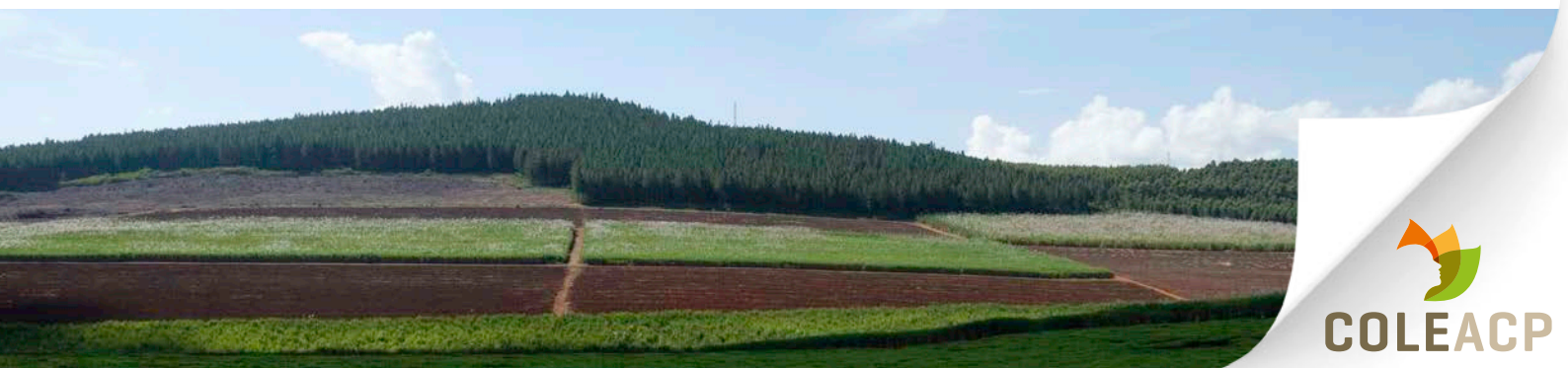




TRAINING --- MANUAL

- ENVIRONMENTAL MANAGEMENT -

SUSTAINABLE AIR QUALITY MANAGEMENT



COLEACP

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Training objectives:

From this chapter, the trainee will be able to:

- Know the definition of air pollution
- Identify the main air pollutant types
- Understand the challenges of air pollution
- Know the composition of the atmosphere and its layers
- Understand the impact of air pollution on health, the environment and agriculture.
- Know the role of major international agreements and the legal framework for air quality, emissions and limit values.

1. INTRODUCTION

According to the WHO¹, air pollution is “contamination of the indoor or outdoor environment by any chemical, physical or biological agent that modifies the natural characteristics of the atmosphere.” The pollutants at issue are gases or particles that **originate from natural** (e.g. forest fires) **or anthropogenic sources**. The primary causes of air pollution involve the burning of **fossil fuels** (coal, oil and gas) by humans. Road transportation, industries, the housing industry and **agriculture** count among the principal creators of air pollution. Agriculture also shares some of the responsibility for the presence of **greenhouse gases** and **particulate matter** in the atmosphere. Ambient air pollution, however, in turn impacts agriculture and the healthiness of its products (presence, via atmospheric deposition on plants and land surfaces, of toxic compounds such as heavy metals, dioxins, polycyclic aromatic compounds or PAHs).

1

For complete information, see the WHO website at: [https://www.who.int/fr/news-room/fact-sheets/detail/ambient-\(outdoor\)-air-quality-and-health](https://www.who.int/fr/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health)

The **air pollution** we breathe is a major problem for today's society. It has an **impact on health and the environment** and, therefore, has **significant economic repercussions**. Exposure to particulate matter (PM) and various gases **affects human health**. The most harmful pollutants to public health are, chiefly, carbon monoxide (CO), ozone gas (O₃), nitrogen dioxide (NO₂), sulphur dioxide (SO₂), persistent organic pollutants (POPs) and 'pesticides' in the air. Air pollution has many effects on health because the pollutants responsible for the pollution are also highly varied. According to the WHO, "both outdoor and indoor air pollution can lead to potentially deadly respiratory diseases, among other diseases." Furthermore, air pollution interferes with the health of natural ecosystems and production in agricultural and silvicultural systems.

Emissions, transport, transformation, deposits: air pollution is **the product of a collection of complex phenomena**. **The development of policies and recommendations** on air quality management and for reduction strategies **requires a qualitative and quantitative assessment of each of these sources' contributions** to the concentrations observed in the air.

As in other business sectors, the various players of the **agricultural sector** must develop **realistic solutions to limit emissions and the effects of air contamination...** and apply them as soon as possible. To do so, knowledge about the atmosphere (its composition, its regulating mechanisms), air pollution (types, concentrations, effects) and the sources of pollution, **from the local scale up to the international scale**, must be shared between players. This is required to implement solutions adapted to local economic conditions and to each scale (e.g. from the farm to the country and international agreements).

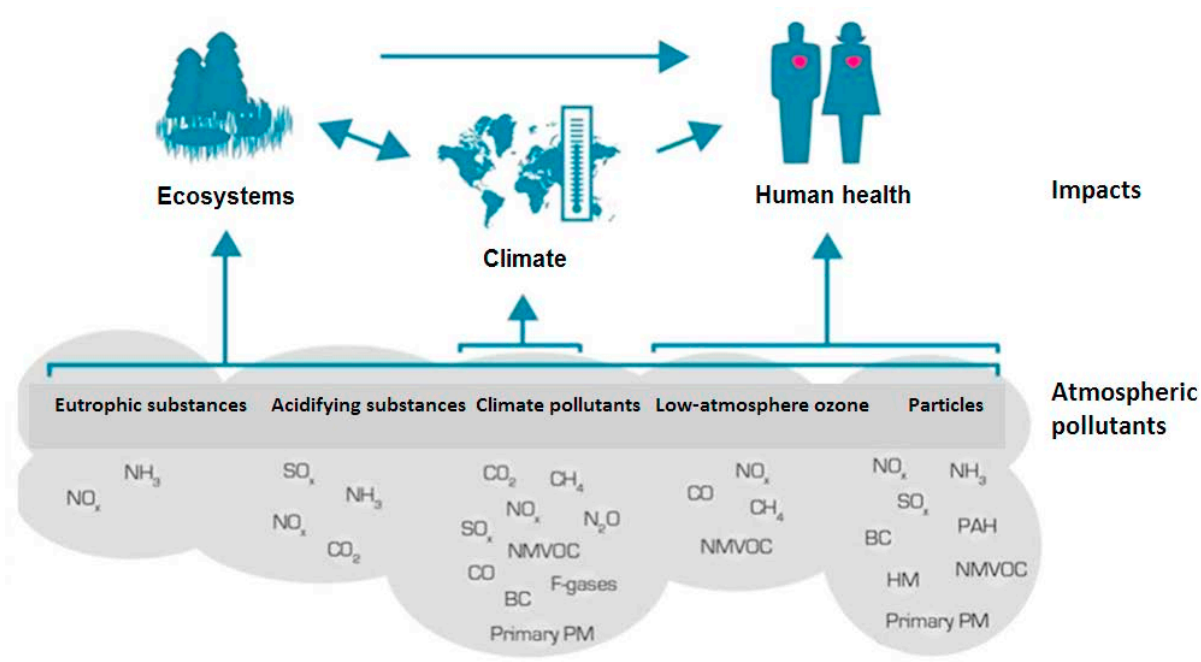


Figure 1 - Atmospheric pollutants and observed impacts

2. AIR COMPOSITION AND QUALITY

To better understand the role of agriculture in atmospheric pollutant emissions, such as how **agricultural inputs** (fertilisers and phytopharmaceutical products) can act as atmospheric pollutants, we must first briefly discuss the layers of the atmosphere, which will allow us to define the factors behind the dispersal of these pollutants in the atmosphere then cover the forms these atmospheric pollutants can take.

2.1. Structure and composition of the atmosphere

The atmosphere is a roughly 700 km thick gaseous envelope that is held around our rotating planet by gravity. Its pressure decreases at greater altitudes (100 times lower at an altitude of 30 km and a million times lower at 100 km). Temperatures are vertically distributed.

The atmosphere can be schematically divided into **4 zones**, according to altitude:

- the troposphere (lowest layer, altitude of 8 to 16 km)
- the stratosphere (up to an altitude of 48 km)
- the mesosphere (up to an altitude of 80 km)
- the thermosphere (highest layer, up to an altitude of 700 km)

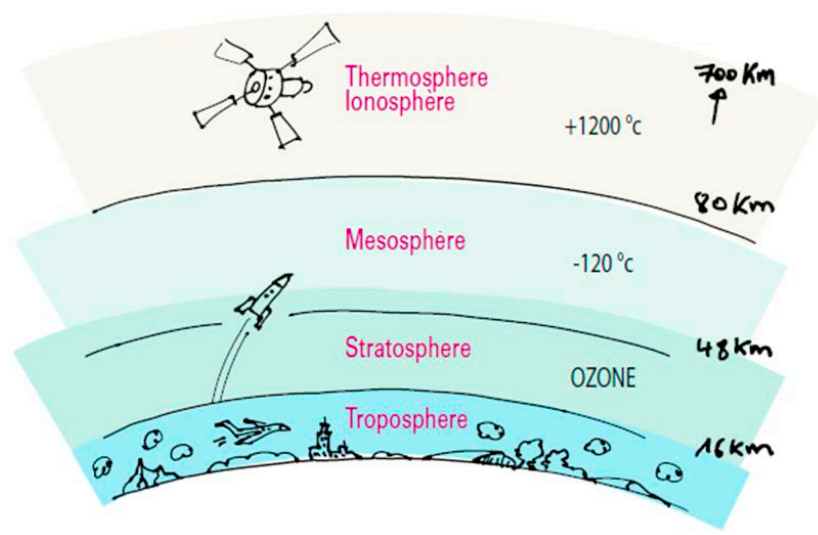


Figure 2 - Vertical stratification of the atmosphere

Atmospheric matter occurs in gaseous and condensed states (liquid water, snow, aerosols, etc.). The percentages of nitrogen, oxygen and argon are constant throughout the atmosphere, whereas the percentages of water, carbon dioxide, sulphur dioxide and ozone vary with altitude. The **troposphere** contains up to 80% of the atmosphere's mass. Its temperature decreases by 6.5°C per kilometre. It is composed primarily of nitrogen (78%), oxygen (21%) and nearly all of the water vapour in the atmosphere. In the stratosphere, the temperature is constant at first, but then increases with altitude due to the absorption of solar UV rays by ozone (O₃) and molecular oxygen (O₂). This increase in temperature greatly prevents air convection. As a result, most climatic phenomena (storm-bearing clouds, cumulonimbus, etc.) are confined to the troposphere. Generally speaking, the **Earth's climate** depends heavily on the interplay between the Sun's heat and the atmosphere as a whole. **Meteorology and climatology** are specifically interested in the events which occur in the lowest layer, the troposphere.

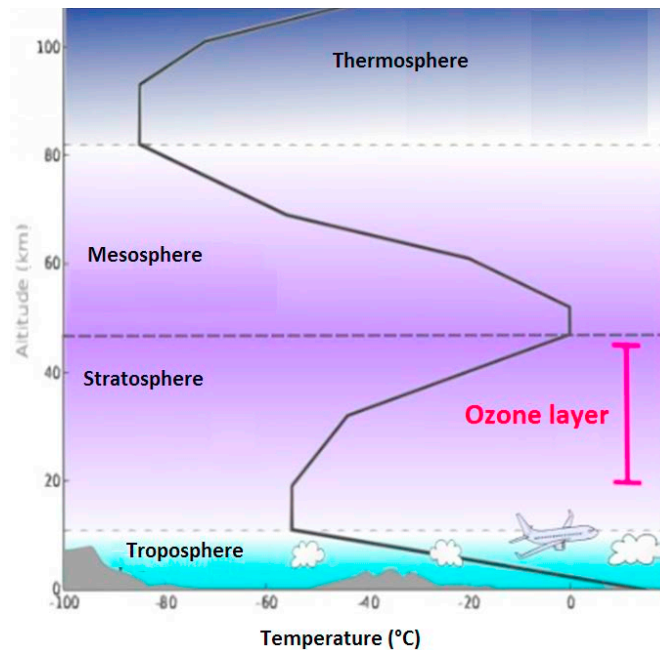


Figure 3 – Temperature variations in the layers of the atmosphere

The troposphere is therefore the most turbulent layer. **It is** constantly disturbed by vertical and horizontal movements. Vertical turbulence is due to the proximity of the Earth's surface, which generates both **mechanical updrafts** (due to friction between air masses and obstacles on Earth's surface) and **thermal updrafts** (air currents, due to instability and thermal convection). **These phenomena explain why pollutants** (such as pesticides sprayed on a plot of crops) **can be dispersed vertically into the atmosphere, then travel long distances!**

The layer of the atmosphere of greatest interest to us is the section of the troposphere which extends up to an average altitude of 1 km, called the '**Atmospheric Boundary Layer**' (ABL). It is **directly affected by the Earth's surface** (landmasses, oceans, lakes, etc.), **on the diurnal scale**.

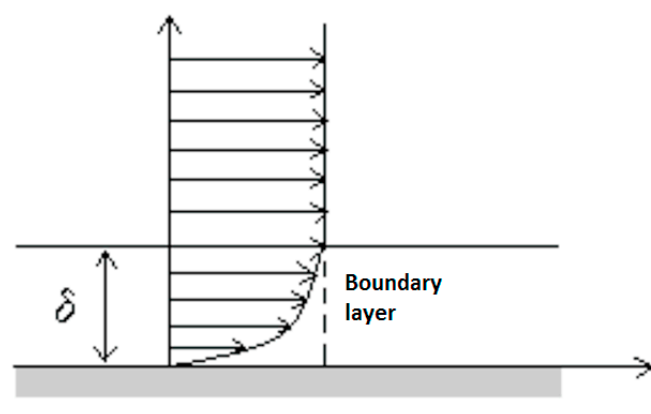


Figure 4 - The atmospheric boundary layer (ABL): roughness and vertical velocity profiles (at a certain altitude, wind speed is no longer influenced by the roughness of the land surface). In the ABL, the effects of the surface are felt in less than an hour.

The ABL is characterised by transfers of energy between the surface and the atmosphere (air friction on the surface, presence of obstacles). Its study is crucial to understanding pollution episodes because **pollutants emitted on the ground are mixed and diluted in the ABL**. 'Roughness' describes the dynamic effects caused by surface irregularities (mountains, buildings, hedges, etc.).

2.2. Mix of pollutants in the atmosphere and rate of diffusion

The concentration of an atmospheric pollutant depends not only on **dispersion** mechanisms and **vertical and horizontal transport** mechanisms in the atmosphere (turbulence), but also on **the pollutant's lifespan**. For example, a pesticide can degrade (e.g. reaction to light known as 'photolysis') or settle on the ground.

Dispersion depends on atmospheric **turbulence**. There are two turbulence scales:

- **On a small scale**, instability is influenced by mechanical (due to the roughness of the Earth's surface) and thermal exchanges between the ground and the air in the atmospheric boundary layer.
- **On a large scale**, instability is connected to meteorological conditions on the planetary scale.

Turbulence is linked to the stability of the atmosphere. In fact, air stability depends on changes in **air temperature in relation to altitude**, in **thermal turbulence** and in **mechanical turbulence**:

- **When the atmosphere is unstable**, the air is warmer near the ground than higher up. In this case, conditions are favourable to vertical air movement: turbulence is strong and dispersion is facilitated. Pollutants such as sprayed pesticides therefore **tend to rise**. This phenomenon occurs especially during the day, when air temperature decreases rapidly with altitude.
- **When the atmosphere is stable**, the air is colder near the ground than higher up. This is known as a temperature inversion, which can be partial or total. In this case, the vertical turbulence is fairly weak and pollutants therefore **tend to stay near the ground**. This phenomenon occurs under certain conditions, such as at night, when the temperature rises with altitude.

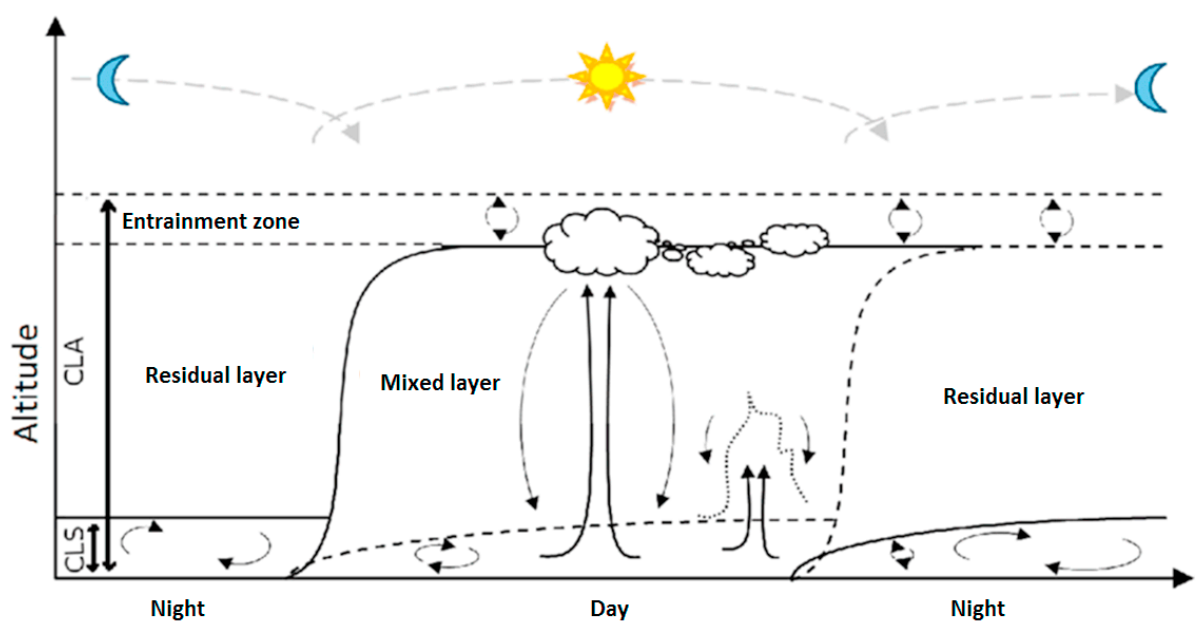


Figure 5 - Atmospheric boundary layer (ABL) cycle over 24 hours. CLS = Atmospheric surface layer
CLA = Atmospheric boundary layer (ABL)

When the ambient air and a pollutant are at the same temperature, the pollutant isn't subject to any forces.

