levels of shade-tree cover (30 percent) in cocoa agroforestry systems in Ghana were found to have a neutral effect on yields and a positive effect on biodiversity (tree and bird richness), compared with cocoa production in full-sun monoculture. Any further increase in shade-tree cover (up to 80 percent) strongly enhanced biodiversity, albeit at the cost of drastically reduced cocoa yield (and water availability) (Blaser *et al.*, 2018). |
| T | A three-year on-farm experiment compared the effects of conventional, organic and slash-and-mulch agroforestry practices in smallholder maize-bean production systems in a mountainous area of El Salvador. While the effect on individual ecosystem services was quite variable, the sum of all measured composite indicators – erosion control, water regulation, biodiversity, soil composition and carbon storage – showed clear advantages of slash-and-mulch agroforestry practices over conventional and organic practices. However, this environmental advantage came with moderate to substantial yield reductions (depending on the type of agroforestry system). While yield stabilization and increase are expected in the long term, in the short term there is a trade-off (Kearney *et al.*, 2019). |

| Sustainability | Enabling environment |
|---|---|
| Although agroforests have substantially lower biodiversity than natural forests – pointing to an advantage of production intensification combined with land-sparing strategies for biodiversity conservation – in contexts of human-dominated landscapes with limited potential for land sparing, they could still play a crucial role in conserving biodiversity (Blaser *et al.*, 2018). | The reduction of environmental costs through sustainable intensification and land sparing only works if set-aside areas for nature conservation are protected by targeted policies, laws and regulations, such as strict land-use zoning, conditional access to markets and restricted rural subsidies. Otherwise, the profitability of higher-yielding systems is likely to result in increased conversion of natural to agricultural land. Such measures should also be complemented by demand-side interventions in order to counter trends towards overconsumption of calorie-rich but nutrient-deficient foods (Balmford *et al.*, 2018). |

## Methodologies & Tools

1. **Integrated Farm System Model (IFSM):** Whole-farm simulation model to assess productivity, profitability and environmental impacts of different farm configurations. [see page 79]

# Income vs. Social/environmental sustainability

| Objective 1.B | Increasing food producers' incomes | Social and environmental sustainability | Objective 1.C |
|---|---|---|---|

Increases in incomes and/or profitability that are derived from intensification of production are often associated with environmental trade-offs. However, higher incomes are likely to show synergies with poverty reduction and improved food security. Several CSA practices promoted in smallholder crop systems were found to offer synergies between profitability and social and environmental benefits.

## Indicators & *metrics*

**Farm income,** e.g.:

- *Annual income [USD/year]*

**Internal rate of return (IRR):** i.e. the estimate of the profitability of an investment (adoption of a practice or production system) considered over its entire lifetime.

- *IRR [%]*

**Poverty rate:** proportion of the population living under USD 1.25 USD per person per day, e.g.:

- *Proportion of population beneath poverty line [%]*

**Income-based food security (IBFS):** proportion of the population with sufficient income available to purchase a representative food basket, e.g.:

- *Proportion of population food-secure according to IBFS threshold [%]*

**Economic value of social or environmental externalities:** expressed as absolute economic values per hectare for alternative practices, e.g.:

- *Value of change in Biodiversity Index [USD/ha]*
- *Value of carbon sequestered [USD/ha]*
- *Value of avoided soil erosion [USD/ha]*
- *Value of avoided pesticide use [USD/ha]*
- *Value of additional employment opportunities [USD/ha]*

**Water use:** amount of water used per unit area, product unit or food nutrient unit, e.g.:

- *Tonnes of water per hectare [t/ha]*
- *Tonnes of water per kg of human-digestible protein [t/kg HDP]*

**Energy use:** amount of energy used per unit area, product unit or food nutrient unit, e.g.:

- *Terajoule per hectare [TJ/ha]*
- *Megajoule per kg of human-digestible protein [MJ/kg HDP]*

**Loss of reactive nitrogen:** amount of nitrogen (N) in reactive forms lost per unit area, product unit or food nutrient unit, e.g.:

- *Reactive N lost per hectare [kg N/ha]*
- *Reactive N lost per kg of human-digestible protein [kg N/kg HDP]*

## Examples

S

The adoption of improved cattle feeding practices in smallholder livestock systems in Lushoto district, Tanzania, is expected to be economically viable for the majority of households in the study area and lead to higher incomes, as well as reduced poverty rates and improved food security among the modeled farm population within the district (Shikuku *et al.*, 2017).

Methodologies/tools applied (refer to list at bottom of this sheet): 1, 2

A cost-benefit analysis – including costs of environmental and social externalities – was used to assess the performance of eight CSA practices being promoted among farmers operating maize/bean production systems in the Dry Corridor of Guatemala. Synergies between profitability and positive externalities – including biodiversity, carbon sequestration, prevention of soil and water contamination and employment opportunities – were found for all practices except stone barriers, which turned out to be non-profitable, despite positive externalities (Sain *et al*., 2017).

In a farm simulation of medium and large beef cattle farms in the state of Mato Grosso, Brazil, integrated crop-livestock systems (soybean-beef cattle) show higher productivity and incomes, compared with pure livestock systems (extensive or rotational grazing). However, this scenario also presents the highest environmental cost per hectare (energy use, water use and nitrogen losses), which is mainly attributed to the higher cattle stocking rate. Only if calculated per unit of production (human-digestible protein) and under extreme climate change (RCP 8.5) – which disproportionately impacts productivity in the two less intensive systems – do the integrated systems present the lower environmental cost (Gil *et al*., 2018).

Methodologies/tools applied (refer to list at bottom of this sheet): 3

## Methodologies & Tools

1. **RUMINANT model:** Dynamic estimation of methane ($CH_4$) emissions based on livestock diet. Static estimation of livestock growth and milk yield. [see page 80]
2. **Trade-off Analysis for Multi-Dimensional Impact Assessment (TOA-MD) model:** Parsimonious model (minimal input data) that predicts adoption rate of alternative options (compared with baseline) based on greatest expected economic benefit. [see page 76]
3. **Integrated Farm System Model (IFSM):** Whole-farm simulation model to assess productivity, profitability and environmental impacts of different farm configurations. [see page 79]

## A1.5 Synergies and trade-offs within CSA Pillar 2 'Adaptation'

No relationships between objectives within CSA Pillar 2 were identified within the reviewed literature.

## A1.6 Synergies and trade-offs within CSA Pillar 3 'Mitigation'

### Carbon stocks vs. Emissions

| Objective 3.A | Increasing carbon stocks in soils and biomass | Reducing emission intensities of agricultural products | Objective 3.B |
|---|---|---|---|

A potential trade-off between GHG emissions and carbon storage in soils was observed in cropping systems, where declining GHG emissions were associated with a loss of soil carbon (see example below; Weller *et al.*, 2016). Several studies reported global warming potential as an aggregate indicator, some including, others excluding carbon stock changes in soil or biomass. It was not therefore possible to analyse this relationship on a broader basis of studies. Closer assessment would probably also identify synergies between carbon stocks and emission reductions, for example where increased soil organic carbon stocks result in higher soil fertility, thereby reducing the need for external inputs such as fertilizers and their associated GHG footprint.

#### Indicators & *metrics*

**Soil organic carbon stock change,** e.g.:

- *Megagrams (= tonnes) of carbon (C) per hectare [Mt C/ha]*

**Global warming potential:** expressed as emissions of carbon dioxide equivalent ($CO_2$eq) e.g. per unit area:

- *Kilograms of $CO_2$eq per hectare [kg $CO_2$eq/ha]*

#### Examples

T

Field experiments comparing the traditional double paddy rice cropping system with diversified cropping systems (wet season: paddy rice; dry season: maize or aerobic rice) in the Philippines showed that, while the diversified systems reduced the overall global warming potential of the system, the soil carbon stocks in the paddy rice-maize system diminished over the course of three years. In the medium to long term, this presents a trade-off, not only with carbon storage, but also with soil fertility, possibly affecting yields and incomes. The diversified rotations also required significantly less irrigation water at relatively stable average annual grain yields – although there was a tendency for higher yields in the paddy rice-maize rotation and for lower yields in the paddy rice-aerobic rice rotation, compared with the traditional system – which qualifies the rotation systems as possible drought adaptation strategies (Weller *et al.*, 2016).

## Carbon stocks vs. Renewables

| Objective 3.A | Increasing carbon stocks in soils and biomass | Replacing fossil fuels with renewable energies | Objective 3.C |
|---|---|---|---|

As far as bioenergy is concerned, synergies between increasing provision of renewable energy – and replacing fossil fuels – and increasing carbon stocks is possible at global scale. However, this assessment is based on assumptions of a sustainable development pathway, including the effective conservation and restoration of carbon-rich natural habitats.

### Indicators & *metrics*

**Land-use change emissions:** expressed as annual net carbon dioxide ($CO_2$) emissions from carbon stock changes in land-use systems globally:

- *Tonnes of $CO_2$ per year [t $CO_2$/year]*

**Biomass production:** annual global production of energy crops for bioenergy and biochemicals, expressed as energy content:

- *Exajoule per year [EJ/year]*

### Examples

S

Global long-term projections of biomass production and use for bioenergy show that bioenergy can constitute an important element in climate change mitigation efforts aimed at reaching the goals of the Paris Agreement – i.e. limiting global warming to 2.0 °C or even 1.5 °C. It is estimated that an increase in biomass supply – mainly from production on abandoned agricultural land, as well as from natural habitats and agricultural residues and, in particular, for production of second generation biofuels – could meet up to 50 percent of global energy demand by 2100, while emissions from land-use change would decrease and, after 2050, become negative. This means that the objectives of replacing fossil energy with bioenergy and increasing carbon stocks in soils and biomass can potentially be achieved in synergy. It is important to note that these projections are based on sustainable development pathways, specifically Shared Socioeconomic Pathways 1 and 2, which assume a 'food-first' principle, strict implementation of carbon stock conservation and restoration in natural habitats, behaviour change towards more sustainable consumption, and technological advances that lead to higher yields and efficiency in food and biomass production (Daioglou *et al*., 2019).[11]

[11] The Shared Socioeconomic Pathways are a set of five alternative scenarios that describe possible futures of socioeconomic development and provide baseline assumptions for climate change projections presented by the IPCC.

## Emissions vs. Renewables

| Objective 3.B | Reducing emission intensities of agricultural products | Replacing fossil fuels with renewable energies | Objective 3.C |
| --- | --- | --- | --- |

Bioenergy production from agricultural biomass presents a potential trade-off between emission reductions and increased provision of renewable energy. If low GHG emission intensities in biomass production systems are associated with low-input agriculture and low yields, this will also limit the amount of bioenergy that can be produced from the biomass. Increasing biomass productivity, and hence the bioenergy yield, will also raise GHG emission intensities..

### Indicators & *metrics*

**GHG emission intensity:** GHG emissions per unit of production, e.g.:

- *Kilograms of carbon dioxide equivalent ($CO_2$eq) per energy unit of biogas vehicle fuel (megajoule) [kg $CO_2$eq/MJ]*

**Biogas feedstock productivity:** yield of biomass for biogas production per unit area, e.g.:

- *Tonnes of biomass dry matter per hectare [t/ha]*

### Examples

The cultivation of perennial legume-grass mixtures (species-poor and species-rich) as a feedstock for biogas vehicle fuel production on marginal soils in Sweden showed that biogas produced from unfertilized fields had consistently lower GHG emission intensity per energy unit than that from fields with fertilized treatments. However, the overall yield of biomass – and hence biogas – per hectare was also lower (Carlsson *et al*., 2017).

### Sustainability

Perennial legume-grass mixtures with low nitrogen fertilizer inputs provide high and stable biomass production at a low risk of nitrogen loss to the environment.