Table 1 - Typical times for the atmospheric transport of an air pollutant

Transport	Typical dispersion time
In the ABL	1 hour to 1 day
In the troposphere	1 week to 1 month
From the troposphere to the stratosphere	5 to 10 years
Continental	1 week
Intercontinental	2 weeks
Interhemispheric	1 year

3. EFFECTS OF ATMOSPHERIC POLLUTION: MAIN FACTS

The most reliable source on the effects of atmospheric pollution is certainly the WHO, which lists the following facts on its Web site.

- **Air pollution represents a major environmental health risk.** By reducing levels of atmospheric pollution, countries can reduce the morbidity burden from cerebrovascular accidents, cardiac disease, lung cancer and chronic or acute respiratory diseases, including asthma.
- The cardiovascular and respiratory health of the population, both in the short term and long term, is inversely proportional to the level of atmospheric pollution. We have more and more data which demonstrates the link between ambient air pollution and cardiovascular risks, including studies carried out in heavily polluted areas.
- The WHO's general guidelines on air quality assess the effects of atmospheric pollution on health and provide thresholds above which air pollution becomes harmful to health.
- In 2016, **91% of the global population lived in areas where WHO air quality guidelines were not being complied with.**
- In 2016, **an estimated 4.2 million premature deaths** were caused by ambient pollution (of outside air) in urban, suburban and rural areas. This mortality rate is due to exposure to particles 2.5 microns across or smaller (PM_{2.5}), which cause cardiovascular and respiratory diseases and cancers.
- Roughly **91% of these premature deaths occurred in low- and middle-income countries**, with the majority recorded in the South-East Asia and Western Pacific WHO Regions.
- It is possible to limit some of the sources of urban atmospheric pollution by adopting policies and investing in more eco-friendly modes of transportation, as well as in housing, electricity production, high-efficiency industries and improved waste management in cities.
- In addition to outdoor air pollution, **domestic smoke pollution poses a serious health risk** to about 3 billion people, who cook their food and heat and light their homes using biomass-based fuels, oil and coal.

According to the World Health Organisation's (WHO) estimates, a lack of clean air caused nearly 7 million deaths in 2012 (one out eight people worldwide). Although low- and middle-income countries sustained the largest human losses², industrialised nations nonetheless had a significant morbidity burden. Approximately 600,000 deaths were recorded in Europe for the same year.

² Low- and middle-income countries (in particular, the South-East Asia and Western Pacific regions) accounted for 88% of the 7 million premature deaths caused by atmospheric pollution in 2012.

Table 2 - Distribution of the principal causes of death linked to global air pollution in 2012 (Source: WHO, 2012)

Illnesses caused by atmospheric pollution	% (out of 7 million premature deaths)
Cerebrovascular accident (CVA)	34
Lung cancer	36
Cardiac disease	27

The WHO estimates that in 2016, 58% of the premature deaths linked to outdoor air pollution were due to **coronary heart disease and cerebrovascular accidents** and 18% to **chronic obstructive pulmonary disease or acute lower respiratory tract infections**. The remaining 6% are attributed to **lung cancer**. The conclusions of an assessment carried out in 2013 by the WHO's International Agency for Research on Cancer (IARC) revealed that **outdoor air pollution is carcinogenic**, with particulate matter associated most closely with an increased incidence of cancers and, in particular, **lung cancers**. A link was also found between atmospheric pollution and an increase in the incidence of **urinary tract and bladder cancers**.

For a country like France, the annual health cost of outdoor air pollution to society is estimated at 20 to 30 billion euros (CGDD Report, 2013), which represents 1.4% to 2.1% of the national GDP. The cost is comparable to the health cost of tobacco. In Europe, deposits of atmospheric pollutants affect the biodiversity at two-thirds of the protected sites of the European Natura 2000 network (European Commission, 2013).

4. TYPES OF ATMOSPHERIC POLLUTION AND EFFECTS ON HEALTH³

4.1. Particulate matter

4.1.1. Definition and main sources

'**Particulate matter**' is categorised based on its size and emission source. It is made up of a **complex mix of solid and liquid particles of organic and mineral** substances suspended in the air. It is generally composed of (in addition to water):

- elementary carbon (carbon soot from engine fuels),
- a mineral component (**substances created by soil erosion, sulphates, nitrates, ammonia**, sodium chloride, mineral substances: lead, zinc, etc.),
- organic substances (such as VOCs or **Volatile Organic Compounds** – in particular, those resulting from fungicides, herbicides, insecticides etc. used on crops –, pollen grains, hydrocarbons, ketones, mushroom spores etc.).

Particulate matter is a **common indirect indicator** of air pollution. **It affects more people than any other pollutant.**

The **largest particles** are known as '**dust**'. The largest particles are rich in mineral fractions produced by mechanical processes (dirt particles created by erosion, sea salt, etc.).

Particles which are **smaller than 100 micrometres** (from 10^{-9} to 10^{-6} m) are known either as '**aerosols**' (e.g. droplets < 100 µm emitted into the atmosphere during pesticide spraying), or, when the particles are even smaller, as '**particulate matter**' (or PM). Chronic exposure to particulate matter contributes to the risk of developing cardiovascular and respiratory diseases and lung cancer.

Particles smaller than 10 µm (\leq PM10) can enter and be trapped deep inside the lungs. This means **those which are smaller or equal to 2.5 µ (\leq PM2.5) are even more harmful to health**. They can breach the blood-air barrier and enter the bloodstream.

For public health reasons, two categories of particulate matter are subject to **increased monitoring** in **air quality** studies:

- **PM10** (Particulate Matter < 10 µm). Air quality measurements are generally given in average daily or annual concentrations of PM10 particles per cubic metre of air. Routine air quality measurements generally express concentrations of these particles in micrograms per cubic metre ($\mu\text{g}/\text{m}^3$).
- **PM2.5** (Particulate Matter < 2,5 µm), which contain organic matter and secondary substances (e.g. ammonium nitrate, sulphates). The concentration of particulate matter in the air (PM2.5 or smaller) is also provided when sufficiently sensitive measurement devices are available.

Livestock farming and field crop farming emit dust and particulate matter (PM10 and PM2.5). Agricultural emissions of these main contaminants come from crops during **soil work**, harvesting and **crop residue burning**. In livestock farming, the emissions come mainly from livestock production buildings. These diffuse emissions, although occasional, **are significant** because they occur over large areas.

3 Most of this information was taken from the WHO website

Particles which form via abrasion or which are suspended in the air are generally larger than 1-2 μm (wind erosion, pollen, etc.).

Medium-sized particles (between 0.1 and 1 μm) mostly come from secondary sources and form via **the conversion of gases into particles from the precursors** SO_2 , NO_x and NH_3 and from VOCs.

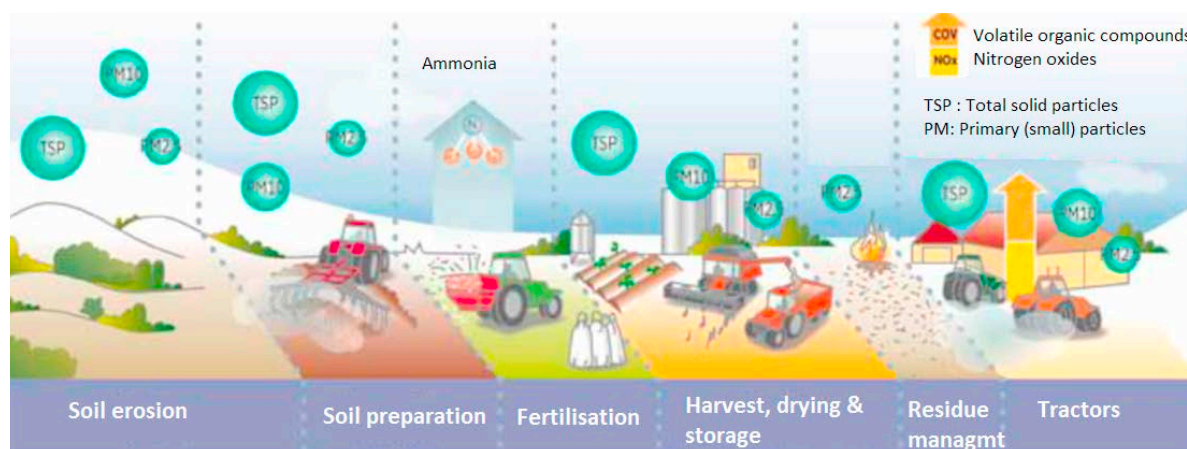


Figure 6 - Main agricultural atmospheric pollutants (TSP = total solid suspended particles)

Pollution thresholds have been exceeded several times in large European cities over the past few years. This was due to an accumulation of particulate matter, composed largely of ammonium nitrate and ammonium sulphate. **Ammonia**, which is mainly emitted via the intensive spreading of **nitrogen fertilisers** in spring, contributes significantly to the formation of these particles, which can persist in the atmosphere for several days and thus be transported over long distances.

The **agricultural pollutants** measured for the air quality index are:

- Gaseous species linked to photochemical pollution (ozone, nitrogen oxides NO_x , volatile organic compounds, etc.),
- **Acidifying substances** (sulphur dioxide (SO_2), ammonia (NH_3), etc.)
- **Particulate pollutants** ($\text{PM}_{2.5}$ and PM_{10} of sulphate SO_4 , ammonium NH_4^+ , nitrates NO_3 , etc.)
- **Greenhouse gases** such as **methane** CH_4 , nitrous oxide N_2O and carbon dioxide CO_2 .

4.1.2. Effects of particulate matter on health

There is a close quantitative relationship between exposure to high concentrations of particles (PM_{10} and $\text{PM}_{2.5}$) and an increase in mortality and morbidity rates, both daily and over the longer term. Likewise, the mortality linked to such exposure decreases as concentrations of small and particulate matter are reduced, assuming that other factors remain the same. Such a relationship allows decision-makers to plan ways in which particulate air pollution can be reduced to benefit public health.

Small particle pollution has an impact on health, even at low concentrations; in fact, **no threshold has been identified under which it does not have an impact on health**. That's why the 2005 WHO guidelines recommend working towards **limiting** the concentrations of suspended particles as much as possible.

4.1.3. Limit values

The WHO, which established a **clear correlation** between concentrations of fine dust and multiple adverse effects on health, mainly in terms of respiratory and cardiovascular illnesses, recommends the following **indicative values**:

Table 3 - WHO guideline values (WHO website, 2019)

PM10	20 µg/m ³	Indicative limit value (directive) for annual average
	50 µg/m ³	Indicative limit value for daily average; 99th percentile (this value cannot be exceeded more than 3 days per year)
PM2.5	10 µg/m ³	Indicative limit value (directive) for annual average
	25 µg/m ³	Indicative limit value for daily average; 99th percentile (this value cannot be exceeded more than 3 days per year)

According to the WHO Guidelines on air quality, lowering the annual average concentration of particulate matter PM2.5 from 35 µg/m³, a level commonly recorded in many developing cities, to 10 µg/m³, i.e. the level recommended by the WHO, **could reduce the mortality rate linked to air pollution by about 15%**.

These binding values are also set at the European Union level by the directive on ambient air quality and clean air (Directive 2008/50/EC):

Table 4 - Limit values of the European legislation on air quality

PM10	40 µg/m ³	Indicative limit value for yearly average
	50 µg/m ³	Indicative limit value for daily average (this value cannot be exceeded more than 35 days per year)
PM2.5	25 µg/m ³	Limit value for yearly average in 2015
	20 µg/m ³	Limit value for yearly average in 2020

4.2. Ozone (O₃)

4.2.1. Definition and main sources

The protective ozone layers in the upper atmosphere should not be confused with the ozone found near the ground, which is one of the main components of photochemical smog. In this case, ozone forms as a part of photochemical reactions (in other words, that occur in the presence of sunlight) between various pollutants, such as nitrogen oxides (NO_x) emitted by vehicles and industry and volatile organic compounds (VOCs) emitted by vehicles, solvents and industry. Concentration spikes have been observed during sunny periods.

4.2.2. Effects on health

At excessive concentrations, ozone has a marked effect on human health. Respiratory problems, asthma crises, reduced lung function and respiratory illnesses have been observed.

4.2.3. Limit values

100 $\mu\text{g}/\text{m}^3$ average over 8 hours.

Based on recently proven links between daily mortality and the concentration of ozone in the air, the threshold ozone value recommended in the WHO guidelines on air quality was lowered compared to previous versions, which recommended 120 $\mu\text{g}/\text{m}^3$.

4.3. Nitrogen dioxide (NO_2)

4.3.1. Definition and main sources

NO_2 in the air has the following effects:

- At concentrations greater than 200 $\mu\text{g}/\text{m}^3$, over short periods, it's a toxic gas which causes serious inflammation of the respiratory tract.
- When exposed to ultraviolet rays, it's the main substance responsible for the formation of nitrate aerosols, which make up a large percentage of $\text{PM}_{2.5}$, and ozone.

Man-made emissions of NO_2 are caused primarily by combustion (heating, electricity production, boat and vehicle motors).

4.3.2. Effects on health

Epidemiological studies have demonstrated that bronchial symptoms in asthmatic children worsen with long-term NO_2 exposure. A decrease in lung function is also associated with currently measured (or observed) concentrations in European and North American cities.

4.3.3. Limit values

40 $\mu\text{g}/\text{m}^3$ yearly average

200 $\mu\text{g}/\text{m}^3$ hourly average

The current WHO guideline value of 40 $\mu\text{g}/\text{m}^3$ (yearly average) was set to protect the public from the detrimental effects of gaseous NO_2 on health.

4.4. Sulphur dioxide (SO_2)

4.4.1. Definition and main sources

SO_2 is a colourless gas with a pungent odour. It is produced by burning fossil fuels (coal and oil) and smelting iron ore containing sulphur. The main anthropogenic source of SO_2 is the burning of fossil fuels containing sulphur for household heating, electricity production or motor vehicles.

4.4.2. Effects on health

SO_2 affects the respiratory system and lung function and causes ocular irritation. Inflammation of the respiratory tract results in coughing, mucous production, asthma attacks, chronic bronchitis and increased susceptibility to respiratory infections. The

number of hospital admissions for cardiac diseases and the mortality rate increase on days with high concentrations of SO_2 .

4.4.3. *Limit values*

20 $\mu\text{g}/\text{m}^3$ average over 24 hours

500 $\mu\text{g}/\text{m}^3$ average over 10 minutes

SO_2 concentrations cannot exceed 500 $\mu\text{g}/\text{m}^3$ on average over 10 minutes. According to certain studies, some asthma sufferers note changes in their lung function and respiratory symptoms appear after being exposed to SO_2 for only 10 minutes.

We now know that SO_2 affects health at much lower concentrations than previously believed. More protection is necessary. Although we don't know the exact causes behind the effects of SO_2 at low concentrations, it's likely that by lowering them, we can also reduce exposure to related pollutants.

5. TYPES OF ATMOSPHERIC POLLUTANTS AND EFFECTS ON THE ENVIRONMENT

5.1. Effects of atmospheric pollutants on the environment

Pollutants, released by industries (including intensive agriculture) and cars, penetrate the atmosphere and after being transformed play a part in **the acidification and eutrophication of natural environments**. For example, the reaction of atmospheric SO_2 with water produces sulphuric acid, the main constituent of **acid rain** and a cause of deforestation, through oxidation and hydrolysis. As for nitrogen oxides, they produce nitric acids which are just as devastating. These 'acid clouds' can travel more than 1,500 km from the source of pollution. From the atmosphere, these acids can either create dry deposits (which are deposited on the ground and washed away to surface waters) or wet deposits (rain, snow, fog).



Figure 7 - Effect of acid rain on a forest

These acids, like deposits of **ammonia and particles**, **modify the water and soil quality** in natural environments and, depending on their chemical form, promote **their acidification and eutrophication**.

Ammonia and ammonium deposits **acidify the soil** and thereby affect sensitive ecosystems. On agricultural land, the acidification can be mitigated with liming. When deposited, the secondary particles can act as an **additional nitrogen input** for ecosystems. These deposits can favour the growth of certain species of fauna and flora to the detriment of other species and result in **a loss of biodiversity** locally.

Some natural phenomena are also the source of primary particle emissions. This is notably the case with wind erosion, sea spray, volcanic eruptions and forest and bush fires.

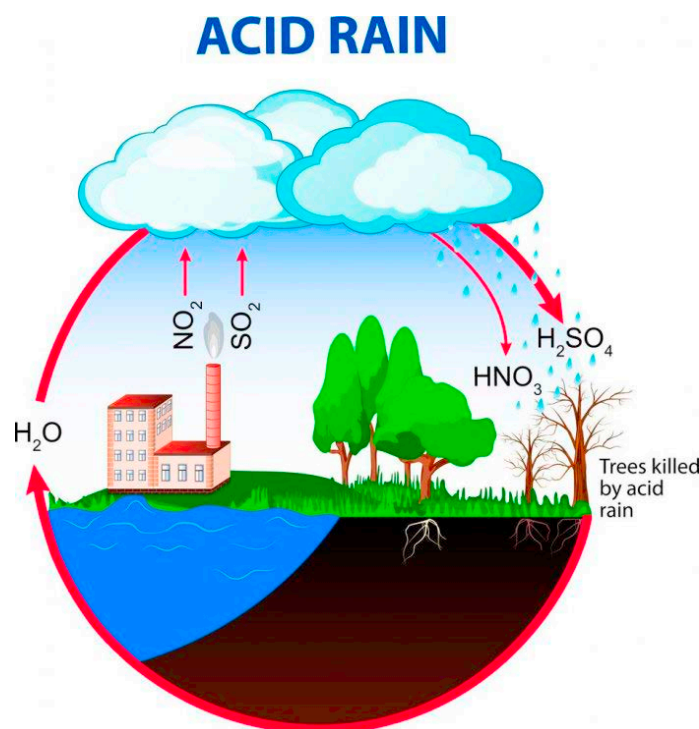


Figure 8 - Diagram depicting the formation of acid rain (Source: Internet Geography)

Particles are also involved in **the transport and deposition of toxic pollutants** (metals or persistent organic pollutants such as dioxins).

Atmospheric pollutants also play a role in **global warming** (this is the case for greenhouse gases, in particular those released by agricultural activities). On the contrary, the effects of particles on climate change are more complex and difficult to quantify. Depending on the type of particle, sunlight is absorbed (creating heat as a result) or reflected (thereby cooling the air). The smallest particles can also serve as condensation nuclei during cloud formation and thus affect hydrological regimes.