# Annex 2

## Summary of indicators by CSA objectives

**Table A2.1: Summary of indicators by CSA objectives, as reported in the characterization sheets in Annex 1**

In addition to the indicator name, the table provides explanations (Indicator specifications); examples of metrics (Metrics); the scale of application as reported in the reviewed literature (Application scale); examples of ex-ante assessment methodologies and tools that use a given indicator – insofar as available in the menu of tools and methodologies in Annex 3 – with reference to the related section in Annex 3 (Methodology/tool); examples of studies that use a given indicator (Examples); and the list of CSA objectives that a given indicator is compared to in the reviewed literature – using the alphanumerical codes provided in Table 1, p. 6 (CSA objectives).

| Indicator | Indicator specifications | Metrics | Application scale | Methodology/ tool | Examples | CSA objectives |
|---|---|---|---|---|---|---|
| **1.A – Productivity** | | | | | | |
| Yield (crop) | *Expressed as amount of crop product harvested per unit area, e.g. wheat grain or biomass dry matter* | • Tonnes per hectare [t/ha] | Field | APSIM (A3.4.1) | Aryal *et al.* (2016)<br>Blaser *et al.* (2018)<br>Carlsson *et al.* (2017)<br>Haughey *et al.* (2018)<br>Hochman *et al.* (2017)<br>Hofer *et al.* (2016)<br>Huang *et al.* (2018)<br>Isbell *et al.* (2017)<br>Jat *et al.* (2020)<br>Sapkota *et al.* (2017)<br>Thierfelder *et al.* (2015) | 1.B, 1.C, 2.B, 2.C, 3.B |
| Yield (livestock) | *Expressed as amount of livestock product per livestock unit in a given time period* | • Litres of milk per cow and day [L/d] | Farm | RUMINANT model (A3.5.2) | Shikuku *et al.* (2017) | 3.B |
| Yield (nutrients, calories) | *Expressed as amount of human-digestible protein (HDP) and food energy content produced per unit area* | • Kilograms of HDP per hectare [kg HDP/ha]<br>• Megacalories of food energy per hectare [Mcal/ha] | Field/Farm | IFSM (A3.4.2) | Gil *et al.* (2018) | 1.B, 1.C, 2.A, 3.B |
| Land cost | *The inverse of crop yield, i.e. units of land required during one year for the production of one product unit* | • Hectare-years per tonne of grain [ha-years/t]<br>• Hectare-years per tonne of carcass weight [ha-years/t] | Farm | | Balmford *et al.* (2018) | 1.C, 3.B |
| Irrigation water productivity | *Expressed as gross margin/net revenue per unit of irrigation water* | • Net revenue in Indian rupees (INR) per millilitre of irrigation water [INR/ml] | Farm | APSIM (A3.4.1) | Hochman *et al.* (2017) | 2.B |
| Partial factor productivity | *Product per unit of one specific input factor, such as fertilizer, e.g. nitrogen (N) or phosphorous oxide ($P_2O_5$)* | • Kilograms of grain per kg of N [kg/kg N]<br>• Kilograms of grain per kg of $P_2O_5$ [kg/kg $P_2O_5$ ] | Field | | Sapkota *et al.* (2014) | 3.B |
| Land productivity | *Expressed as total revenues from agricultural produce per unit area of cultivated land* | • Revenue per hectare [USD/ha] | Farm | | Rosset *et al.* (2011) | 2.C |
| Labour productivity | *Expressed as total revenues from agricultural produce per unit of labour, e.g. per farm worker* | • Revenue per farm worker [USD/worker] | Farm | | Rosset *et al.* (2011) | 2.C |
| Daily dietary energy production | *Food energy that can be provisioned by agriculture per capita and day for a given geographical region* | • Kilocalories per capita per day [kcal/capita/day] | Region | | Lee *et al.* (2019) | 3.A |

| Indicator | Indicator specifications | Metrics | Application scale | Methodology/tool | Examples | CSA objectives |
|---|---|---|---|---|---|---|
| **1.B – Income** | | | | | | |
| Gross margin/Net income/ Net revenue | *Expressed as net revenue, i.e. income from sale of produce minus production costs, either referred to one specific farm product or for the entire farm enterprise* | • Net revenue per hectare [USD/ha]<br>• Net income per farm [USD/farm] | Field/Farm | IFSM (A3.4.2)<br>TOA-MD (A3.2.1)<br>APSIM (A3.4.1) | Aryal *et al.* (2015)<br>Gil *et al.* (2018)<br>Jat *et al.* (2020)<br>Hochman *et al.* (2017)<br>Paul *et al.* (2019)<br>Shikuku *et al.* (2017)<br>Thierfelder *et al.* (2015)<br>Tuong *et al.* (2018) | 1.A, 1.B, 1.C, 2.A, 2.B, 3.B |
| Returns on family labour | *Expressed as net income per unit of family labour* | • Net revenue per person per day [USD/person-day] | Farm | - | Tuong *et al.* (2018) | 2.B |
| Returns on labour | *Expressed as the ratio of gross margin to labour cost* | • Gross margin-labour cost ratio | Field | - | Thierfelder *et al.* (2015) | 1.A |
| Benefit-cost ratio | *Ratio of gross income and total production cost* | • Gross income-production cost ratio | Farm | CBA (A3.1) | Aryal *et al.* (2015)<br>Kiwia *et al.* (2019) | 2.B, 3.B |
| Returns on investment | *Expressed as ratio of gross margin to variable production costs* | • Gross margin-variable production costs ratio | Field | - | Thierfelder *et al.* (2015) | 1.A |
| Marginal rate of return | *Ratio of differences in marginal net returns and marginal costs between two alternative systems* | • Marginal net returns-marginal costs ratio | Farm | CBA (A3.1) | Kiwia *et al.* (2019) | 2.B |
| Net present value (NPV) | *Incremental flow of net benefits generated by the alternatives being compared over their lifecycle* | • NPV | Farm | CBA (A3.1) | Kiwia *et al.* (2019) | 2.B |
| Internal rate of return (IRR) | *Estimate of the profitability of an investment (adoption of a practice or production system) considered over its entire lifetime* | • IRR [%] | Farm | CBA (A3.1) | Sain *et al.* (2017) | 1.C |
| Impact of extreme climate events on farm income | *Expressed as share of harvest lost or as net revenue (profit or loss) derived from crops, calculated based on pre-impact market prices of the extreme event (e.g. hurricane)* | • Net revenue per hectare [USD/ha]<br>Share of harvest lost [%] | Farm | - | Holt-Giménez (2002)<br>Philpott *et al.* (2008) | 2.C |
| Additional crop value | *Income advantage of an agro-ecological production system over a conventional system, derived from yield difference and market price* | • Economic value (currency) per hectare [USD/ha] | Field/Farm | - | Aryal *et al.* (2016) | 2.C |
| Opportunity cost of carbon conservation and/or sequestration | *Value of forgone income opportunities, e.g. agricultural and charcoal production, expressed as net present value* | • Net present value per hectare [USD/ha] | District | Implementation cost approach (A3.1.2) | Fisher *et al.* (2011) | 3.A |