Strong links **connect particulate pollution and the formation of ozone**. Primary particles impact the photo-oxidant reactions behind the formation of ozone.

Atmospheric pollutants also directly impact the physiological processes of **plants**. This is especially the case for ozone and CO_2 . Exposure to elevated concentrations of ozone negatively affects photosynthesis, whereas exposure to elevated CO_2 levels positively affects it (fertilising effect of CO_2). Elevated concentrations of CO_2 also act as an antiperspirant by reducing the number of stomata and their openness, leading to more efficient water consumption.

An increase in nitrogen oxides (NO_x), methane (CH_4) or carbon monoxide (CO) results, via a series of photochemical reactions, in an increase of the ozone present in the atmosphere, which has **toxic effects on plants**.

On the other hand, the **effects of particles on plants** are not well known. Nonetheless, limited gaseous exchanges, deteriorated cuticles and reduced photosynthesis have been observed in plants.

5.2. Greenhouse gases

The “greenhouse effect” is a **natural phenomenon** which maintains the temperature of the Earth’s surface at an average of 15°C. Thanks to the greenhouse effect, a portion of the energy of the solar rays which reach our planet is retained at the Earth’s surface by greenhouse gases, while the rest of it returns to space. **Without this phenomenon, life on Earth would not exist.**

However, anthropogenic greenhouse gas (GHG) emissions increase their concentrations in the atmosphere and, as a result, the **amount of heat retained on the Earth’s surface also increases**. This phenomenon is at the root of both **global warming** and **climate change**.

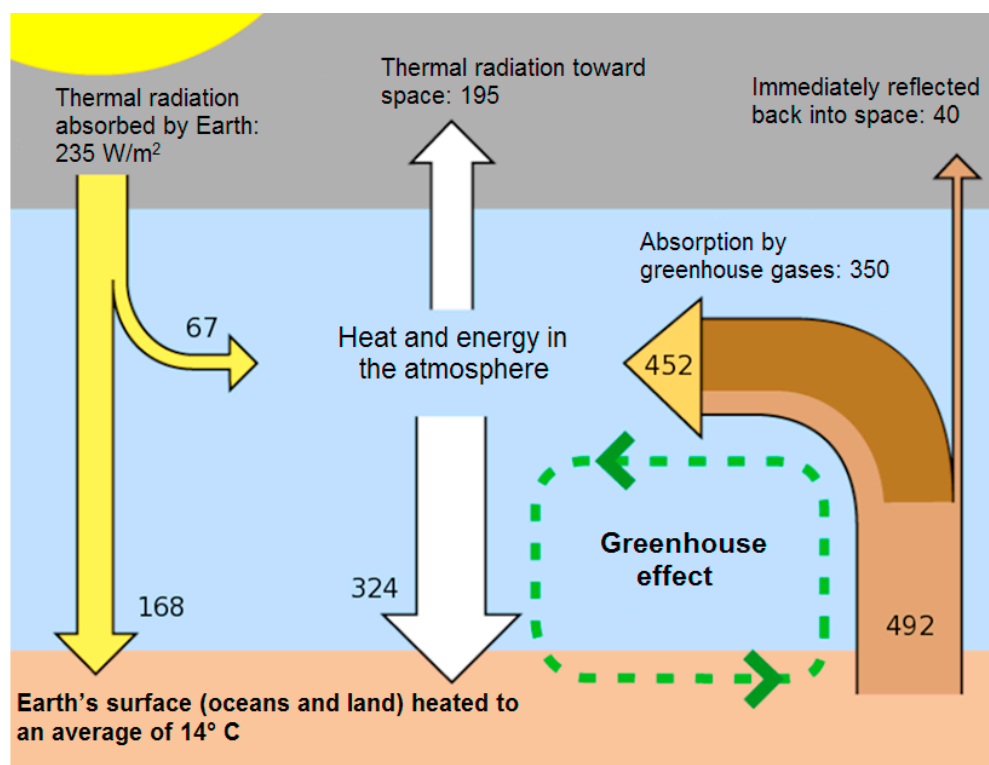


Figure 9 - The greenhouse effect (figures in W/m²)

Greenhouse gases do not all have the same effect on the atmosphere’s warming. Each greenhouse gas’ contribution to the greenhouse effect is expressed with an indicator known as the **global warming potential (GWP)**, a unit of measure equal to a gas’ total effect on global warming over the course of 100 years. This value is measured relative to CO₂. For example, 1 kg of CH₄ released into the atmosphere will have the same effect as 25 kg of CO₂ over a century.

Since greenhouse gases do not all have the same impact on the climate, they are measured in CO₂ equivalent (CO₂eq) to compare them. This unit is calculated as follows:

$$\text{CO}_2 \text{ equivalent tonne of a gas} = \text{tonne of the gas} \times \text{GWP of the gas}$$

Table 3 - global warming potential (GWP) of greenhouse gases (source: 4th IPCC report, 2007)

Type of greenhouse gas	Lifespan in atmosphere	Global warming potential
CO2	100 years	1 (by convention)
CH4	1 year	25
N2O	120 years	298

5.3. Contribution of agriculture to atmospheric pollution

5.3.1. Types of atmospheric pollutants generated by agriculture

The atmospheric pollutants generated by agriculture are gases dispersed in the air (primarily nitrous oxide – N₂O –, ammonia – NH₃ – and methane – CH₄) or particles, solids or liquids suspended in the air. These are ‘primary’ pollutants (like all of the atmospheric pollutants generated by human activity). In the atmosphere, however, the gases released by agriculture can combine with other elements present in the air (in particular, nitrogen oxides or sulphur) and form ‘secondary’ pollutants. The resulting particulate atmospheric pollution is therefore both primary and secondary.

5.3.2. Agriculture and the greenhouse effect

Agriculture releases **methane** (CH₄ - livestock farming and soils), **nitrous oxide** (N₂O - nitrogen fertilisers and animal waste management) and **carbon dioxide** (CO₂ - energy consumption). Depending on its practices and its impact on land use, agriculture can promote either the storage of carbon in the soil or its release. Agriculture accounts for nearly 13.5% of greenhouse gas emissions, before including emissions tied to deforestation, which increases the amount to 17%. Agriculture is responsible for more than 70% of global emissions of nitrous oxide and 50% of methane emissions.

Between 1990 and 2004, agricultural emissions grew modestly, by about 13% (mainly methane and nitrous oxide). However, **there is a significant difference between developing countries and emerging economies**, where agricultural emissions grew overall (+28%), and industrialised nations, where they fell (-12%).

Whereas agricultural emissions are falling in most industrialised nations, there has been a large increase in agricultural emissions from developing countries. The globalisation of trade and demographic growth are a part of the explanation for this. While methane is the main gas emitted in the South, nitrous oxide is the leading agricultural emission in the North (ADEME, 2010).

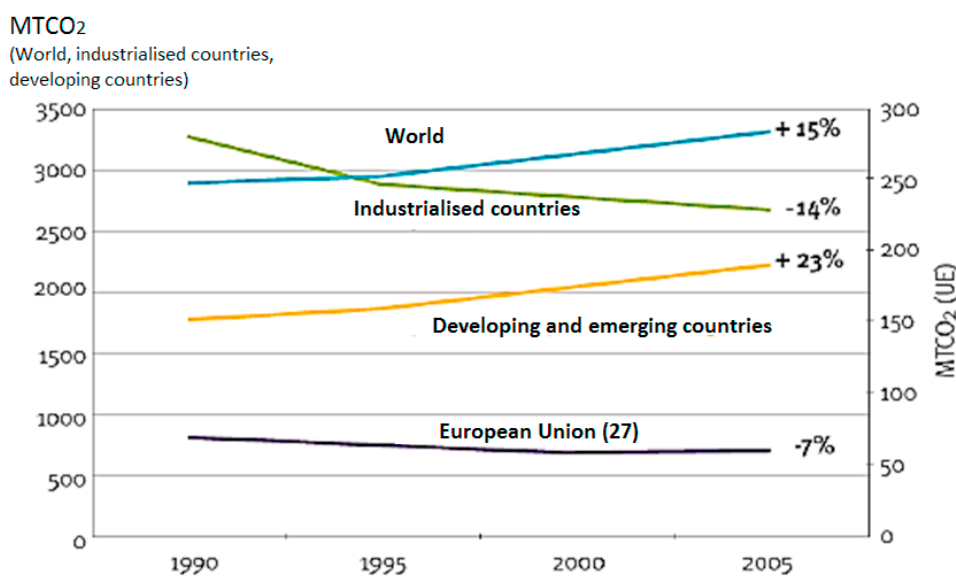


Figure 10 - Agricultural methane emissions (source: FAO statistics)

Agricultural zones are therefore major sources of atmospheric pollutants, of which the best known are greenhouse gases (GHG) and particulate matter. In 2012, plant and livestock production contributed nearly **24% of global greenhouse gas emissions**. According to the 2015 report on air quality published by the European Environmental Agency (EEA), the agriculture sector in EU-28 is the leading emitter of ammonia⁴ (NH₃) and methane and the third largest emitter of primary PM₁₀.

Like other business sectors, agriculture is a source of atmospheric pollution. It releases emissions of nitrogen compounds into the atmosphere. These include, in particular, ammonia (NH₃) and nitrous oxides (NO_x), particles and pesticides. These emissions are connected to livestock farming practices (buildings, storage, spreading, etc.) and crop practices (soil preparation, fertilisation, harvesting, etc.).



Figure 7 - Examples of crop practices which result in atmospheric pollution

The substances emitted by agriculture form a true **cocktail of chemical pollutants** in the air, which make up '**atmospheric pollution**', or "the introduction by humans, directly or indirectly, in the atmosphere and enclosed spaces, of substances which have adverse consequences which could endanger human health, harm biological resources and ecosystems, affect climate change, degrade material goods, cause olfactory pollution" (definition of atmospheric pollution according the French law on air quality and the reasonable use of energy, 1996).

A distinguishing feature of agricultural emissions is that they include both point source (buildings and storage) and diffuse source (fields, crops) pollution. Though they have relatively low surface intensity, diffuse emissions are nonetheless significant because they occur over large areas. They are, however, heavily affected by weather conditions and soil type, which makes them highly variable in time and space and difficult to predict.

5.4. Effects of atmospheric pollution on agriculture

Agricultural and silvicultural zones are simultaneously sources of atmospheric pollution and sinks for it. They can be **affected by atmospheric pollutant deposits** on various levels. **Agricultural yields** are also affected by atmospheric pollutants. Heavy exposure to **ozone**, a powerful oxidant which, in particular, affects photosynthesis, causes drops in crop and forest production ranging from 3% to 20%. These losses are a significant economic issue and, in some countries, constitute a threat to food security.

By comparison, elevated concentrations of atmospheric CO₂ have a positive influence on photosynthesis. This is known as the **fertilising effect of CO₂**. CO₂ also has an **antiperspirant effect**: an increase in CO₂ in the atmosphere reduces the number of stomata and their openness, reducing the plant's perspiration and leading to more efficient water consumption.

The **healthiness of food products** from agricultural operations located near major roads can be adversely affected by the deposition of pollutants such as trace metals (e.g. heavy metals like Pb and Cd) and POPs which accumulate in the soil and in plants. The impact on health of consuming these products is still poorly known but safety margins between crops and major roadways are recommended for certain food supply chains.

6. CREATING A FRAMEWORK FOR AIR QUALITY MANAGEMENT

6.1. The need to act in unison

Most sources of outdoor pollution are out of the reach of any individual's control and require cooperative action at the local, national and regional levels from the heads of the transportation, energy, waste management, urban planning and agriculture sectors.

There are numerous examples available of policies which have reduced air pollution in the transportation, urban planning, electricity production and industrial sectors:

- **industrial:** promoting non-polluting technologies which limit emissions from industrial chimneys; improved urban and agricultural waste management, including capturing methane from waste (to use as biogas), as an alternative to incineration;
- **energy:** guaranteeing access to clean and financially accessible solutions for cooking, heating and lighting;
- **transportation:** making the shift to non-polluting electricity production methods; favouring rapid public transit, walking and cycling lanes in cities, as well as intercity transport of merchandise and passengers; prioritising the use of more eco-friendly industrial diesel vehicles, low-emissions vehicles and fuels (in particular, fuels with low sulphur content);
- **urban planning:** improving the energy efficiency of buildings; making cities greener and more energy efficient.
- **electricity production:** spreading the use of low-emissions fuels and non-combustion renewable energy sources (e.g. solar, wind or hydroelectric); promoting the cogeneration of heat and electricity; and, favouring decentralised energy production (e.g. mini grids or rooftop solar panels);
- **urban and agricultural waste management:** implementing waste reduction, sorting, recycling, reuse and reprocessing strategies; improved biological waste management methods, such as anaerobic waste digestion for producing biogas, represent affordable alternative solutions to incinerating solid waste. If it cannot be avoided, waste incineration must be based on combustion technologies with strict emissions monitoring.

6.2. Concluding international agreements

The **Kyoto Protocol** (1997) is the fruit of political negotiations between the United States, the European Union and developing countries.

Its objective was to limit emissions of six greenhouse gases – carbon dioxide (CO₂), methane (CH₄), nitric oxide (NO), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF₆) – by setting emissions quotas for developed countries, the largest greenhouse gas emitters. After 2012, greenhouse gas emissions in the countries committed to the Kyoto Protocol had to be lower than those in 2012.

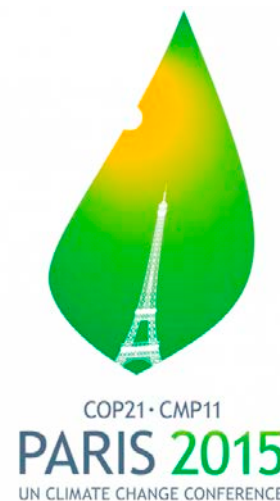
In order to accomplish this, most of these countries agreed to **reduce their greenhouse gas emissions by at least 5%**. This objective was attained. However, **greenhouse gas emissions in emerging nations increased** while the Kyoto Protocol was in effect and the **atmospheric concentration of CO₂ grew by more than 10%**.

The mobilisation of the international community on climate issues through the Kyoto Protocol was deemed insufficient given the climate challenges. In addition, the lack of sanctions in cases of non-compliance with the commitments, the lack of involvement of developing countries and emerging nations and the priority given to economic and industrial development were criticised.

Due to these criticisms and the ineffectiveness of the Kyoto Protocol, a new agreement, the **Paris Agreement**, was developed during **COP21** (Paris Climate Change Conference).

The goal of COP21 was to create a new protocol for greenhouse gas emissions in order to limit global warming to under 2°C. In order to do so, the Paris Agreement stipulates that all countries involved revisit their commitments to reducing greenhouse gas emissions every five years. In addition, it recognises the shared yet differing responsibility of each country, which was not the case with the Kyoto Protocol. The Paris Agreement entered into force on 4 November 2016, after being ratified by 55 countries representing at least 55% of greenhouse gas emissions.

On 8 May 2017, 145 countries, representing 82.95% of greenhouse gas emissions, had ratified the agreement.



6.2. Creating a legal framework for air quality management

We will review the major points of the regulatory framework on air quality, focusing primarily on legislation relating to atmospheric pollution produced by agricultural activities. Please refer to the content of each Directive for the limit values.

Various legislative supplements are issued from a '**framework directive**'⁵.

a) Directive 2008/50/EC defines air quality objectives, notably ambitious and cost-effective measures to improve human health and the quality of the environment by 2020. It also defines how to assess these measures and take corrective steps if the objectives are not reached. It provides that the public be kept informed. This directive allows the majority of the existing legislation⁶ on air quality to be combined into a single document which includes the following key components:

- **Thresholds, limit values and target figures are established** in order to assess the presence of each of the pollutants covered by the directive: sulphur dioxide, nitrogen dioxide, particles, lead, benzene and carbon monoxide.
- The national authorities are responsible for selecting **specific bodies** to complete these tasks using data collected at chosen sample points.

⁵ There is a framework directive on water that shares the same principle.

⁶ Directive 96/62/EC on ambient air quality assessment and management, as well as:

- Directive 1999/30/EC relating to the setting of limit values for sulphur dioxide, nitrogen dioxide and nitrogen oxides, particulate matter and lead in ambient air;
- Directive 2000/69/EC relating to limit values for benzene and carbon monoxide in ambient air;
- Directive 2002/3/EC relating to ozone in ambient air;
- Council Decision 97/101/EC establishing a reciprocal exchange of information and data from networks and individual stations measuring ambient air pollution within the Member States.

- When pollution levels exceed the thresholds set at a location, **air quality plans must be introduced** to remedy the situation. They may contain specific measures to protect vulnerable groups such as children.
- If there is a risk of exceeding the permissible thresholds for pollution, **short-term action plans must be implemented** (for example, reducing road traffic, construction or certain industrial activities in order to prevent the risk).
- The national authorities must ensure that the public, as well as environmental and consumer associations and others, including healthcare organisations and trade federations, are **informed of the ambient air quality** (or outdoor air quality) in their area.
- European governments must publish annual reports regarding all of the pollutants covered by this directive.

b) The Air Quality Framework Directive (Council Directive 96/62/EC): it was prescribed by the Fifth Environment Action Programme and states the **fundamental principles of a shared strategy** which aims to establish ambient air quality objectives as a means to reduce or prevent harm to the environment and health by establishing ambient air quality objectives. It implements shared ambient air quality assessment criteria and methods and the dissemination of air quality information.

Limit values and alert thresholds are proposed for the following pollutants:

- sulphur dioxide, nitrogen dioxide and nitrogen oxides, particles and lead;
- benzene and carbon monoxide;
- ozone;
- polycyclic aromatic hydrocarbons (PAHs), cadmium, arsenic, nickel and mercury.

The Framework Directive requires that **ambient air quality be assessed** across the EU territory. The assessment can be carried out via different methods: either by measuring, by mathematical modelling, by a combination of these two methods or by estimating. The assessment is obligatory in urban areas with more than 250,000 inhabitants and in areas where concentrations are near limit values. For cases where limit values are exceeded, member countries must establish **a programme to reach the limit values** within a set time-frame. The programme, accessible to the public, must include the following information:

- the location of the pollution;
- the type and assessment of the pollution;
- the source of the pollution.

Countries are required to establish **a list of the zones and urban areas where pollution levels are higher than the limit values**. In the event an alert threshold is exceeded, member countries must inform the population and communicate all pertinent information to the Commission (level of pollution recorded, duration of alert, etc.). If some geographic zones and urban areas have pollution levels which are lower than the limit values, member countries must maintain these levels below the limit values.

- c) **Directive 1999/30/EC**: in order to preserve or improve the ambient air quality, the European Union established **limit values** for concentrations in the ambient air of sulphur dioxide, nitrogen dioxide and nitrogen oxides, particles and lead and alert thresholds for concentrations of sulphur dioxide and nitrogen dioxide. In addition, it establishes common methods and criteria for assessing concentrations and collects all pertinent information on concentrations to inform the public.

6.4. Creating a legal framework for permitted emissions

- a) **Directive 2001/81/EC on national emission ceilings for certain atmospheric pollutants** was adopted on 23 October 2001⁷. It aims to limit emissions of acidifying and eutrophication pollutants and ozone precursors in order to better protect the environment and human health in the Community against the risk of harmful effects due to the acidification and eutrophication of the soil and ground-level ozone, and to make progress on the long-term objective of not exceeding any critical levels or loads and effectively protecting all individuals against the known risks to health caused by air pollution, by setting national emissions caps with 2010 and 2020 as reference years and proceeding with subsequent reviews.

It set **emissions caps** for sulphur dioxide (SO₂), nitrogen oxides (NO_x), volatile organic compounds (VOCs) and ammonia (NH₃) for each Member State. The directive also provided that Member States establish national emissions reduction programmes in order to comply with the caps set for emissions of the four pollutants by 2010. The European Commission is committed to reducing excess acidic deposits in areas where ecosystems are affected by eutrophication by 2020. At the European level, this entails a **27% reduction in global ammonia emissions by 2020** versus 2000 levels.

- b) **Directive 2004/107/EC** of the European Parliament and of the Council of 15 December 2004 relates to **arsenic, cadmium, mercury, nickel and polycyclic aromatic hydrocarbons (PAHs)** in the ambient air. This directive marks the final step in the recasting process launched by Framework Directive 96/62/EC for European legislation relating to the presence of pollutants which pose a risk to human health. Given that **the targeted substances are carcinogens** to humans and that no thresholds for their toxic effects on individuals' health have been identified, the current directive takes an approach that favours minimal exposure to these pollutants. It doesn't set a limit value for polycyclic aromatic hydrocarbons, but uses benzo(a)pyrene as a marker of the cancer risk tied to these pollutants and establishes a target value to be complied with insofar as possible for this substance.
- c) **Directive 2010/75/EU on industrial emissions**, known as the **IED Directive** outlines, at the EU level, an integrated approach for preventing and controlling pollution emitted by the industrial and agricultural facilities which fall under its scope of application. Its objective is to attain a high level of environmental protection through the integrated prevention and reduction of pollution from a broad range of industrial and agricultural activities. It is the counterpart for chronic risks to Directive 2012/18/EU of 4 July 2012 (the Seveso III Directive).

⁷ The 1999 Gothenburg Protocol to Abate Acidification, Eutrophication and Ground-level Ozone was signed as part of the 1979 Geneva Convention on Long-range Transboundary Air Pollution.

One of its guiding principles is the use of the best available techniques (BAT) to prevent pollution of all types. It requires Member States to base the authorisation conditions for affected facilities on BAT performances.

The IED replaces Directive 2008/1/EC, the IPPC Directive, concerning integrated pollution prevention and reduction.

It combines seven different existing directives relating to industrial emissions into one law and reinforces all of the major principles of the IPPC Directive by slightly expanding its scope of application and introducing new provisions for restoring the state of the soil. It also bolsters public participation. Its guiding principles are:

- using the BATs for the operating activities in question. BATs must be used as the foundation for setting emissions limit values (ELVs) and other authorisation conditions.
- periodic review of the authorisation conditions.
- restoration of the site to a state at least equivalent to the state described in a 'baseline report', which describes the state of the soil and groundwater before commissioning.

6.5. Establishing standards for maximum workplace exposure values

As of 2017, the European Commission has established a new list of indicative occupational exposure limit values (IOELVs) to protect workers against the risks of exposure to dangerous chemicals (Directive 2017/164). The list includes 31 chemicals such as carbon monoxide, sulphur dioxide, hydrogen cyanide, manganese and diacetyl.

Indicative occupational exposure limit values (IOELVs) are the limits of the time-weighted average of the concentration of a chemical in the air within the breathing zone of a worker over a specified reference period. IOELVs are linked to health, are determined based on the most recent scientific data and are adopted by the European Commission. An IOELV must help employers define and assess risks and apply protective and preventive measures. It is the exposure threshold below which, in general, the chemicals concerned should not have any harmful effects after a short exposure or daily exposure over an entire professional career.

The indicative limit values are measured over:

- an 8-hour reference period (as a time-weighted average, long-term exposure limit values); and
- a shorter reference period for certain chemicals, usually 1 minute (as a time-weighted average, short-term exposure limit values).

Member States are required to establish a national occupational exposure limit value for any chemical with an EU-level indicative occupational exposure limit value. In doing so, Member States must, of course, take both the limit value at the EU level and national law and practice into account.

7. APPENDIX: AIR QUALITY MEASUREMENT TECHNIQUES

7.1. Types of air

Indoor air is air contained in closed environments, such as housing, healthcare establishments and transportation. This dynamic space is characterised by pollution coming from outside and pollution from indoor sources linked to the building and its occupants. Indoor pollution is a growing concern for our contemporary societies because buildings are increasingly well insulated, which reduces energy losses but drastically limits air renewal.

Measuring the ambient air consists of quantitatively determining the main pollutants found in it. The general prescriptive approach targets different kinds of objectives, such as reducing health risks for human populations and following up on the limit values for protecting crops or ecosystems (the case of O_3). The time periods examined vary depending on the pollutant in question and the objective: calendar year, summertime, day or hour. Depending on the case, the calculation methods are: average (yearly, daily) moving average (over 8 hours), median or percentile.

7.2. Samples

Sampling and analysis of indoor or ambient air is a direct measurement of pollution and aims to provide specific quantification of the exposure of targets determined in a risk study. Two sampling methods are of interest: **(1) the active method** (pumping), where air is pulled into the sampling system; and, **(2) the passive method** (no pumping), where the pollutant is captured by the sampling system via diffusion. Active sampling enables quantitative analysis whereas passive sampling, with its greater exposure time, allows for a smoother measurement that avoids one-off fluctuations. Two desorption methods for analysis are available for sorbent sampling on a medium: thermal desorption and solvent-based desorption.

7.3. Measurement systems

■ Real-time measurement system

Continuous analysis devices can specifically determine the presence of one or more given pollutants, such as nitrous oxides, carbon dioxide or suspended particles (PM_{10} , $PM_{2.5}$). Detection in these systems focuses around a physiochemical property of the pollutant. The analysis devices continuously pull air through a reaction chamber and permanently provide a measurement signal which shows current concentration levels. This type of device is used in 'telemetric networks' to monitor air quality from a distance.

■ Non real-time measurement systems

These consist of tried and tested techniques in which on-site sampling is automated and analysis is conducted in a laboratory after samples are collected. When taking samples, air is pulled at a constant rate through a 'trap' where the pollutant is caught. The total sampled volume is calculated based on the sample time period and the airflow rate. The analysis gives the total mass of sampled pollutant and the average concentration for the sampling period can be calculated based on these two quantities. Analysis of the

dynamic aspects of pollution is not possible. In addition, the results of the measurements are only known after a two-week period, which makes a warning function unworkable. The results are nonetheless of great interest for statistical interpretation and studying air pollution.

■ Routine ambient air measurement

Non real-time measurement systems are generally preferred. These consist of automated sampling systems for the gaseous state only or both the gaseous and particulate states.

For ammonia:

Ammonia is generally trapped to create an ammonium salt through a reaction with an acidic solution. The trapping is done directly via sparging on a soaked filter or in a tube filled with soaked silica gel. Laboratory analysis is either carried out immediately or after extraction from the permeable medium, via UV-visible spectrophotometry using the blue indophenol method (NFT90-015-24 standard) or via ion chromatography with conductometric detection. These methods are extremely precise and make it possible to achieve a detection limit under 1 ppb. However, aerosols containing ammonium ions can also be trapped during sampling and distort the results. For this reason, sampling devices generally sample both the particulate and gaseous states.

For dusts:

There is a whole range of measurement methods which can help selectively determine the size of suspended dust particles or some of their constituents. They include manual gravimetric methods, which consist in collecting dust samples on filters or sheets and then weighing them after they are prepared at the prescribed humidity and temperature.

Example: 'High Volume Sampler' measurement devices which pull large volumes (about 30 m³/h) through a filter. The different sampling heads for PM₁₀ and PM_{2.5} catch particles in the airflow based on their size before sample collection. Automatic methods, on the other hand, continuously record a signal which does not directly correspond to a weight as per the reference method (manual gravimetric analysis). The measured signal must be converted into a mass concentration and verified with the reference method.



Chapter 2

Impact of agricultural practices on air quality

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Training objectives:

From this chapter, the trainee will be able to:

- Understand the effect of agricultural practices on air quality and the complex relationships between agriculture and air quality
- Distinguish between the role of fertilisers and other inputs in atmospheric pollution
- Understand how fertilisers impact air quality
- Understand the dispersion mechanisms of pollutants in the air
- Understand how pesticides contaminate the atmosphere and disperse via the air

1. IMPACT OF AGRICULTURAL PRACTICES ON AIR QUALITY

1.1. Agriculture: a special industry in terms of air pollution

It is recognised that agriculture plays a large part in changes in air quality. **This is all the more so because the practices used are aggressive for the environment and do not comply with the principles of agroecology.** The interactions between air quality and agricultural practices are an emerging and recurring topic.

The paradox of agriculture is that agricultural areas are **both sources and sinks** for air pollutants **depending on the practices used** (conventional vs agroecological or organic agriculture). Industrial agriculture is believed to be currently responsible for nearly 35% of greenhouse gas emissions (GHGs: notably CO₂ and methane) while, on the other hand, agricultural soils are very important carbon sinks. Agriculture is also a **special sector**:

- which **emits** GHGs and atmospheric pollutants (primarily ammonia and NH₃);
- which is a **victim** of atmospheric pollution (lower yields, deterioration of soil, water and plant product quality, deterioration of biodiversity, etc.).

The change in air quality can be due to the presence of natural or anthropogenic:

- biological pollutants: pollen, viruses, bacteria, spores, mite excrement (present regardless of the practices);
- **physical pollutants: dust ripped from the ground** by wind erosion or dispersed in the air following **tillage, soot** from incomplete combustion of hydrocarbons by engines or various types of particles. Sustainable production methods, which reduce soil work (e.g. permaculture) and with which the lumpy structure of the soil better resists wind erosion, emit less dust in the air.
- **chemical pollutants**: gases like **nitrogen monoxide** (NO), **nitrogen dioxide** (NO₂), **methane, pesticides** or many other **Volatile Organic Compounds** (VOCs) can be emitted in large quantities by intensive agriculture. However, even more traditional systems which set wood fires or agricultural fires to clear brush before planting release a number of atmospheric pollutants (including polycyclic aromatic hydrocarbons or PAHs). Knowledge of these emissions (quantity, distribution and acceptable concentration limits) is partial and data are variable. With respect to pesticides, for example, studies on air pollution are quite recent (or under way) and no concentration thresholds have currently been set.



Figure 1 - Agricultural fires: a significant source of pollutant emissions in the air
Source: OMPE - Organisation Mondiale pour la Protection de l'Environnement

Under certain circumstances (e.g. thermal inversions, periods of hot weather), the particles in suspension and gases create **pollutant cocktails** whose concentration and duration are enough to become **toxic and/or ecotoxic**. These pollutants can also interact with light (this is known as photochemical pollution) and produce tropospheric⁸ ozone during hot, sunny periods. This is a major pollutant which causes respiratory problems.

Agriculture contributes to emissions of **nitrogen compounds, VOCs, methane and pesticides**, as well as **primary particles**. Quantitatively speaking, pollutants from agricultural flows may seem low compared to other industries. However, emissions become significant and diffuse over such large areas. According to a number of sources, agriculture and forests emit 53% of all suspended particles (20% of PM₁₀, 9% of PM_{2.5} and 6% of PM₁), 89% of nitrous oxide (N₂O), 76% of methane, 10% of nitrogen oxides (NO_x), 50% of biogenic VOCs and 97% of the ammonia in the air (with livestock accounting for 77 % of emissions). NO_x and VOCs are **ozone precursors**. Ammonia and acids are **fine particle precursors**. Due to their size (about one micrometre to a hundred micrometres in diameter), fine particles are spread by the wind and nanoparticles may even act like gases. Once emitted (for example, during a fire or pesticide spraying), they can remain suspended in the air for hours, days and even months.

It has been observed in both developed and developing countries that:

- there are multiple sources of agricultural emissions, that **inputs play a preponderant role and that this role is increasing** in ACP countries;
- emissions depend on factors which are often outside of the farmer's control (weather, climate change, etc.);
- some factors are, nevertheless, partially under the farmer's control (practices used, equipment used).

8 Ozone which forms in the lower layers of the atmosphere

In agriculture, **soil preparation, fertilising, the use of phytopharmaceutical products and crop operations** will cause the emission of primary particles depending on the type of soil (the more the soil is degraded, the faster it will generate dust) and the weather (the dryer the soil, the more dust it will generate; the hotter it is, the more intense the volatilisation). Air pollution is also indirect: it is linked to the presence, the volatilisation and the accumulation (atmospheric fallout) of soil pollutants (pesticides, fertilisers and livestock effluent). As a result of the deterioration of soil fertility, air pollution reduces agricultural productivity and increases farmer dependence on fertilisers and, notably, on nitrogen-based fertilisers (and, therefore, the risk of soil and groundwater pollution by nitrates). In the end, **this creates a vicious circle between air and soil pollution**. While nitrogen is an essential element for plant growth, excessive use in conventional agriculture causes problems.

With livestock, particle emissions can occur in buildings, effluent storage, effluent spreading and pastures⁹. Ammonia emissions from conventional agriculture, which is a heavy consumer of inputs, and intensive livestock farming continue to increase... and this doesn't take into consideration the damage caused by slash-and-burn farming, which creates significant air pollution.

1.2. Impact of accidental and voluntary vegetation fires

According to the FAO¹⁰, biomass combustion ("burning") is a common phenomenon which **is widespread in the tropics**. Fires that burn vegetation are frequent and cover large areas, regardless if they are set by people for various reasons, or by lightning. Fires fed by wood, charcoal and crop residue are the main source of household energy for cooking and heating. Fire is also used to eliminate biomass when clearing land for farming or, after harvest, to rid the ground of unwanted field residue.

All of these fires are a **significant source of trace gases and particles in suspension** released in the atmosphere. Forest fires have many impacts on the environment and, notably, on air quality and, eventually, on health.

In a study carried out in 2012, ANSES (France) inventoried the main classes of chemical compounds detected in the smoke from plant fires. The study first emphasised that the composition of the smoke varied depending on the exact type of combustible, its density and dampness, burning conditions and the distance from the source. Smoke contains many different chemical substances including **carbon dioxide (CO₂), carbon monoxide (CO), volatile and semi-volatile organic compounds, particles, nitrogen oxides (NO_x)** and many others. It is estimated that biomass burning around the world generates approximately 3,460 TgC of carbon dioxide, 350 TgC of carbon monoxide, 38 TgC of methane, 24 TgC of non-methane hydrocarbons (C₂ - C₁₀), 8.5 Tg of nitrogen in the form of nitric oxide (NO), low but equally significant quantities of other trace gases such as methyl chloride and 104 Tg of suspended particles (Hao *et al.* 1990, Andreae 1991).

The ANSES report emphasises **two types of pollutants**, given the amount of emissions and their effect on health:

9 "Comment l'agriculture participe à la pollution de l'air", *Natura-Sciences*, 26 March 2018.

10 P.G.H. FROST, *Fire in southern African woodlands: origins, impacts, effects and control*, Rome, FAO

- **Suspended particles:** they are the most significant air pollutant compared to the regulatory thresholds set in areas impacted by smoke. About **80% of the mass of smoke consists of fine particles** (diameter < 2.5 µm). These characteristics mean that they spread more easily over long distances, which can reach several hundred kilometres. The short-term levels reached in the air (several hours to several days) can be particularly high (several tens to hundreds of µg/m³). The role played by suspended particles has been demonstrated in respiratory problems, as a trigger for asthma and in the increased number of deaths due to cardiovascular or respiratory illnesses, notably in more sensitive people.
- **Carbon monoxide (CO):** a clear odourless gas. It is produced by the incomplete combustion of organic material and, notably, by vegetation fires. Firefighters are particularly exposed to it. The highest levels are seen during slow burning phases, particularly near the fire. Carbon monoxide takes the place of oxygen in blood haemoglobin resulting in a lack of oxygenation of the nervous system, the heart and the blood vessels. Prolonged exposure can result in coma or death.

Smoke from fires may be responsible for the death of 339,000 people a year around the world according to some researchers (cardiovascular and respiratory problems), of which, 157,000 deaths in sub-Saharan Africa alone (*Le Monde*, 2012).

The amount of biomass burnt each year is currently estimated at 6,230-8,700 Tg dm yr⁻¹, of which approximately 87% in the tropics. Of the latter, approximately half (49%) is attributed to savanna fires which include both natural and farming fires. The rest comes from burning wood, crop residue and felled trees, approximately in the same proportions. It is estimated that 42% of emissions in the tropics come from Africa.

The FAO believes that the burning of biomass makes a significant contribution to **greenhouse gas emissions (CO₂ released)** and to tropospheric ozone precursors. The ANSES study concluded that the pollutants in vegetation fire smoke can fall on, spread to, and undergo chemical modifications **on the ground and in water. The quality of groundwater** is, therefore, threatened by these fires.

The following table provides estimates of the amount of biomass burned each year by savanna fires, around the world and in Africa.

Table 1 – Estimate of the quantity of biomass burned each year by savanna fires (Tg dm yr⁻¹):

Southern Africa	West Africa	Africa	World
			1,190
			600-3,200
1,200	1,228	2,428	3,691
			3,690
	90-480	1,294	
		2,520	
		1,300-2,500	2,500-3,700
561-1,743 (213-2,812)			
177 (90-264)			

The following table shows the emissions from the fires as a share of total global emissions. Note that the estimates of the quantity of biomass burned each year vary significantly and the emissions calculations are therefore not very precise.