| Indicator | Indicator specifications | Metrics | Application scale | Methodology/tool | Examples | CSA objectives |
|---|---|---|---|---|---|---|
| **1.C – Social/environmental sustainability** | | | | | | |
| Food security | *Expressed as probability of a household to reduce meals, following livelihood impacts such as a drought* | • Percentage of households [%] | Households in a community, district, etc. | - | Janzen and Carter (2019) | 2.A |
| Food security | *Expressed as provision of basic caloric needs per person per day in a given geographical area, e.g. a community* | • Kilocalories available per person per day [kcal/person/day] | Community | - | Palm *et al.* (2010) | 3.A |
| Food availability | *Expressed as the calories available per family member, where household size is quantified in terms of male adult equivalents, based on the energy requirements of each household member by gender and age* | • Kilocalories per person per day [kcal/person/day] | Household | - | Paul *et al.* (2018) | 3.B |
| Income-based food security (IBFS) | *Proportion of the population with sufficient income available to purchase a representative food basket* | • Proportion of population food-secure according to IBFS threshold [%] | District | TOA-MD (A3.2.1) | Shikuku *et al.* (2017) | 1.B, 3.B |
| Poverty rate | *Proportion of the population living under USD 1.25 per person per day* | • Proportion of population beneath poverty line [%] | District | TOA-MD (A3.2.1) | Shikuku *et al.* (2017) | 1.B, 3.B |
| Economic security | *Expressed as average household income at the river basin scale* | • Annual household income [USD/y] | Households in a river basin | Nexus Webs (A3.3.1) | Colloff *et al.* (2019) | 2.B |
| Natural food, fuel and materials | *Economic value of foods, fuels and materials collected from natural habitats at the river basin scale* | • Economic value [USD] | River basin | Nexus Webs (A3.3.1) | Colloff *et al.* (2019) | 2.B |
| Economic value of social or environmental externalities | *Expressed as absolute economic values per hectare for alternative practices* | • Value of change in Biodiversity Index [USD/ha]<br>• Value of carbon sequestered [USD/ha]<br>• Value of avoided soil erosion [USD/ha]<br>• Value of avoided pesticide use [USD/ha]<br>• Value of additional employment opportunities [USD/ha] | District | CBA (A3.1) | Sain *et al.* (2017) | 1.B |
| Environmental security | *Composite index representing ecosystem services and river health at the river basin scale, on a scale from 0 to 1* | • Environmental security score | River basin | Nexus Webs (A3.3.1) | Colloff *et al.* (2019) | 2.B |
| Soil loss | *Expressed as the amount of soil eroded per unit of product* | • Kilograms of soil per tonne of energy-corrected milk (ECM) [kg/t] | Field | - | Balmford *et al.* (2018) | 1.A |
| Loss of reactive nitrogen | *Nitrogen (N) lost from the production system to the environment, per unit area or per unit of product* | • Kilograms of N per hectare [kg N/ha]<br>• Kilograms of N per human-digestible protein [kg N/kg HDP] | Farm | IFSM (A3.4.2) | Gil *et al.* (2018) | 1.A, 1.B, 2.A, 3.B |
| Nitrate and phosphorous leaching | *Expressed as amount of total nitrogen (N) or phosphorous (P) leached beyond the root zone per hectare or per unit of product during the cropping season* | • Kilograms of N leached per hectare [kg N/ha]<br>• Kilograms of N leached per tonne of wheat [kg N/kg]<br>• Kilograms of P leached per tonne of energy-corrected milk (ECM) [kg P/kg] | Field/Farm | APSIM (A3.4.1) | Hochman *et al.* (2017)<br>Balmford *et al.* (2018) | 1.A, 2.B |

| Indicator | Indicator specifications | Metrics | Application scale | Methodology/tool | Examples | CSA objectives |
|---|---|---|---|---|---|---|
| Water use/Water cost | *Amount of water used for on-farm production activities, per unit area or per unit of product* | • Tonnes of water per hectare [t/ha]<br>• Tonnes of water per HDP [t/kg HDP]<br>• Cubic metres of water per tonne of rice [$m^3$/t] | Farm | IFSM (A3.4.2) | Gil *et al.* (2018)<br>Balmford *et al.* (2018) | 1.A, 1.B, 2.A, 3.B |
| Water use | *Expressed as cumulative irrigation depth over the cropping season* | • Irrigation water depth in millimetres [mm] | Farm | APSIM (A3.4.1) | Hochman *et al.* (2017) | 2.B |
| Groundwater recharge | *Expressed as cumulative amount of deep percolation over the cropping season* | • Percolation water depth in millimetres [mm] | Farm | APSIM (A3.4.1) | Hochman *et al.* (2017) | 2.B |
| Change in surface runoff | *As an indication of changes in the hydrology of a watershed/river basin affecting environmental flows and water availability for downstream water users and ecosystems* | • Absolute change in runoff expressed as water depth [mm]<br>• Relative change in runoff [%] | Watershed/ River basin | Thornthwaite-Mather water balance modeling approach (A3.6.1) | Trabucco *et al.* (2008) | 3.A |
| Energy use | *Amount of energy used for on-farm production activities, per unit area or per unit of product* | • Terajoule per hectare [TJ/ha]<br>• Megajoule per HDP [MJ/kg HDP] | Farm | IFSM (A3.4.2) | Gil *et al.* (2018) | 1.A, 1.B, 2.A, 3.B |
| Biodiversity | *Relative difference in biodiversity indicators between agro-ecological practices and conventional practices* | • Relative difference in tree richness [%]<br>• Relative difference in bird richness [%] | Field | - | Blaser *et al.* (2018) | 1.A, 2.C, 3.A |
| **2.A – Livelihood resilience** | | | | | | |
| Income stability | *Expressed as farm income, i.e. net revenues from sale of agricultural produce, of alternative farm systems under different climate change scenarios* | • Net revenue per hectare [USD/ha] | Field/Farm | IFSM (A3.4.2) | Gil *et al.* (2018) | 1.A, 1.B, 1.C, 3.B |
| Probability of selling productive assets | *Expressed as probability of a household selling productive assets, following livelihood impacts such as drought* | • Percentage of households [%] | Households in a community, district, etc. | - | Janzen and Carter (2019) | 1.C |
| **2.B – Production system adaptation** | | | | | | |
| Yield stability | *Expressed as coefficient of variation (CV), i.e. standard deviation divided by the mean, of a time series of observed or simulated crop yields. It can be expressed as a ratio or percentage, with low values indicating high stability* | • CV of crop yields over a given period of time [%] | Field/Farm | APSIM (A3.4.1) | Hochman *et al.* (2017)<br>Kiwia *et al.* (2019) | 1.A, 1.B, 1.C, 3.B |
| Income stability | *Expressed as percentage deviation from yields in a normal year* | • Yield deviation [%] | Farm | - | Tuong *et al.* (2018) | 1.B |
| Annual farm nitrogen balance | *Net balance of nitrogen imports and exports* | • Nitrogen (N) balance per farm [kg N/farm] | Farm | - | Paul *et al.* (2019) | 1.B, 3.B |
| Irrigated area | *Depending on water allocation for climate change adaption at the river basin scale* | • Hectares of cropland under irrigation [ha] | River basin | Nexus Webs (A3.3.1) | Colloff *et al.* (2019) | 1.C, 3.C |