Table 2 – Comparison of estimated worldwide emissions from biomass burning and all emissions from all sources combined, biomass burning included [source: Andreae, 1991]

Chemical compounds	Emissions (Tg element yr ⁻¹)		Share of biomass burning (%)
	Biomass burning	All sources	
Carbon dioxide (gross)	3,460	8,700	40
Carbon dioxide (net) ¹	1,800	7,000	26
Carbon monoxide	350	1,100	32
Methane	38	380	10
Non-methane hydrocarbons ²	24	100	24
Nitric oxide	8.5	40	21
Methyl chloride	0.5	2.3	22
Total particulate matter	104	1,530	7
Particulate organic matter	69	180	39
Elemental carbon (black carbon)	19	< 22	> 86

¹ Net emissions of CO₂ are equal to the gross emissions less the quantity reabsorbed by growing plants

² Excluding isoprenoids and terpenes

The trace gases created by fires contribute both to the greenhouse effect and the chemical reactivity of the atmosphere.

Savanna fires in Africa are considered to be a primary cause of the significant annual peak in tropospheric ozone which covers all of the Atlantic Ocean from Africa to South America in September and October (Fishman *et al.* 1991). Burning biomass also produces large quantities of particles smaller than a micron which remain suspended in the atmosphere for long periods of time, reducing air quality and visibility. This problem is made worse in southern Africa by the relatively stable atmosphere during the dry season, which enables the development of strong thermal inversions which trap particles in the lower layers of the atmosphere. This is made worse by the presence of a wide subcontinental circular atmospheric flow which recirculates a large part of the emissions around southern Africa during the dry season (Garstang *et al.* 1996).

These negative effects **must be offset against the apparent benefits of burning the vegetation**, as perceived by the local populations. The benefits include: a second harvest of herbaceous plants in certain areas, used by livestock farmers to increase the protein intake of their livestock; control of bush growth, which can result in increased pasture yields for livestock; the cleaning of roads between housing, facilitating the detection of predators and other dangerous animals and the control of parasites such as ticks (*Acaridae*). Vegetation fires can also be caused by the poor control of fires set to clear and prepare plots for crops, to create firebreaks, to make charcoal and to create smoke for beehives to harvest honey and when burning certain areas to drive out game (Trapnell 1959, Kikula 1986).

1.3. Role of agricultural inputs in atmospheric pollution

Agriculture has undergone many changes over the past half-century. In addition to technological advances - selection of high-yield species, irrigation, mechanisation, improved storage techniques - the use of '**inputs**' (fertilisers and phytopharmaceutical products) has also made a significant contribution to increasing production yields and profitability. In order to promote plant growth and maximise harvests, farmers make massive use of **nitrogen fertilisers and pesticides**. They **have mechanised soil work** and they make heavy use of irrigation which requires changes to the topography of large crop areas.

Fertilisers provide plants with the nutrition they need to grow and which may be lacking in soil which is not fertile enough or overworked. Phytopharmaceutical treatments reduce the competition from weeds and limit the damage done to crops and harvested products by pests, viruses, fungi, and pathogenic bacteria. The problem is that plants only absorb half of these fertilisers and that only a minimal fraction of the pesticides really reach their target. **The rest ends up in the atmosphere, the soil and water, polluting rivers and damaging aquatic biodiversity.** The inputs are spread on a large scale in the environment and can **end up in the atmosphere**, either **immediately** when applied, or **indirectly** through wind erosion or the vaporisation of deposits on the areas treated. We know, for example, that phytopharmaceutical deposits on plants and on the ground can return to the air as a gas via complex processes.

As a result, agricultural inputs have **many negative externalities** which threaten human populations and upset the equilibrium of ecosystems:

- **Fertilisers** (organic or chemical) **can be a source of air pollution** via volatilisation and, especially, of water when they are applied in amounts greater than what the crops and soil can absorb. Excess nitrogen and phosphates can be leached into groundwater or run off into bodies of water. This nutrient overload in lakes, reservoirs and ponds leads to a proliferation of algae which destroys the aquatic fauna and flora (eutrophication). In addition, the spreading of fertilisers on agricultural soil accounts for over 30% of nitrous oxide emissions.
- **Phytopharmaceutical products** are singled out as a possible cause for the decline in bee colonies and other pollinators and of biodiversity in general. It is a known fact that certain phytopharmaceutical products negatively impact the health of their users, of workers who come into contact with residual deposits and of consumers exposed to residue in their food (e.g. impact on the nervous system, genetic heritage and on hormonal equilibrium in the case of substances which disrupt the endocrine system of human beings).

Studies have shown that pollutants in the soil have a negative impact on the growth of vegetable crops by reducing their capacity to capture and fix nitrogen, a process which is essential for their growth and yields. Tillage further weakens the soil structure.

2. ATMOSPHERIC POLLUTION CAUSED BY FERTILISERS

2.1. Air pollution from fertilisers

As a result of their structure and composition, some soils (portion of clay-humus, presence of micro-organisms, aeration, etc.) are naturally more fertile than others. When these soils are used for intensive farming, they become increasingly poorer when no 'regeneration' is implemented. This is why farmers use a number of techniques to maintain soil fertility, including the use of fertilisers¹¹ which provide different types of nutrients (N, P, K, oligo-elements) which are lacking or have been exhausted by crops.

Fertilisers include organic and chemical fertilisers obtained by mixing or from synthetic sources.

Organic fertilisers include solid and liquid livestock excretions, liquid manure + straw and macerated manure, which are valuable and very popular sources of organic material even though they have to be used carefully to avoid harming the environment. However, they are not available locally without livestock farming. The enteric fermentation of cattle (about 45% of the total) and the management of pig excrement (about 20%) are responsible for methane emissions. Ruminants, in particular, have three pre-gastric digestive compartments for which rumen is the basis of bacterial digestion of forage plants. Methane is a secondary product of digestion which is expelled by the animals by belching or flatulence (cows, sheep, goats, etc.). It can also come from manure and liquid manure from these animals. The creation and use of this type of organic fertilisers, required by the soil, generates atmospheric pollution in the form of released methane.

There are three important families of **chemical (synthetic) fertilisers**:

- **Nitrogen fertilisers:** nitrogen is naturally present in the atmosphere. It is very important for the growth of the aerial parts of plants.
- **Potassium fertilisers:** potash stimulates flowering and fruit growth. It is naturally present in soil.
- **Phosphate fertilisers:** provide phosphorous to the soil which boosts root growth and increases plant resistance. These fertilisers can also be formulated with nitrogen (ammonium phosphate) or aluminium (aluminium phosphate).

Below, we provide more detail on the mechanisms that create atmospheric pollution **via ammoniacal nitrogen and nitrous oxide**, because **nitrogen-based fertilisers are primarily responsible for air pollution**.

Nitrogen pollution in agriculture is primarily in the form of nitrous oxide (N_2O), ammonia (NH_3) and nitrates (NO_3). The excess nitrogen is redistributed in different forms in water and also **in the air**.

The **volatilisation** of nitrous oxide (or nitric oxide) and of ammonia is the main way in which nitrogen is lost **during the spreading of livestock effluent** (liquid manure, manure etc.) **or ammonium-rich fertilisers like urea** – $\text{CO}(\text{NH}_2)_2$ – or **ammonitrate** (mineral nitrogen fertiliser based on ammonium nitrate, NH_4NO_3). All of the physical-chemical reactions involved in the formation and destruction of nitrogen in the biosphere must

11 A distinction must be made between conditioners and fertilisers (organic or chemical). Conditioners help to improve the structural and chemical qualities of the soil (e.g. calcium and magnesium conditioners, composts, etc.).

be assimilated to understand the transfer process of nitrous or ammoniacal nitrogen to the atmosphere.

The nitrogen cycle involves 3 reservoirs: organic nitrogen (humus, etc.), mineral nitrogen (NO_2^- , etc.) and gaseous nitrogen (N_2 , N_2O , etc.).

Three basic processes are involved in recycling nitrogen (see figure 2):

1. **The bacterial conversion of atmospheric dinitrogen** (N_2) into nitrogen (NH_4^+) which is adsorbed by plants and animals. The NH_4^+ adsorbed onto the clay-humus complex or present as a solution in the soil is usually transformed into NH_3 (ammonia);
2. **The nitrification** which transforms the products of fixation (NH_4^+ , NH_3) into NO_x (e.g.: nitrates, NO_3^-) in oxygen-poor soils (O_2):

Nitrification: NH_4^+ (Nitrosomonas) \leftrightarrow NO_2^- (nitrobacteria) \leftrightarrow NO_3^- (nitrates)

3. **The denitrification** which returns the nitrogen to the atmosphere in its molecular N_2 form with CO_2 and nitrous oxide N_2O as secondary products. These are 'denitrifying' bacteria which operate by reducing the nitrate ion NO_3^- , which is easily soluble in the soil solution thanks to the hydrogen links it establishes with water molecules and easily absorbable by plants, into a nitrite ion NO_2^- , then into nitric oxide NO , then to N_2O (nitrous oxide) and, finally, into dinitrogen N_2 , which is released into the atmosphere from the soil by volatilisation.

Denitrification $\text{NO}_3^- \leftrightarrow \text{N}_2\text{O} / \text{N}_2 \uparrow$ (nitrous oxide/dinitrogen)

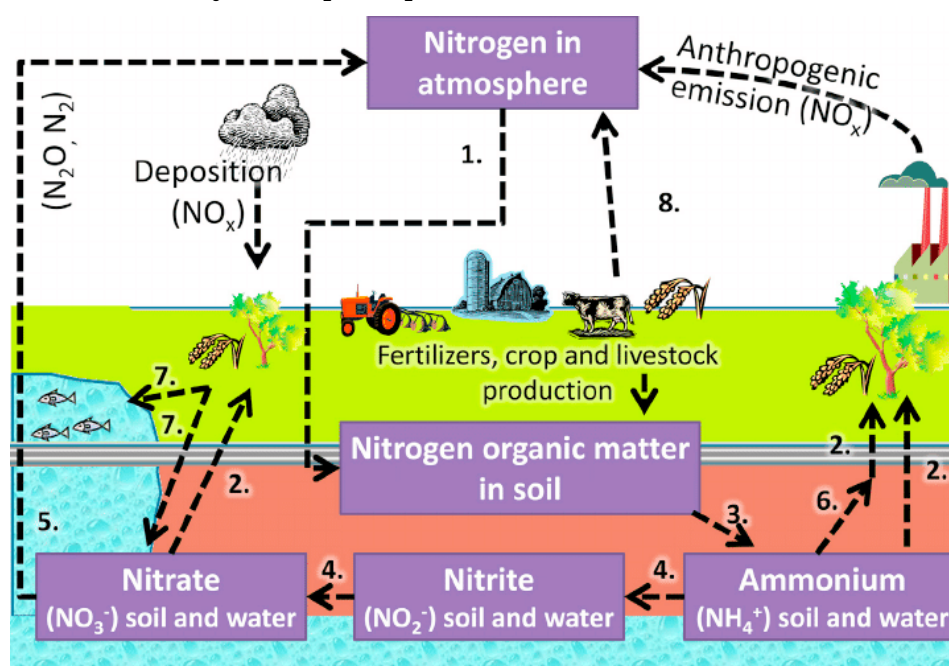


Figure 2 - The nitrogen cycle: explanation of the various emissions in the atmosphere

However, these processes are **very slow** and the application of excessive nitrogen fertilisers and agricultural effluent limits the assimilation process for ammonium NH_4^+ , ammonia NH_3 and nitrates NO_3^- (the most common ionised forms of nitrogen fertiliser).

However, **livestock play a leading role** (during the production, storage and spreading of effluents) in the volatilisation of ammoniacal nitrogen (as they do in releasing methane).

Nearly half of all ammonia emissions from hog, cattle and poultry farms are produced in **livestock buildings**. When a cow urinates in a pasture, the urea and uric acid quickly

seep into the ground before they hydrolyse and release ammonia which is retained by the clay-humus soil complex. On the contrary, when a cow urinates on concrete, there is obviously no seeping and a **significant amount of the nitrogen excreted is quickly volatilised**. The process is accelerated because the urine is mixed with dung, which contains ureases, enzymes which catalyse the hydrolysis of the urea into ammonia and CO₂.

The **storage of farm effluents** before they are spread facilitates the contact of the excrement with the air.

Lastly, **the spreading of the livestock effluents generates over a third of total ammonia emissions**. Ammonia is released from ammonium by the soil or plants. Ammoniacal nitrogen is the form obtained after complete mineralisation of all of the organic nitrogen compounds in the soil.

The presence of ammoniacal nitrogen in a solution in contact with air will consistently result in the volatilisation of ammonia due to a simple change in state:



or



The intensity of the volatilisation process during spreading will depend on the characteristics of the soil, outdoor conditions (temperature, humidity, etc.), the formulation of the product (table 1) or the spreading method used.

Table 3 – Losses via NH₃ volatilisation in the atmosphere during the spreading of various nitrogen fertilisers (Source: Aspa, 2015)

Types of fertiliser	NH3-N losses (kg/kg of N spread)
Ammonitrates	0.015
Ammonium sulphate	0.200
Urea	0.170
Ammonia	0.120
NP, NK, NPK fertiliser	0.015

Due to its acid-base character, ammonia will interact with the acid compounds in the atmosphere (e.g. H₂SO₄ or HNO₃) to form **secondary aerosols** of ammonium salts ((NH₄)₂SO₄ or NH₄NO₃). A small fraction can be oxidised into NO_x in the presence of hydroxyl radicals which can lead to the **production of tropospheric ozone** (between the ground and 12 km in altitude). As a powerful oxidiser, ozone acts on the physiological processes of plants, notably on photosynthesis, **which results in lower crop and forest production**.

Within the first kilometres, the primary process is the **deposition of dry aerosols** or of ammonia near the sources. Ammonia and ammonium salts can also be transported over long distances depending on climate conditions (up to a few hundred kilometres) and deposited during damp weather (rain, fog, etc.). Nitrogen deposited in this way enters the nitrogen cycle of the ecosystem where the deposit occurred.

The deposition of ammonia or ammonium also results in the **intensification of soil nitrification (soil acidification)**. A certain number of natural or semi-natural terrestrial ecosystems are very sensitive to nitrogen deposits. This eutrophication can result in local **flora and fauna biodiversity loss**.

All soils emit nitrous oxide, but agricultural soil emits more. It is essentially the result of two bacterial processes in the soil: nitrification (semi-arid environment) and denitrification (in irrigated or wet areas). N_2O is an intermediate product which is always emitted during denitrification. It can be emitted if denitrification is incomplete (doesn't result in final N_2). By contrast, in the case of nitrification, N_2O is a secondary product.

Nitrous oxide emissions primarily depend on soil characteristics such as its oxygen content, the pool of carbon and nitrates available, the temperature and the soil pH. When the amount of carbon in the soil is high (e.g.: incorporation of crop residues), the soil receives less oxygen. N_2O is only involved in photochemical reactions in the stratosphere (at 12 to 50 km in altitude).

2.2. Dispersion in the air of pollutants generated by fertilisers

If we use the strictest WHO values as reference points, **over 80% of the urban population of the EU is exposed** to excessive concentrations of PM_{10} (we unfortunately don't have any figures for the major cities of ACP countries, but given the state of the vehicles, the situation is probably comparable, despite the fact that there are no domestic furnaces). This is due to the fact that certain pollutants can **stay in the atmosphere long enough to be transported** from one country to another and **from one continent to another** or, in certain cases, around the world.

The intercontinental travel of particles and their precursors explains in part why the improvement in air quality in Europe is not proportional to the decrease in particulate emissions and particle precursors. Emissions of particle precursors have decreased overall in the EU: -54% for sulphur oxides (-44% in the 32 EEA countries); -26% for nitrogen oxides (-23% in the 32 EEA countries); -10% for ammonia (-8% in the 32 EEA countries).

However, **these reduced emissions do not always translate into lower exposure to particles**. The proportion of the European urban population exposed to PM_{10} concentration levels in excess of the values set by EU legislation continue to be high (1841% for the EU-15 and 23-41% for the 32 EEA countries). It has decreased only slightly over the past decade. Nevertheless, between 2001 and 2010, direct PM_{10} and $PM_{2.5}$ emissions decreased by 14% in the EU and by 15% in the 32 member countries of the EEA.

One of the difficulties in making short-term forecasts (of a few days) for changes in pollution thresholds is that the **sources of ammonia** from agricultural and livestock activities **are not well understood**. Ammonia is the **least understood of the pollutants** regulated by European air quality directives: its emissions areas are not very precise and it is difficult to monitor overall. Ammonia is now being monitored in the atmosphere. In high concentrations, ammonia (NH_3 , a foul-smelling irritant) is responsible for cascading environmental effects. It deposits on surfaces and, in addition to being acidifying, its chemical evolution in the soil and water can result in eutrophication phenomena caused by excess nitrogen. The selective detection of ammonia in the atmosphere is of significant value for meeting several objectives;

- quantifying temporal and spatial variations in ammonia concentrations over the long-term and therefore enabling verification of the effectiveness of the reduction measures implemented at the local and European levels;
- qualifying and quantifying the role of ammonia in the formation of fine suspended particles (ammonia is an ammonium nitrate and sulphate precursor).

Thanks to measurement by satellite¹², researchers were able to continuously track maps of ammonia concentration in the air over a year and compare them to recent atmospheric models. This work revealed that the ammonia sources provided by current inventories of the agricultural valleys of the northern hemisphere (America and Europe) were underestimated. A network¹³ has measured the concentrations of ammonia in 23 European countries since 1986. A decrease in NH₃ emissions was observed during the period from 1990 to 2003, particularly in eastern countries. Lithuania saw its emissions decrease by 60% and Bulgaria by 58%, while Spain experienced an increase of 20% over the same period.

There are **significant seasonal variations** in ammonia concentrations which differ depending on the main source of emissions. Ammonia concentrations are higher in the summer in rural areas which are far from the sources. On the other hand, if livestock is farmed in the area, the maximum ammonia concentration levels coincide with spreading times. Different times of the year can be impacted depending on the types of crops: pastures peak at the end of the winter or in early spring and cereal crops peak at the end of fall.

12 Infrared measurements by the IASI satellite of the *Centre National d'Etude Spatiale* (CNES) and the European Meteorological Satellites (Eumetsat), an intergovernmental organisation founded in 1986.

13 EMEP (European Monitoring and Evaluation Programme) which has 71 measurement sites.

3. ATMOSPHERIC POLLUTION CAUSED BY PLANT PROTECTION PRODUCTS

3.1. Air pollution from plant protection products

Agriculture makes significant use of **plant protection products** (commonly called '**pesticides**'). There is a risk that their main active ingredients are emitted into the environment (air, soil and water). It is estimated that 25% to 75% of the mixture sprayed doesn't deposit on its targets.

Until now, pesticide pollution has been primarily perceived as a result of its presence in surface water and groundwater¹⁴ (the water primarily used as drinking water), soil and foodstuffs. **However, the atmosphere plays an essential role in the dissemination of pesticides at the local, regional and global levels.** However, due to a lack of measurements of pesticides in the air and their potential consequences, this diffuse contamination went unnoticed and was underestimated for a long time.

As a result, the legislation on ambient air quality set at the national or European levels doesn't set **limit values** for atmospheric pesticide residue, although this is the case for other pollutants like nitrous oxide, sulphur dioxide and fine particles. The number of studies on phytopharmaceutical atmospheric pollutants is increasing at the local level in urban centres and highly agricultural areas. Certified air quality monitoring non-profits are compiling regional lists of the chemicals to be watched and are attempting to **set guideline values** for active substances and their derived products as part of studies of the exposure of the local population and the environment.

Pesticides can be applied to fields in several ways. However, this is usually accomplished by **spraying droplets** on the plants (particularly insecticides and fungicides) or on the ground (especially herbicides). Atmospheric pollution can occur in several different ways during this operation, involving different mechanisms:

- **direct contamination** during application due to losses **from drift** (loss by vertical and horizontal transfer of part of the mixture sprayed in the atmosphere);
- **indirect contamination post-application** either **by volatilisation** from the ground or the cover treated or **by wind erosion**.

The presence of pesticides in the air can be explained by several **phenomena** (e.g. drift, volatilisation, erosion, etc.), a number of **physico-chemical properties** (e.g. the partition between the gaseous-aqueous-solid phases, the persistence of the active substance in the air, etc.) and the impact of the **application techniques** used (e.g. equipment, volume/ha, droplet size, working pressure, type of nozzle, etc.) and the **weather conditions** (e.g. air temperature, relative humidity, wind speed, etc.).

Atmospheric transfers **can take place over long periods of time** which explains the persistence of certain pesticides in the air outside of spreading periods. The overall process is the result of an **equilibrium displacement** between the liquid or solid and gaseous phases. Many parameters and interactions come into play in volatilisation during spreading and after treatment, which makes determining the conditions of such a transfer process complex. Depending on their transfer mode, pesticides can end up in the atmosphere in three different forms: as a gas, liquid or solid (particulate).

¹⁴ The maximum admissible concentration for pesticides in tap water is 0.1 µg/litre and per pesticide and 0.5 µg/litre for the total of all pesticides detected in the water) according to European regulations (Directive 98/83/EC).

Table 2 - Pesticide phase depending on the type of transfer in the air

Type of transfer in the air	Pesticide phases
Drift	Liquid
Wind erosion	Solid (particulate)
Volatilisation	Gaseous

Once in the air, pesticides can move from one phase to another according to the physico-chemical characteristics and weather conditions. The different states are important, in particular for transport over greater or lesser distances.

3.2. Air contamination by drift at application time

The effectiveness of phytosanitary treatments depends on the uniform spreading of the spray mixture on the area treated. The effectiveness of spraying depends to a great extent on the **quality of the product used**, and on the skill of the user (ability to set parameters: nozzle type, pressure, advance speed, etc. in order to obtain the volume of mixture required for a hectare).

While there are many different spraying systems, **spraying using a nozzle boom with liquid under pressure** is the technique most commonly used worldwide. It is the best-suited technique for the application of liquid agrochemical compounds for all volumes/ha and for the greatest number of crops.

While this large equipment is increasingly commonplace in ACP countries, few small-scale farmers can afford it. It would, in addition, be out of proportion for the surface area they farm. Many vegetable farmers have, at best, a **backpack sprayer** (with a lance and a slit nozzle) **where pressure is maintained by hand pumping**, and sometimes a centrifugal wand (in this case, the spray is applied via the high-speed rotation of a disk to which the liquid is drawn by gravity. This type of equipment is primarily used to treat cotton plants). Sometimes a simple plastic bottle squeezed by hand whose cap has been punched with holes is used as a “sprayer”. This method is highly ineffectual. Some farmers apply the pesticides with a broom or a branch dipped in the mixture.

A basic liquid pressure nozzle consists of a calibrated opening. Liquid is put under pressure upstream and forced through the opening at high speed. The narrowing causes disruptions in the **flow speed** of the liquid when it travels through the opening (rubbing, turbulence, etc.) and when it exits and comes into contact with the ambient air. Herbicides are generally applied to the ground whereas insecticides and fungicides are directed to the aerial parts of the crops. The disruptions cause the liquid to **divide into droplets which are more or less consistent**.



Figure 3 - Spraying using a nozzle boom with liquid under pressure: drifting droplets are visible behind the boom
(Photo: B. Schiffers)

■ Origin of the phenomenon and definition of drift

The mixture is split into **different fractions** when sprayed. The total volume of mixture sprayed is the sum of these fractions. The fractions are found on the plants and soil of the fields sprayed, on the plants and soil around the fields and in the air. One fraction is missing. Volatilisation occurs during spraying and results in the loss of a fraction of the mixture (figure 4). **Spray drift** refers to the atmospheric transport of small pesticide droplets or vapour **outside of the area treated** by the wind at the time of application or shortly afterwards. It is measured as a **% of the volume applied per hectare** (drift usually accounts for a few %)¹⁵. In extreme cases, the missing fraction can amount to nearly 30% of the total mixture sprayed.

The fractions vary depending on a number of parameters:

- weather conditions (temperature, relative humidity, wind speed);
- the type of sprayer used (size of droplets created);
- the spraying parameters (speed, pressure, nozzle type, product sprayed, etc.).

Part of the drift normally deposits near the application point (sedimentary drift), but **another part remains in the atmosphere longer and can be transported over longer distances (wind drift)**. This is why, depending on their ecotoxicity, a space must be left between the last nozzle of the spray boom and waterways (the buffer strip or non-treated zone) in order to protect them from excess contamination¹⁶.

15 Drift is expressed as a percentage of the total amount sprayed per area unit treated (EFSA 2014).

16 See also COLEACP Manual 9, *Water protection and conservation*, Chapter 4.

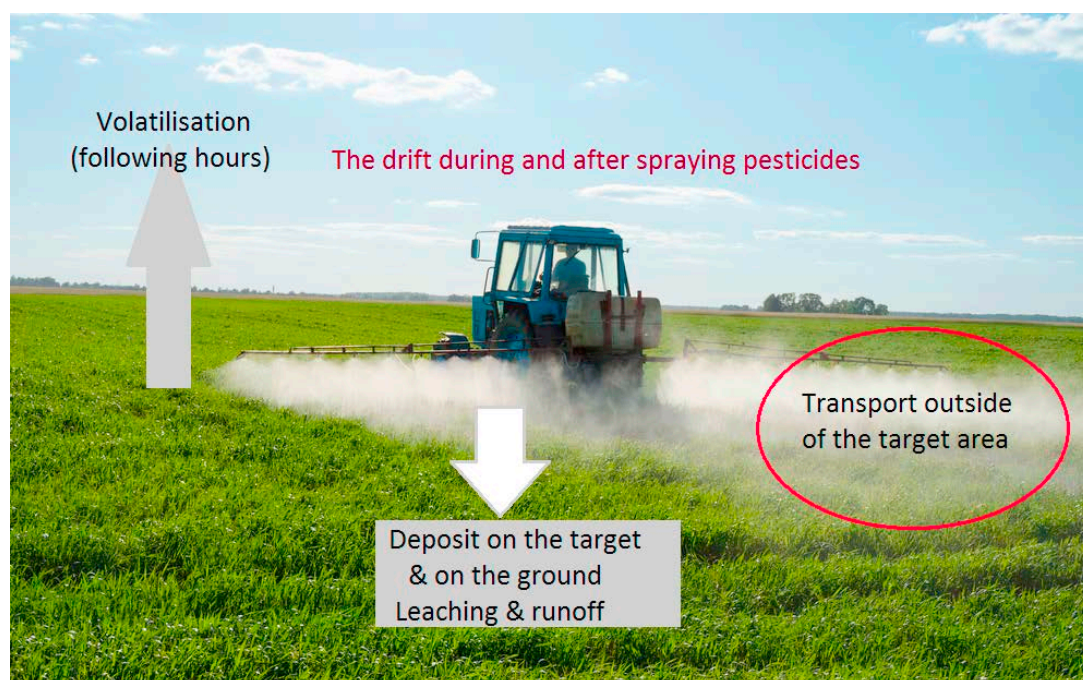


Figure 4 - This figure shows all of the phenomena that can occur during application: volatilisation, interception and deposit on plants, run off in the soil and percolation in the soil profile and, for part of the volume applied, transport outside of the target area by the wind (or 'drift').

There is also '**indirect drift**' due to losses of pesticide after application via **soil erosion or volatilisation from the soil and plants**. Depending on their physico-chemical properties, certain active substances are retained (adsorbed) by soil particles (in the clay-humus complex or CHC) which has an effect on their volatilisation or their suspension in the air by the wind. The substances or formulations (e.g.: DP or WP granules or powders) on the soil surface and the soil particles on which the substances are adsorbed can be subject to wind erosion and be carried far away. The fraction of the mixture spread which is subject to this type of erosion is not known for sure (according to some authors, it varies from 1% to 7% of the mixture).

■ Factors impacting drift

Many factors impact the amount of drift. Some factors are mechanical (e.g. working pressure or type of nozzle used), others depend on the farmer's practices (e.g. the height of the boom, the advance speed, the volume of mixture per hectare). However, the most important factors are most certainly those related to the size of the droplets and atmospheric conditions such as wind speed and direction during application and the temperature and relative humidity in the air.

a) Effect of droplet size on drift

Droplet size plays an important part in **spreading and crop coverage** and, therefore, in the effectiveness of the pesticide applied. Different size droplets form during spraying. Volume Median Diameter (VMD) is the most commonly used parameter to describe droplet size. A droplet size classification standard with a nozzle colour code has been defined by the American Society of Agricultural and Biological Engineers (ASABE) based on the VMD. It is commonly used in agriculture, for example, for TeeJet Technologies nozzles.

Tableau 5 - Droplet size classification according to the ASABE S572.1 standard
(Source: TeeJet Technologies)

Category	Symbol	Colour code	VMD (µm)
Extremely fine		Purple	< 60
Very fine	VF	Red	61-105
Fine	F	Orange	106-235
Medium	M	Yellow	236-340
Coarse	C	Blue	341-403
Very coarse	VC	Green	404-502
Extremely coarse	XC	White	503-665
Ultra coarse		Black	>665

The behaviour of a droplet in the air (released with initial velocity) can be described by Stokes Law:

$$v = \frac{g d^2 \rho_d}{18\eta}$$

v : constant velocity of the droplet at equilibrium (m/s)

d : droplet diameter (m)

g : acceleration of gravity (m/s²)

ρ_d : droplet density (kg/m³)

η : viscosity of the air (Ns/m²)

It is apparent that **the rate of fall is strongly correlated with the diameter of the droplet.**

Tableau 6 - Rate at which droplets fall in the air based on their size (Source: www.ianr.unl.edu/pubs.pesticides/g1001.htm)

Droplet diameter (in µm)	Rate of fall
1	28 hours
10	17 minutes
100	11 seconds
200	4 seconds
400	2 seconds

The largest drops (> 100-150 µm) are strongly affected by gravitational forces and, therefore, fall according to the classical laws of ballistics. On the other hand, smaller droplets stay more easily in the ambient air and are subject to turbulence and weather conditions, which change their theoretical trajectory. The **distances** small drops can be carried can be significant, **ranging from a few metres to several hundred metres.**

Drift increases inversely with droplet size. **Droplet size is, therefore, the factor with the greatest impact on drift.** It is therefore important to manage droplet spectrum limits, i.e. the diameter of the smallest and largest droplets, as well as the number of droplets

produced in each size category. **Droplets which are too fine** (under 100 μm) **reach their target haphazardly** given the long fall time and their sensitivity to the wind. Droplets which are too big (over 600 μm) reach their target quickly but can run off. The diameter of drops must be between 200 and 300 μm to ensure optimal application conditions. The fall speeds of droplets in the air vary based on their diameter.

b) Pressure

Spraying pressure is also an important parameter. The size of drops often decreases when it increases, but the speed at which the drops exit the nozzle also increases. In general, an increase in the initial speed of the drops results in decreased drift.

c) Effect of the nozzle type on drift

There are two main types of spray nozzles: flat spray nozzles and cone nozzles (used less often). Flat nozzles ensure good distribution of the droplets during spraying. There are 'anti-drift nozzles' which produce larger drops with the same pressure without reducing the flow via the creation of a thicker jet.

d) Effect of spraying height on drift

The fall time of droplets increases as the height of the boom increases, making them more sensitive to weather conditions. Relative humidity is particularly important because, when this parameter is low, droplet size has a greater tendency to decrease making it more sensitive to drift or horizontal transport.

e) Effect of formulation on drift

The physico-chemical properties of the mixture also have an impact on drift. Note that active substances are never used as is. They are applied in the form of commercial formulations (PPPs) which contain **co-formulants** which improve their stability and their effectiveness. Co-formulants and adjuvants added to the container at the time of spraying (e.g.: spreaders, wetters, safeners, etc.) can have a significant impact on what happens to pesticides after their application because they modify the physico-chemical properties of the mixture (e.g. reduced surface tension) resulting in the creation of fine droplets which are more prone to drift.

Parameters such as the evaporation rate, viscosity, surface tension and density determine the persistence and mobility of the droplets. Low surface tension reduces the size of droplets, which facilitates their dispersion and volatilisation in the air. The presence of a volatile solvent in the formulation accentuates this effect. Higher mixture viscosity results in the formation of larger droplets, which reduces the risk of drift. Vapour pressure measures the tendency of a material (liquid or solid) to vaporise. The higher the parameter, the greater the tendency to vaporise (substances are often characterised by their Henry constant). It's preferable to use an active substance with low volatility if fine droplets must be applied in order to avoid decreasing the diameter of the droplets. The formation of aerosols should be avoided as much as possible because it creates a greater risk of drift.

f) Effect of wind on drift

Pesticide drift increases considerably as **wind speed rises**. The displacement energy required to carry droplets is provided directly to the liquid by the spraying pressure. Resistance increases with speed and decreases with droplet diameter: fine droplets, whose speed on exiting the nozzle is high, are more easily slowed down by the air. Wind influences the trajectory and direction of the droplets. Small-diameter droplets

are significantly impacted by air movements. High wind speed (in excess of 5 m/s or approximately 18 km/h) further increases drift. It is therefore recommended that treatment be stopped when wind speed exceeds 15 km/h.

g) Effect of relative humidity and air temperature on drift

Climate conditions also play a part. The higher the **temperature**, the faster droplets dry out (not including rising convection movements). This means that less product will reach the plants (due to drift caused by a smaller droplet volume and by volatilisation in the air). With respect to **hygrometry**, the danger is represented by extremes. If relative humidity is too high there will be a loss of product through run-off (mixture running off from leaves onto the ground). Inversely, when it is too low and/or the temperature is too high, the droplets dry out too quickly. It has also been reported that pesticide vapours can be re-concentrated in fog droplets and deposited on the plants again.

A droplet can only reach its target when its fall time (t) is less than its lifespan. **Lifespan increases with droplet diameter and relative humidity.** However, it decreases as the ambient air temperature increases. This behaviour is described using the following formula:

$$t = \frac{d^2}{80\Delta T}$$

t : droplet fall time

d : average droplet diameter (in μm)

ΔT : difference in temperature in $^{\circ}\text{C}$ between dry and damp thermometers.

As a result, RH has a significant impact on the distribution of the mixture in the different 'fractions'.

h) Effect of the equipment and technique used on drift

The size of droplets depends on the type and size of the nozzle, the working pressure and the spraying height. As we have seen, the type of nozzle determines the droplet size at a given pressure.

A **large volume** of mixture/ha or **high pressure** will increase drift.

The **greater the spraying height**, the sooner the end of the droplet's lifespan is reached. Its basic diameter is reduced and, therefore, it becomes more susceptible to drift. An increase in displacement speed can push the jet towards the back of the sprayer and place it in rising air currents and swirling air which will trap the fine droplets and can contribute to drift.

Drift, although limited, is also possible with small equipment. It can be more significant with centrifugal wands, but is lower beyond 6 to 8 metres for backpack sprayers (Gouda *et al.*, 2018).

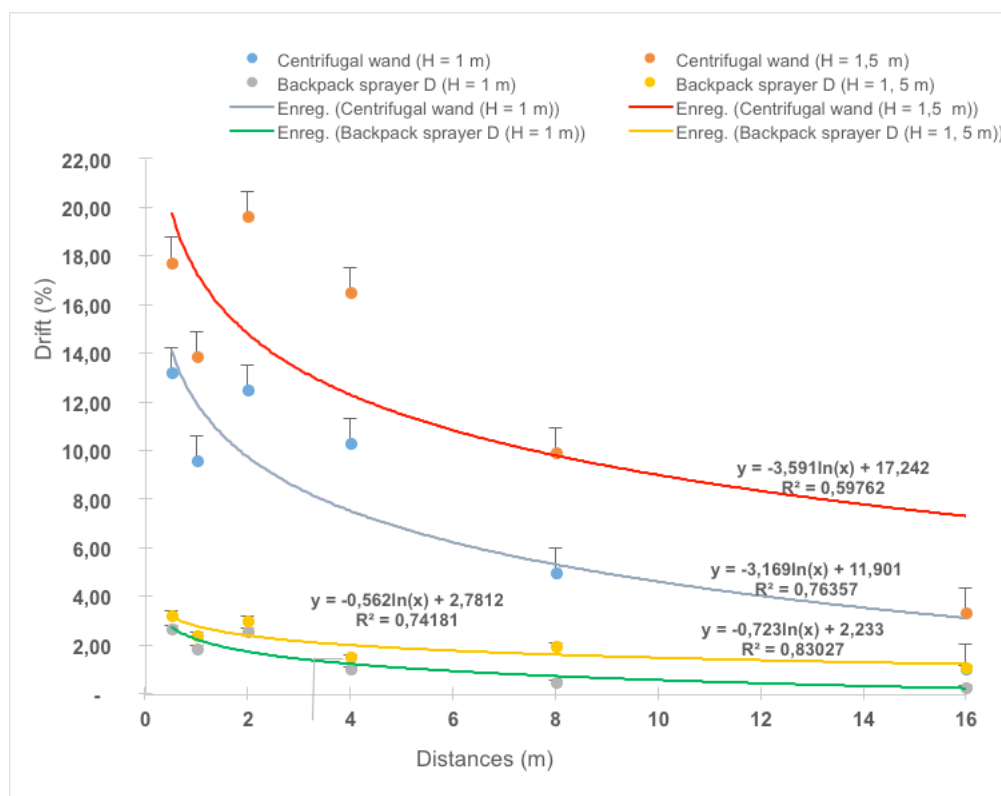


Figure 5 - Comparison of the percentages of drift generated by the two sprayers (backpack and centrifugal wand) depending on the different spraying heights ($H = 1$ m and $H = 1.5$ m) and depending on the distances from the point of emission (from 0.5 to 16 metres) (Gouda *et al.*, 2018).