| Indicator | Indicator specifications | Metrics | Application scale | Methodology/tool | Examples | CSA objectives |
|---|---|---|---|---|---|---|
| Water available for irrigation | *Depending on water allocation for climate change adaption at the river basin scale* | • Cubic metres of water allocated to irrigation [$m^3$] | River basin | Nexus Webs (A3.3.1) | Colloff *et al.* (2019) | 1.C, 3.C |
| Irrigation water use | *As an indicator of improved efficiency in the use of water resources for irrigation* | • Irrigation water depth applied per year [mm/year] | Field | - | Weller *et al.* (2016) | 3.A, 3.B |
| Change in surface runoff | *As an indication of changes in the hydrology of a watershed/river basin affecting water-dependent adaptation options, specifically irrigation, for downstream populations* | • Absolute change in runoff expressed as water depth [mm]<br>• Relative change in runoff [%] | Watershed/River basin | Thornthwaite-Mather water balance modeling approach (A3.6.1) | Trabucco *et al.* (2008) | 3.A |
| **2.C – Agro-ecosystem resilience** | | | | | | |
| Initial damage | *Damage to standing crops estimated immediately after extreme event* | • Percent of production value lost [%] | Field/Farm | - | Rosset *et al.* (2011) | 1.A |
| Yield penalty | *Change in crop yield compared with normal year (baseline), e.g. caused by untimely excessive rainfall* | • Yield reduction compared with normal year [%] | Field/Farm | - | Aryal *et al.* (2016) | 1.A, 1.B |
| Recovery of productive potential | *60/120/180 days after extreme event* | • Percentage of productive potential [%] | Farm | - | Rosset *et al.* (2011) | 1.A |
| Stability index | *Expressed as the ratio of mean value of a series of yield measurements (over a range of environmental variation in space and/or time) to the standard deviation of yields (inverse of the coefficient of variation)* | • (dimensionless) | Farm | - | Isbell *et al.* (2017) | 1.A |
| Impact of extreme climate events on agro-ecosystem | *Impact of a hurricane on soil resources on conventional farms vs. adopters of agro-ecological practices* | • Depth of topsoil [cm]<br>• Depth to moist soil [cm]<br>• Vegetation cover [%]<br>• Area affected by rill erosion [$m^2$/ha]<br>• Volume of gully erosion [$m^3$/ha]<br>• Area affected by landslides [$m^2$/ha] | Farm | - | Holt-Giménez (2002)<br>Philpott *et al.* (2008) | 1.B |
| Dry season maximum temperature | *Relative difference of the above-canopy temperature between agro-ecological and conventional practices, e.g. above-cocoa canopy in agroforestry vs. conventional system* | • Relative difference in dry season maximum temperature [%] | Field | - | Blaser *et al.* (2018) | 1.C, 3.A |
| Dry season soil moisture | *Relative difference of soil moisture between agro-ecological and conventional practices* | • Relative difference in dry season soil moisture [%] | Field | - | Blaser *et al.* (2018) | 1.C, 3.A |
| Change in surface runoff | *As an indication of changes in the hydrology of a watershed/river basin affecting water availability and flooding risks in agro-ecosystems* | • Absolute change in runoff expressed as water depth [mm]<br>• Relative change in runoff [%] | Watershed/River basin | Thornthwaite-Mather water balance modeling approach (A3.6.1) | Trabucco *et al.* (2008) | 3.A |