3.3. Contamination of the atmosphere by volatilisation and wind erosion

■ Dispersion by volatilisation

Volatilisation describes the phenomenon of **dispersion in the atmosphere which occurs following phytopharmaceutical treatments**.

Post-application evaporation (or sublimation) of phytopharmaceutical deposits consists first of the diffusion of deposits in gas form via a thin layer of air (about one millimetre) called the stagnant layer which is immediately adjacent to the surface treated. This is followed by mixing in higher layers of the atmosphere. The vaporisation of phytopharmaceutical deposits post-application is more significant from plant cover than from the ground due to the action of the retention forces of the latter's mineral and organic components.

The volatilisation flow of the active substance is governed by many factors including:

- its vapour pressure and solubility in water (partition between air and water)
- the value of the Henry constant (volatilisation from the aqueous phase)
- its K_{oc} sorption coefficient (volatilisation from the solid phase)
- its half-life in the air (persistence in the air)

It isn't always known that hydrophobic substances with high molecular weights (like DDT, an organochlorine insecticide which is no longer approved for agricultural use) which have very low vapour pressures and, therefore, very weak atmospheric concentrations can, nevertheless, be significantly volatilised in the atmosphere because they are also

not very water soluble. The **Henry constant¹⁷ (K_H) is, therefore, a better suited indicator than vapour pressure to assess the volatility** of an active substance active immediately after its application on plants because it takes its solubility in soil water into account. The K_H quantifies the partition at equilibrium of a substance between the solution in which it is dissolved and the air. The Henry constant of a compound corresponds to the ratio between its vapour pressure (P , partial gas pressure in vapour phase) and its hydrosolubility (C_{water} , concentration of gas in the liquid phase):

$$K_H = P / C_{\text{water}} \quad (\text{Pa.m}^3/\text{mol})$$

The higher the K_H , the more the substance will have a tendency to volatilise: the compounds in the following table which have a Henry constant greater than $2.5 \cdot 10^{-5} \text{ Pa.m}^3/\text{mol}$ are considered to be volatile [Source: Marliere; 2001].¹⁸

Table 7 - Solubility and Henry's Law of different active substances

Active substance	Solubility in water (mg/L) at 25 °C	KH values (Pa.m ³ /mol) at 25 °C	Type
Atrazine	35.0	$1.5 \cdot 10^{-4}$	herbicide
Chlorpyrifos-ethyl	1.07	0.91	insecticide
Diuron	36.4	$5.1 \cdot 10^{-5}$	herbicide
α and β Endosulfan	0.41(α) and (0.23) β	1.45	insecticide
Glyphosate	10500	$2.1 \cdot 10^{-7}$	herbicide
Mancozeb	2 – 20	$< 5.9 \cdot 10^{-4}$	fungicide

The K_{oc} coefficient is the partition coefficient between the organic carbon in the soil (organic material) and the water in the soil (*i.e.* the water film around soil particles). This coefficient measures the distribution at equilibrium between the aqueous phase (in which the active substance is dissolved) and the organic matter.¹⁹

The **K_{oc} (in litre/kg) = $K / (\%OC)$** where K is the 'soil-water partition coefficient' which measures the degree of adsorption of the pesticide by the soil and the %OC is the percentage of organic carbon in the soil ('humus') considered. The volatility of pesticides in the soil involves the concepts of partition between soil and the water in the soil. Given that pesticides are organic substances, it is assumed that these compounds have a greater affinity for the clay-humus complex (complex which forms between clays and the organic components of the soil if the soil is rich in organic matter). The coefficient depends solely on the nature of the active substance and virtually not on the soil type at all.

The time of a half-life (**DT_{50} in the atmosphere (in hours or in days)** is an indicator of the **persistence** of a chemical compound in the air. If the half-life of the pesticide increases, the concentration in the atmosphere increases also because the degradation does not offset volatilisation. Examples of this are chlordecone (100 years), atrazine (2.3 days) and alachlore (4 hours). The destructive photochemical effects and oxidation reduce the risk of acute environmental effects of pesticides released in the atmosphere.

17 Henry's Law: the solubility of a gas in a liquid is proportional to its partial pressure above the liquid.

18 F. MARLIÈRE, *Pesticides in the ambient air*, Laboratoire central de surveillance de la qualité de l'air, INERIS, 2001, pp. 1-56.

19 See also COLEACP Manual 9, *Soil protection and conservation*, Chapter 2.

■ Dispersion by wind erosion

Wind erosion, defined as the contamination of the air by the deposits adsorbed on soil particles and torn away by the wind, is particularly evident in windy regions, large open plains and light soils and involves crops with little plant cover.

■ Concentration and distribution of pesticides in the air

The life of phytopharmaceutical substances in the environment is strongly impacted by their ability to move from one environment to another. In dispersion models, the air is seen as a 'compartment' (like water and soil). A compartment is a homogeneous subset of the environment defined by its size, physical and chemical properties and its relationships with other compartments and via which the transfer of pollutants is possible from one compartment to another.

In the atmosphere, phytopharmaceutical substances are distributed between the aqueous, gaseous and particulate phases of the air. The pollution measurement unit for a substance in the air is its volume concentration ($\mu\text{g}/\text{m}^3$) or its mass concentration ($\mu\text{g}/\text{kg}$). Two components must be taken into account: displacement in the air and persistence in the air.

Displacement in the air results from two mechanisms acting at the same time:

1. atmospheric movements disperse the pollutant by mixing with the less polluted ambient air and, therefore, tend to reduce the concentration level (**diffusion**);
2. the air mass containing the pollutant moves under the effects of turbulent movements (**advection**) which develop in unstable air or are generated by wind shear causing the pesticides to be transported over greater distances.

Persistence is measured by the **time the compound remains in the air. This depends either on the speed of its chemical transformation or of its deposition on the ground.**

Chemical transformations include deterioration by ultraviolet rays (photolysis) or a reaction with oxidising agents or free radicals in the air.

Pesticide deposits occur via atmospheric fallout processes: wet deposits induced by **precipitation** (rain, snow) and **dry deposits** resulting from gases and particles. While dry deposits predominate over short distances, the two deposit methods occur in long distance transport. Deposits of phytopharmaceutical products can be in suspension (particles) or volatilise. This alternating volatilisation/deposition phenomenon, called the **grasshopper effect**²⁰, directs compounds to cold regions of the Earth and can result in the dispersion of the substances on a global scale.

20 The grasshopper effect: a geochemical process which results in an accumulation of certain chemical substances, and particularly persistent organic pollutants (POP), in colder regions, at the poles and on mountain tops.

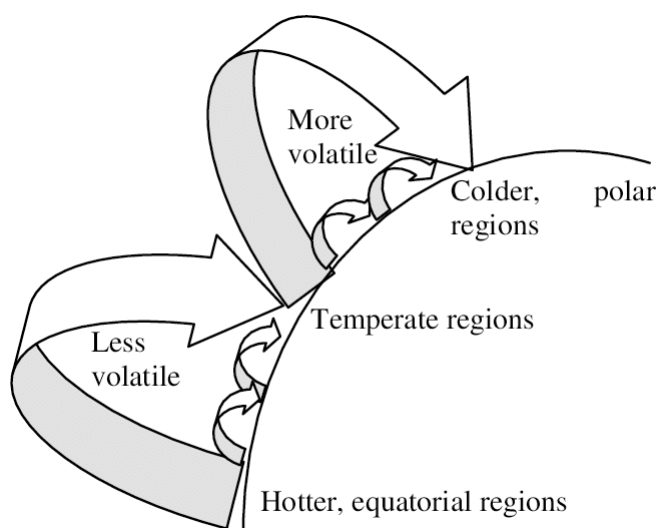


Figure 6 - Representation of the “grasshopper effect” responsible for the dispersion of pesticides on a global scale

The modelling of atmospheric transfers of “phytopharmaceutical” pollutants is **complex** because it requires that the significant variations in conditions encountered during the treatments be taken into account (weather, soil, the porosity of leaves, etc.). Most models (often empirical models) used to describe the atmospheric dispersion of pesticides due to spraying drift describe a phenomenon under the influence of **weather and operating conditions** known at the time of application (weather conditions and operating conditions like speed, the nozzle, volume, pressure, working height, etc.).

3.4. Concentration and distribution of pesticides in the air

■ Concentration of pesticides in the air

There are **no European standards or regulations** governing the sampling and analysis of the pesticides in the ambient air. The Member States have therefore taken the initiative to implement local and regional monitoring of phytopharmaceutical pollutants.

For example, in France, the *Associations Agréées de Surveillance de la Qualité de l’Air* (AASQA) have developed a methodology based on two American methods for the sampling and analysis of pesticides in the ‘air’ compartment.²¹ It consists in sampling the air over a day or a week with a conventional sampling system. The air flow (between 30 and 60 m³/h for daily sampling and 1 m³/h for weekly sampling) passes through a cartridge containing a quartz fibre filter which captures the particles, and a polyurethane foam which traps the pesticides present in the air.

At the end of collection, the filtering cartridges are packaged in cool bags and sent to the laboratory to be analysed based on the recommendations of the EPA methods. The volatile products and particles are extracted (by chemical desorption or by thermodesorption) and analysed together using gas chromatography coupled with mass spectrometry (GC-MS), a method for separating and identifying gas compounds (those which can be vaporised by heating with no decomposition). GC-MS enables the analysis of complex mixtures whose components differ considerably in nature and volatility.

21 EPA TO-4 and EPA TO-10 methods



Figure 7 - Pesticide collection devices for measuring air quality.

In the literature,²² there are two methods for assessing the exposure of populations to the pesticides present in the air.

A first set of methods is based on measurements of the presence of pesticides in the environment (outdoor and indoor air and in dusts) or in biological matrices (blood, serum, urine, breast milk, hair, etc.). A second set uses exposure estimates from information related to the potential use of pesticides near residential areas or statements of pesticide use in the home.

The use of pesticide collection from dusts or the air is an interesting method because the samples obtained in this way show **global aerial exposure**, *i.e.* combining exposure to outdoor use, for example for agriculture, and domestic use (antiparasite and gardening products), for example, for mosquitoes and fleas. The concentration levels in dusts can also highlight accumulated exposure over a (sometimes) long period (one to several months depending on the collection method) while measurements from biological matrices, like urine biomarkers, measure the presence of pesticides in the body at a given time. In a number of works, the exposure indicators are created from the quantity of pesticides thought to have been spread in an area. The quantity spread is estimated using the quantity of chemical substances sold to the farmers in the area or, more often, from the quantities of pesticides used according to the farmers' statements.

22 Results from C. ASCHAN-LEYGONIE, S. BAUDET-MICHEL, C. HARPET, M. AUGENDRE, É. LAVIE, É. GRÉSILLON and M. HECHINGER, "Comment évaluer l'exposition aux pesticides dans l'air de la population ?", *Bibliographical review*, 2015.



Figure 8 - Pesticides in the air: results of a 2016 study on air quality in Île-de-France
(38 chemicals detected out of a potential of 178)

■ Spatial and temporal distribution of pesticides in the air

The field studies carried out in France and Belgium (e.g.: the Expopestes study, 2014-2017) demonstrate that **phytopharmaceutical contaminants are present in outdoor air in both rural and urban areas**. Their presence is observed both during and outside of treatment periods, demonstrating **chronic contamination of the atmosphere**.

The spatial variability of the exposure levels to pesticides in the air can be explained by:

- Higher exposure to pesticides in the air **near fields** (analysis of dusts in homes and of concentrations in the urine of local residents).
- A link between the areas treated and resident exposure (the concentration of pesticides in the air of homes near fields **is higher during treatment periods** than outside of those periods).

The highest levels seen in the ambient air are **representative of the agricultural practices implemented** and of the crops (higher concentrations near orchards). The measurements carried out on agricultural sites dominated by field crops (cereals, maize, sunflower, rapeseed, etc.) showed a **significant presence** in the air of the active substances used for this type of crop.

The percentage of detection of certain chemicals is never zero (it can even reach 100% of samples). Some chemicals are **present 90% of the time** (11 months of the year) during long-term measurement studies (annual or multi-year). This means that there is **not necessarily an obvious link between the growing season** and the times when the pesticides are applied. This is particularly true for lindane, an insecticide banned since 1998.

Other chemicals have high detection percentages during the spring and summer only (folpel, tolylfluanid, chlorothalonil, endosulfan, etc.) or primarily in the fall, like pendimethalin. Lastly, there are also certain chemicals which have never or very rarely been seen (for example, diuron, chlortoluron, simazine and dichlorvos, which is very volatile). Some pesticides have seen their detection levels fall since they were banned, although they were very present before then. This is the case for atrazine, methyl parathion and parathion-ethyl. These three compounds have **nearly completely disappeared** from the ambient air in certain regions since their use was banned. On the other hand, it isn't uncommon to find many pesticides on passive collectors whose use was banned a long time ago. During dry years, for example, dust from the fields is carried far away, taking traces of the pesticides used many years before with it.



Chapter 3

Greenhouse gases and the carbon footprint

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The different methods of calculating GHGs in the agricultural sector	82

Training objectives:

At the end of this chapter, the trainee will be able to:

- Know the characteristics of the different greenhouse gases and their contribution to the problem of climate change
- Identify the sources of GHG emissions within a company
- Carry out a summary analysis of the GHG-emitting items in a company
- Understand the notion of 'carbon sinks'
- Compare different methods of calculating or estimating GHG emissions

1. GREENHOUSE GASES (GHGS) AND CLIMATE

1.1 Introduction

The mass of living matter is mainly in the vegetative or animal form on earth. The conditions encountered largely determine the distribution of resources, which can be assessed by the amount of plant mass present on a surface unit.

There is a close link between humans and climate types. Man prefers to settle in places where **living conditions are favourable** (particularly the availability of food). This explains the large variability observed in global population densities and migration over the centuries. Since the Neolithic period, it has been the agricultural sector (crop and animal production) that has provided most of man's food resources.

Climate change, now a global scientific reality, is an **additional constraint to** human existence and sustainable development. Agriculture contributes to this because of greenhouse gas (GHG) emissions, but also suffers from its impacts given its complexity, the number of people to feed and, above all, the challenges to be met.

The impacts of climate change are even greater in less developed and highly vulnerable countries such as ACP countries. However, the **agricultural sector can mitigate global warming** through the adoption of agricultural practices that promote **carbon storage** in the soil.

1.2. The sun, the main source of energy available on the Earth's surface

The energy available at the Earth's surface comes mainly from the sun in the form of flux or radiation. The average incident solar flux of an average of 342 W/m² arrives perpendicular to the Earth's surface after crossing the atmosphere under the influence of different mechanisms (Figure 1a). This energy consists of light radiation that may or may not be detected by the human eye at different wavelengths: ultraviolet (8%) at a wavelength of 0.2-0.4 µm, blue to red (41%) at a wavelength of 0.4-0.7 µm and near infrared (51%) at a wavelength of 0.7-3.0 µm (Figure 1b).

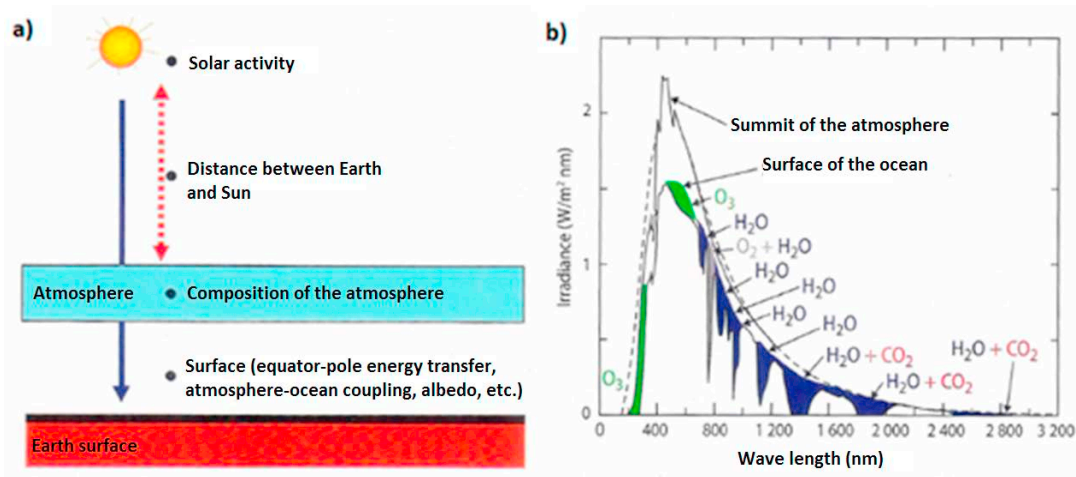


Figure 1: Main stages in the transmission of solar energy to the earth's surface and the different wavelengths (Mélières et Maréchal, 2015)

It should be noted that the composition of the atmosphere at the time of the crossing has a significant impact on the characteristics of solar radiation. Similarly, different mechanisms can occur at the Earth's surface via oscillations coupling large fluid reservoirs (mainly ocean and atmosphere), changes in the earth's energy absorption capacity and its distribution.

1.3 Composition of the atmosphere and energy balance of the earth at equilibrium

The atmosphere is the gaseous layer surrounding the earth and subdivided into layers of varying importance (troposphere, stratosphere, mesosphere, thermosphere and exosphere). It is **mainly composed of three** chemically weakly reactive **gases**:

- molecular nitrogen N₂ (78.08%) ;
- molecular oxygen O₂ (20.95%) ;
- argon Ar (0.93%).