| Indicator | Indicator specifications | Metrics | Application scale | Methodology/tool | Examples | CSA objectives |
|---|---|---|---|---|---|---|
| **3.A – Carbon stocks** | | | | | | |
| Forest area size/ Area re/ afforested | *As an indication of carbon sequestration and/or conservation in forests in a given geographical region* | • Hectares of forested/afforested/reforested land [ha] | Region/ Watershed/ River basin | - | Lee *et al.* (2019)<br>Trabucco *et al.* (2008) | 1.A, 1.C, 2.B, 2.C |
| Carbon conservation and/or sequestration potential | *Net amount of avoided carbon emissions from avoided deforestation or forest degradation, or carbon sequestered through re/afforestation and ecosystem restoration* | • Tonnes of carbon (C) per hectare [t C/ha] | District | Implementation cost approach (A3.1.2) | Fisher *et al.* (2011) | 1.B |
| Carbon dioxide emissions avoided/ GHG mitigation potential | *Amount of carbon dioxide ($CO_2$) emissions avoided through conservation of forest land and prevention of forest degradation or conversion to agricultural land, e.g. under REDD+ projects* | • Tonnes of $CO_2$ per hectare [t $CO_2$/ha] | District/ Community | - | Chomba *et al.* (2016)<br>Palm *et al.* (2010) | 1.C |
| Carbon stock | *Relative difference in carbon stocks in above-ground biomass and soil between alternative practices, e.g. agroforestry vs. conventional crop system* | • Relative difference in above-ground tree biomass carbon stock [%]<br>• Relative difference in carbon stock [%] | Field | - | Blaser *et al.* (2018) | 1.C, 2.C |
| Soil organic carbon stock change | *Expressed as the change in the amount of carbon stored in soil organic matter as a consequence of a change in practices in cropping systems* | • Megagrams (= tonnes) of carbon (C) per hectare [Mt C/ha] | Field | - | Weller *et al.* (2016) | 2.B, 3.B |
| Land-use change emissions | *Expressed as annual net carbon dioxide ($CO_2$) emissions from carbon stock changes in land-use systems globally* | • Tonnes of $CO_2$ per year [t $CO_2$/year] | Global | - | Daioglou *et al.* (2019) | 3.C |
| **3.B – Emissions** | | | | | | |
| GHG emission intensity (product) | *GHG emissions per product unit. Emissions are either assessed for one GHG of specific interest, e.g. methane ($CH_4$), or for all major GHGs, expressed as global warming potential (GWP) with the unit of carbon dioxide equivalent ($CO_2$eq)* | • Litres of $CH_4$ per litre of milk [L $CH_4$/L]<br>• GWP per tonne of grain yield [kg $CO_2$eq/t]<br>• GWP per energy unit of biogas vehicle fuel (megajoule) [kg $CO_2$eq/MJ] | Field/Farm | Cool Farm Tool (A3.5.1)<br>RUMINANT model (A3.5.2) | Balmford *et al.* (2018)<br>Carlsson *et al.* (2017)<br>Huang *et al.* (2018)<br>Sapkota *et al.* (2014)<br>Sapkota *et al.* (2017)<br>Shikuku *et al.* (2017) | 1.A, 1.B, 1.C, 3.C |
| GHG emission intensity (nutrients, calories) | *GHG emissions per unit of nutrient (e.g. human-digestible protein, HDP) or calorie of food energy* | • GWP per HDP [kg $CO_2$eq/kg HDP] | Field/Farm | IFSM (A3.4.2) | Gil *et al.* (2018) | 1.B, 1.C, 2.A |
| GHG emission intensity (area) | *GHG emissions per unit area* | • GWP per hectare [kg $CO_2$eq/ha] | Field/Farm | Cool Farm Tool (A3.5.1)<br>IFSM (A3.4.2)<br>APSIM (A3.4.1) | Aryal *et al.* (2015)<br>Gil *et al.* (2018)<br>Hochman *et al.* (2017)<br>Sapkota *et al.* (2014)<br>Weller *et al.* (2016) | 1.A, 1.B, 1.C, 2.A, 2.B, 3.A |

| Indicator | Indicator specifications | Metrics | Application scale | Methodology/tool | Examples | CSA objectives |
|---|---|---|---|---|---|---|
| GHG emission intensity (farm household) | *GHG emissions per farm household (HH)* | • GWP per farm household [kg $CO_2$eq/HH] | Farm/ Household | - | Paul *et al.* (2018)<br>Paul *et al.* (2019) | 1.B, 1.C, 2.B |
| GHG emission intensity (gross margin) | *GHG emissions per unit of gross margin* | • GWP per USD of gross margin [kg $CO_2$eq/USD] | Farm | APSIM (A3.4.1) | Hochman *et al.* (2017) | 2.B |
| **3.C – Renewables** | | | | | | |
| Hydroelecric power production | *Production of renewable energy form hydroelectric power plants aggregated over the river basin* | • Total amount of energy production in gigawatt-hours [GWh] | River basin | Nexus Webs (A3.3.1) | Colloff *et al.* (2019) | 2.B |
| Biomass production | *Annual global production of energy crops for bioenergy and biochemicals, expressed as energy content* | • Exajoule per year [EJ/year] | Global | - | Daioglou *et al.* (2019) | 3.A |
| Biogas feedstock productivity | *Yield of biomass for biogas production per unit area* | • Tonnes of biomass dry matter per hectare [t/ha] | Field | - | Carlsson *et al.* (2017) | 3.B |

# Annex 3

## Descriptions of methodologies and tools

# A3.1 Cost-benefit analysis

## A3.1.1 Cost-benefit analysis

Cost-benefit analysis (CBA) is an economic assessment method that compares the profitability of various options for action, such as the adoption of alternative agricultural production systems, over a given time frame (Sain *et al*., 2017). CBA accounts for all relevant (economic) flows of costs and benefits. The most common indicators in CBA are the net present value and internal rate of return. Traditionally, externalities such as impacts of agricultural practices on ecosystem services and labour markets are not included in this type of analysis. By assigning price tags to such externalities, these can be included in CBA and provide an indicator not only of profitability for individual food producers, but also of the costs and benefits to ecosystems and society.

Example of application:

- Expanded cost-benefit analysis for CSA practices in the Dry Corridor of Guatemala (Sain *et al*., 2017)

## A3.1.2 Implementation cost approach (for leakage-free REDD+ projects)

Under a forest conservation scenario, for example in the design of REDD+ projects, the implementation cost approach can be used to estimate the costs of sustainably meeting the demand for food and fuel which would have been met by conversion of forest land to agricultural land under a business-as-usual scenario. The underlying assumption is that conservation of forest land would lead to the displacement of agricultural and other income-generating activities – and associated GHG emissions, so-called 'leakage' – rather than stopping them. In addition to the cost of project management, this approach also includes the implementation of targeted measures to compensate the forgone opportunities of food production and income generation caused by the restriction of access to, use and conversion of forest land. This may include, for example, the cost of capacity-building to increase agricultural productivity on existing agricultural land, or the introduction of efficient technologies that reduce demand for a given resource, such as charcoal for cooking stoves. Based on household survey data, agricultural statistics, vegetation maps and experiences from relevant development projects, the carbon conservation potential and the opportunity cost for an average hectare of forest land are calculated, as well as the implementation cost of compensatory measures for one hectare of forest land. The costs are ultimately converted to costs per tonne of carbon, and thus provide an estimate of a carbon price for leakage-free REDD+ projects.

Example of application:

- Estimating the implementation cost of leakage-free REDD+ projects in eastern Tanzania (Fisher *et al*., 2011)

# A3.2 Trade-off analysis

## A3.2.1 Trade-off Analysis Model for Multi-Dimensional Impact Assessment

The Trade-off Analysis Model for Multi-Dimensional Impact Assessment (TOA-MD) is a parsimonious model, i.e. with minimal input data requirements, that simulates the adoption of specific practices or technologies across a given farm population, based on the highest economic return (Antle, 2011; Shikuku *et al*., 2017). Farm populations are stratified by economic parameters derived from household surveys, each stratum, rather than individual farms, being represented in the model by population statistics. TOA-MD has a flexible structure and can accommodate farm systems including crop, livestock and aquaculture activities, as well as off-farm income. Based on the predicted adoption rates for each stratum, and in combination with auxiliary models and indicators (such as for GHG emissions and food security), the impacts of adopting a given technology on incomes, food security and GHG emissions for the whole farm populations can be assessed, and possible trade-offs between these indicators identified.

Example of application:

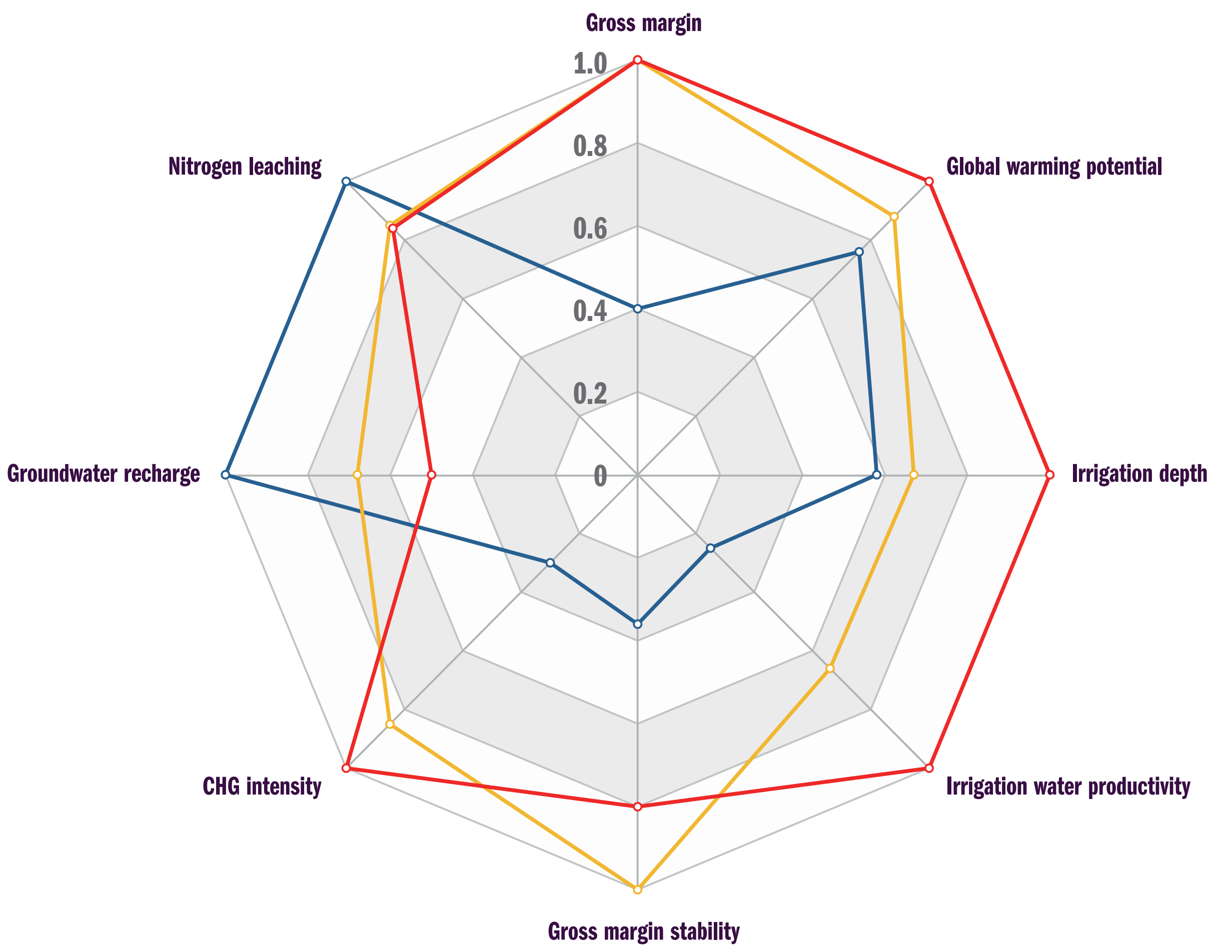
- Dairy production in the United Republic of Tanzania (Shikuku *et al*., 2017)

## A3.2.2 Sustainability polygons

Sustainability polygons are a tool to visualize and evaluate multiple indicators (see Figure 2), thereby enabling the joint assessment of indicators across the CSA pillars, as well as additional sustainability indicators; by comparing baseline with alternative scenarios, the tool makes possible synergies and trade-offs between indicators visible. Each indicator is scaled between 0 (least desirable) and 1 (most desirable), based on the value range of assessed alternatives, and is represented on an axis with 0 at the centre of the plot and 1 at the outside border. The indicator scores of each alternative are connected with lines to form polygons. If one polygon completely encloses another, it means that the corresponding option is more sustainable or climate-smart. If polygon borders overlap, an alternative criterion can be used, i.e. the comparison of the polygon area. The option with the greater polygon area is considered more sustainable. Depending on local priorities, as well as on the value ranges represented by an indicator, weighting of indicators may be required. This is largely subjective and should be validated through stakeholder consultation (Ten Brink, Hosper and Colijn, 1991; in Hochman *et al*., 2017).

Example of application:

- Assessment of adaptation options for rice-based crop rotations in southern India (Hochman *et al*., 2017)




**Performance of a smallscale paddy rice-cotton farm in south India across a set of sustainability indicators under moderate climate scenario for the period 2021-2040. Indicator value 1.0 indicates most desirable, 0.0 least desirable outcome.**

**Current practice:** Irrigated rice (0.8 ha) and rainfed cotton (1.2 ha)

**Adaptation option A:** Reduce irrigated rice area (0.4 ha), increase cotton area (1.6 ha). Improved rules to determine cotton sowing date. Use water saved from rice irrigation to strategically irrigate cotton, with unlimited irrigation applications per season.

**Adaptation option B:** Reduce irrigated rice area (0.2 ha), increase cotton area (1.8 ha). Improved rules to determine cotton sowing date. Use water saved to strategically irrigate cotton, with maximum three irrigation applications per season.

Figure 2: Example of a sustainability polygon comparing a set of indicators across different development scenarios (adapted from Hochman *et al.*, 2017)

# A3.3 Nexus approaches

## A3.3.1 Nexus Webs

Nexus Webs is a conceptual-analytical tool to represent the components and linkages in a river basin (Overton *et al*., 2013). It aims to enable participatory learning on trade-offs and synergies to support inclusive, equitable decision-making on water use and allocation, such as hydropower generation, agriculture and maintenance or restoration of environmental flows. Nexus Webs is based on the water–energy–food nexus and expands it by an explicit environmental dimension. It considers four main river basin components – water use, assets, ecosystem services and well-being – each with several indicators. Indicator values are based on the assessment of a baseline and different water allocation scenarios for the river basin. The indicators are scaled at scores between 0 and 1 for comparability between indicators and components. Visualization through spider web plots – one for each river basin component – makes it possible to identify and put in context linkages across multiple sectors and objectives, including trade-offs and synergies.

Example of application:

- Assessing the social, environmental and economic impacts of water allocation scenarios in the Pangani river basin in northern Tanzania (Colloff *et al*., 2019)

# A3.4 Scenario analysis

## A3.4.1 Agricultural Production Systems sIMulator

The Agricultural Production Systems sIMulator (APSIM) simulates biophysical processes in crop production systems, making it possible to assess the performance of crops under different agro-ecological and climate conditions, as well as management practices (Holzworth *et al*., 2014; Keating *et al*., 2003). It is a platform that features models for a wide range of crop species. Crop performance as well as environmental indicators, including GHG emissions, nitrogen leaching and groundwater recharge, can be simulated for individual crops or multi-field farms. The tool is available at www.apsim.info.

Example of application:

- Assessment of adaptation options for rice-based crop rotations in southern India (Hochman *et al*., 2017)

## A3.4.2 Integrated Farm System Model

The Integrated Farm System Model (IFSM) is a whole-farm simulation model which considers crop and livestock activities at the process level, and interactions between all components (Rotz *et al*., 2018). Available cropping activities in the model include alfalfa, perennial grass, maize, small grain and soybean, as well as pasture production. Livestock activities include beef and dairy cattle. The model requires detailed parameters of farm assets and operations and runs on daily weather data. Simulation results include productivity of each farm component, profitability, and several environmental indicators, including water use, reactive nitrogen loss, energy use and GHG emissions. The latter is based on a partial lifecycle assessment up to the farmgate.

Example of application:

- Assessment of trade-offs of intensification strategies for beef production in Brazil (Gil *et al*., 2018)

### A3.4.3 International Model for Policy Analysis of Agricultural Commodities and Trade

The International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) is a system of models developed by the International Food Policy Research Institute to simulate the behaviour of global agricultural commodity markets and its effects on food prices, food security, land use, GHG emissions and other socio-economic and environmental aspects under different climate change and agricultural production scenarios (Robinson *et al*., 2015). The core of IMPACT is a multi-market partial equilibrium model that is linked to several modules, including climate models, hydrological models, crop simulation models, and land-use models. Model outputs are computed for 320 subnational food production units, which can be aggregated at country, regional or global level.

Example of application:

- Global assessment of the effects of large-scale adoption of CSA practices in maize, wheat and rice production systems on food security and GHG emissions (de Pinto *et al*., 2020)

## A3.5 GHG emissions

### A3.5.1 Cool Farm Tool

The Cool Farm Tool (CFT) is a farm-level decision support tool to estimate GHG emissions from farming systems (Hillier *et al*., 2011). The CFT is open-source software and is based on empirical models of GHG emissions from crop and livestock activities. The tool has low input data requirements, using basic parameters to adapt the models to location-specific conditions. It is available on https://coolfarmtool.org/coolfarmtool.

Example of application:

- Assessment of the effect of precision nutrient management in conservation agriculture-based wheat production systems in northwest India (Sapkota *et al*., 2014)

### A3.5.2 RUMINANT model

RUMINANT is a widely validated model to determine the productivity of and methane ($CH_4$) emissions from livestock production of dairy and beef cattle, sheep and goats. A dynamic model component simulates the enteric fermentation process to estimate $CH_4$ emissions, while a static component predicts the growth of animals and their milk and meat production. Input data required by the model are composition of livestock diet and specifications of animal breeds. The tool can therefore be used to calculate the GHG emission intensity of ruminant livestock products and assess the GHG mitigation potential of changes in livestock diets, for example increasing the share of concentrate feeds, or changes in livestock breeds (Herrero, Fawcett and Jessop, 2002; summarized in Thornton and Herrero, 2010, supporting information).

Examples of application:

- Dairy production in the United Republic of Tanzania (Shikuku *et al*., 2017)
- Beef production in Brazil (Balmford *et al*., 2018)

# A3.6 Natural resources and ecosystem services

## A3.6.1 Thornthwaite-Mather water balance modeling approach

The Thornthwaite-Mather water balance model is a spatially distributed approach to examining the impacts of land-use changes on actual evapotranspiration, soil water content and surface runoff. The model can be implemented in geospatial information systems and requires spatially explicit input data on monthly precipitation, monthly potential evapotranspiration, land-use classes, soil water holding capacity and soil depth (Trabucco *et al*., 2008). The further assessment of localized hydrological impacts of afforestation/reforestation projects requires a digital elevation model and information on growth characteristics of the tree species utilized.

Example of application:

- Impact of afforestation/reforestation on the hydrological system (Trabucco *et al*., 2008)

# Synergies and trade-off in climate-smart agriculture

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