These gases do not undergo phase change and their relative concentration is evenly distributed over the first 80 km of the atmosphere. Next come water vapour H₂O (on average 0.4%) and carbon dioxide CO₂ (0.039%). Other components are clouds, aerosols and other gases including methane CH₄, nitrous oxide N₂O and ozone O₃ that contribute little to atmospheric mass. Although these gases undergo a seasonal cycle, the content of CO₂, N₂O and CH₄ also remains homogeneous on an annual average. However, ozone and water vapour do not behave in the same way. The distribution of water vapour is strongly linked to evaporation and condensation.

The atmosphere is **mainly heated by three factors**:

- the absorption of a fraction (**G**) of the incident solar flux and a fraction (**K**) of the heat flux emitted by the earth's surface;
- the emission of the latent heat flow during the condensation of water vapour;
- direct heating of air in contact with the earth's surface. When the atmosphere emits the radiative flux (**I**) to the surface and the radiative flux (**J**) to space, it cools.

The Earth's surface is constantly heated by the fraction (**H**) of solar radiation transmitted directly through the atmosphere and by the heat flux (**I**) re-emitted by the atmosphere to the Earth's surface. The earth's surface cools as a result of the emission of latent heat fluxes (**E**), sensible heat (**F**) and radiative heat (**D**) emitted by the earth.

When the energy balance is balanced, the temperature is stable, $H+I = F+E+D$ and $E+F+G+K = I+J$.

As we can see, **the average temperature** remains one of the main parameters of climate change. This temperature generally results from an energy balance described by the exchanges of energy flows. The atmosphere also intervenes via the transversal and crucial role of the water cycle in the global climate system (e. g. distribution of precipitation on land) by:

- the energy transferred from the earth's surface to the various atmospheric layers from evaporation and condensation mechanisms;
- water vapour, which is the main contributor to the greenhouse effect;
- clouds that cool and warm both the Earth's surface (reflection of solar radiation and the greenhouse effect).

It should be noted that exchanges between the atmosphere and the Earth's surface are significantly influenced by natural, but also and above all anthropogenic, factors. Overall, the atmospheric layer plays an important role in the energy balance at the Earth's surface through the various mechanisms that interact with solar and land-based fluxes.

1.4. Climate and climate change

The amount of energy received at the Earth's surface and its distribution over the seasons is the main driver of climate. Indeed, the term²³ 'climate' would be derived from the Latin *Climatis* from the Greek *Klima* (inclination of the planet Earth towards the Pole). It determines the weather at a given location and is characterized by the main meteorological parameters (radiation, temperature, precipitation, humidity, pressure) allowing its best description.

These quantities are **variable on the Earth's surface** due to their annual average value and their evolution over the seasons. As a result, there are **different types of climate**, extremely varied according to Köppen's classification (Kottek et al., 2006): humid tropical, subtropical, dry tropical, subarctic, temperate and polar.



According to the UNFCCC (United Nations Framework Convention on Climate Change), "*climate change is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and is in addition to the natural climate variability observed over comparable time periods*".

23 Dictionary of the Académie Française, eighth edition, 1932-1935

Global warming refers to: significant changes in climatic conditions, exceptional phenomena with their frequencies, temperatures outside their usual average value ranges, feedbacks and a continuous increase in GHG concentrations (CO₂ in particular) in the atmosphere.

Climate change reflects all **statistically significant** global changes in the evolution of global climate over long periods of time (usually several decades or more), which are mainly anthropogenic in origin (IPCC, 2013).

Indeed, since 1750, human activities have contributed to significantly changing the chemical composition of the atmosphere. This feedback will continue to impact terrestrial life, natural ecosystems and development for a long time to come. A group of international experts was set up at the end of the 1980s to monitor the impacts caused by increasing GHG concentrations in the atmosphere. Their work showed that since the end of the 19th century the **average temperature at the Earth's surface has increased, by about +1°C at the end of the 20th century**. Several models predict a global warming of **more than 2°C by the end of the 21st century**, if nothing is done (IPCC, 2013). Such a situation would seriously jeopardize life, terrestrial ecosystems, socio-economic activities and our civilization, in other words, sustainable development.

1.5. The main GHGs and the principle of the 'greenhouse effect'

Overall, just over 50% of the sun's radiation is absorbed by the Earth's crust and oceans, 20% by the atmosphere and 30% directly returned by the atmosphere to space.

Visible short-wave **radiation** passes through the atmosphere before being absorbed by the earth's surface, which it heats. Some of the long wavelength thermal radiation emitted by the heated surface is partially absorbed by the atmosphere (especially by some gases present in low concentrations). The second part is transmitted directly to the space leaving the Earth's surface. The absorbed energy flows **heat the atmosphere and are then re-emitted in equal parts to space and the Earth's surface**.

Meanwhile, much of the **infrared radiation** emitted by the sun is captured by the atmosphere and **scattered back to the earth's surface**.

In short, the earth's surface receives (and absorbs) solar radiation that is completely transmitted through the atmosphere, but also a significant part of the infrared flux emitted by the earth's surface. The result of all these mechanisms is the warming of the earth's surface. This is **the greenhouse effect** (Figure 2).

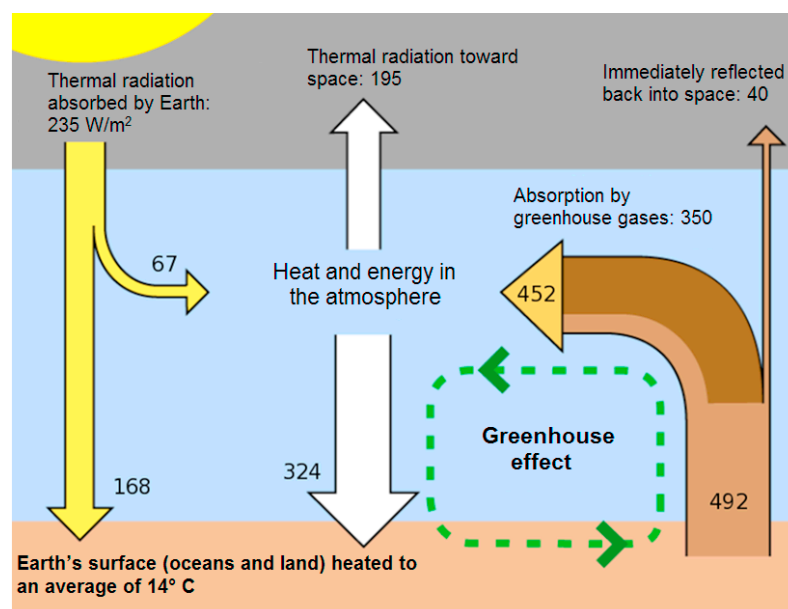


Figure 2: Evolution of solar radiation and the greenhouse effect (translated from <https://fr.wikipedia.org/wiki>)

The greenhouse effect is therefore a natural mechanism that retains heat from the absorption and re-emission of radiation into the atmosphere at the Earth's surface. The main greenhouse gases (GHGs) naturally present in the atmosphere are water vapour (H_2O), carbon dioxide (CO_2), ozone (O_3), methane (CH_4) and nitrous oxide (N_2O).

In the absence of these gases in the atmosphere, almost all of the radiation emitted in the infrared by the Earth's surface would escape. In this case, the earth's surface would maintain its global average temperature at -18°C and cool down more, making life on earth impossible. **The greenhouse effect maintains the global average surface temperature at $+15^\circ\text{C}$.** From this point of view, it is a fully understood mechanism based on well-established scientific principles, and crucial for living beings. Therefore it is not necessary to use models for its description and quantification.

This phenomenon is **totally different from** the reduction in ozone (O_3) concentration, mainly due to chemical destruction by certain compounds in certain layers of the atmosphere. Ozone absorbs the ultraviolet (highly energetic) radiation emitted by the sun, which has been very negative for living things.

The action of GHGs is confirmed by satellite observations of the flows emitted by the earth's surface on the one hand and through the atmosphere on the other. Mean surface temperatures on the earth's surface have also varied widely (from 5 to 7°C) between interglacial and glacial periods (Houghton, 1991). These results are explained by variations in GHG concentrations in the atmosphere, suggesting a **significant positive correlation between GHG concentrations and global average land surface temperatures**.

These observations ultimately make it difficult to determine the cause and effect between these two variables, which are essential for monitoring climate and its global changes. Apart from water vapour (H_2O), other GHGs remain in the atmosphere longer: on average 12 years for methane CH_4 , one century for carbon dioxide CO_2 , 120 years for nitrous oxide N_2O and over 50,000 years for some **halogenated gases** (CF_4 , others).

In recent years, **human activities** have seriously contributed to GHG emissions (Table 1), thus contributing to increasing their concentration in the atmosphere.

Table 1: Some sources of emissions of the main GHGs

Greenhouse gases	Emission sources	
	Natural	Human
Water vapour (H ₂ O)	<ul style="list-style-type: none"> • Water evaporation, especially over the oceans 	<ul style="list-style-type: none"> • Power plants • Irrigation
Carbon dioxide (CO ₂)	<ul style="list-style-type: none"> • Breathing of living beings • Forest fires • Volcanoes.... 	<ul style="list-style-type: none"> • Massive use of fossil fuels for transport, buildings and agriculture • Deforestation
Methane (CH ₄)	<ul style="list-style-type: none"> • Digestion of herbivores • Decomposition of plants • Volcanoes 	<ul style="list-style-type: none"> • Intensification of livestock (cattle) and crops (rice) • Garbage dump
Nitrous oxide (N ₂ O)	<ul style="list-style-type: none"> • Swamps 	<ul style="list-style-type: none"> • Use of nitrogen fertilizers
Lower atmospheric ozone (O ₃)	<ul style="list-style-type: none"> • Lightning 	<ul style="list-style-type: none"> • Industry • Car traffic
Fluorinated gases (CFCs, HFCs, PFCs)	<ul style="list-style-type: none"> • Do not exist in nature 	<ul style="list-style-type: none"> • Gases from aerosol cans and air conditioners

1.6. GHG liability in global warming

The greenhouse effect impacts the global average temperature recorded at the Earth's surface. Thus, any factor (natural or anthropogenic) that induces a significant variation in a term of the energy balance reinforces climate change. In recent decades, the most significant disruption has been **the continued increase in GHG concentrations in the atmosphere**. This has significantly altered the heating fluxes of the Earth's surface, causing radiative forcing that seriously disrupts the climate balance (IPCC 2013).

Métières and Maréchal (2015) had described the influence of the atmospheric composition in the global climate balance through three main mechanisms:

- the reflection of a part of the solar radiation that deprives the earth's surface of heat gain, thus cooling it;
- the absorption of a part of this same radiation, which also deprives the earth's surface of heat and thus cools it down;
- the absorption of thermal radiation emitted by the Earth's surface, which in turn heats it up through the greenhouse effect..

Indeed, the continuous increase in GHG concentrations in the atmosphere **amplifies the greenhouse effect**. One of the consequences is the **modification of the natural cycle of**

exchanges between the atmosphere and the Earth’s surface. Agriculture, Forestry and Other Land Use (AFOLU)²⁴ contributes significantly to total global anthropogenic GHG emissions (Figure 3).

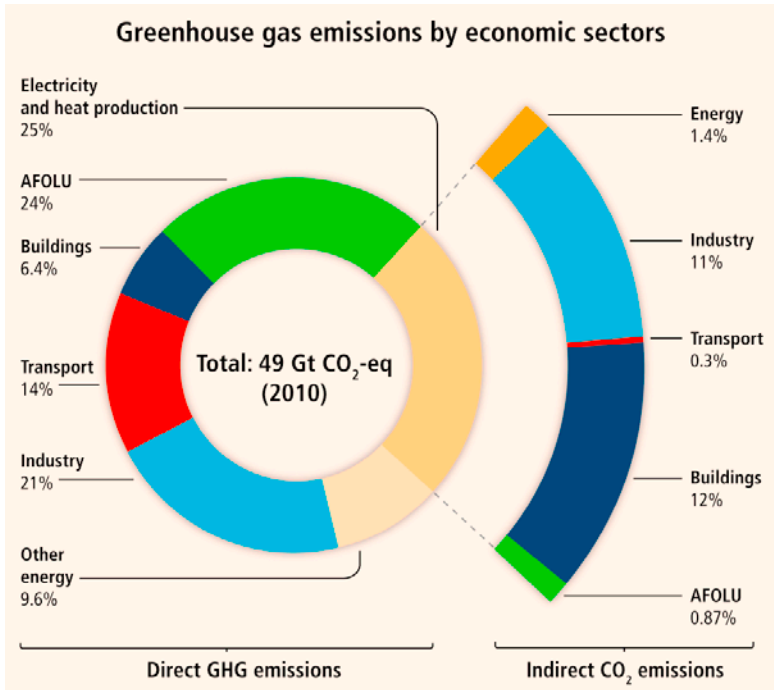


Figure 3: Distribution of global GHG emissions in 2010 by sector (IPCC Fifth Assessment Report)

While **energy and heat production remains the main source of emissions** (25%), land and forest use to meet various human needs (23%), industry (18%) and transport (14.1%) follow. Indeed, the exploitation of fossil fuels (coal, oil, natural gas and lignite) has grown rapidly throughout the world since the 19th century. According to recent studies, the whole **agriculture/food production sector could account for 35% of total global GHG emissions**. In particular, agriculture and forestry together emit 76% of methane, 89% of nitrous oxide (N₂O), 10% of nitrogen oxides (NO_x), 50% of biogenic VOCs and 97% of ammonia in the air²⁵.



Human activities often act not only through increased GHG concentrations, but also **through other effects** related to albedo, aerosol emissions and the water cycle.

Moreover, not all GHGs have the same impact on climate change. The contribution of a gas to the greenhouse effect is expressed through **the GWP26 indicator**, which corresponds to its effect on cumulative global warming over a 100-year period (IPCC, 2013). It applies to CO₂ (**1** by convention), CH₄ (**25**) and N₂O (**298**).

24 Agriculture, Forestry and Other Land Use (AFOLU) is a term from the 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines describing a category of activities which contribute to anthropogenic greenhouse gas emissions. Used in national greenhouse gas inventories, the AFOLU category combines two previously distinct sectors LULUCF (Land Use, Land Use Change and Forestry) and Agriculture

25 It should also be noted that NO_x and VOCs are real ozone precursors.

26 GWP=Global warming potential

A carbon dioxide equivalent or CO2 equivalent, abbreviated as CO2-eq is a metric measure used to compare the emissions from various greenhouse gases on the basis of their global-warming potential (GWP), by converting amounts of other gases to the equivalent amount of carbon dioxide with the same global warming potential. Carbon dioxide equivalents are commonly expressed as million metric tonnes of carbon dioxide equivalents, abbreviated as MMTCDE.

The carbon dioxide equivalent for a gas is derived by multiplying the tonnes of the gas by the associated GWP: $\text{MMTCDE} = (\text{million metric tonnes of a gas}) * [\text{GWP of the gas}]$.

For example, the GWP for methane is 25 and for nitrous oxide 298. This means that emissions of 1 million metric tonnes of methane and nitrous oxide respectively is equivalent to emissions of 25 and 298 million metric tonnes of carbon dioxide.

Source: EUROSTAT, 2019

Radiative forcing also makes it possible to assess the impact of GHGs on the global climate system and compare them (Figure 4). It represents the specific greenhouse effect induced by the gas. According to the IPCC (2013), the greatest contribution to climate change comes from the continuous increase in CO₂ content in the atmosphere since 1750. The calculated total radiative forcing gives a positive value confirming the effective warming of the global climate system. However, if GHG emissions stopped, global warming, and especially its impacts, would only stop after 100 years because of the particularities of GHGs and especially the chain reactions often generated (IPCC, 2013).

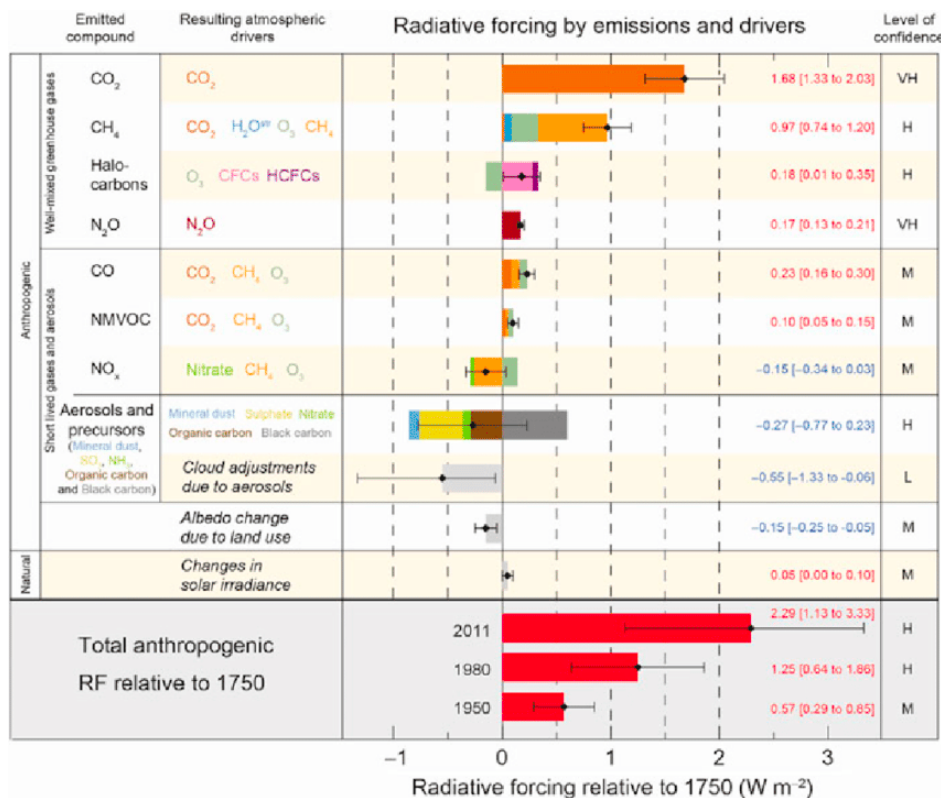


Figure 4: Estimates of the average Radiative Forcing in 2011 compared to 1750 and associated uncertainties regarding the main factors of climate change (IPCC, 2013)

1.7 Role of fossil fuels in GHG emissions

The satisfaction of man's vital needs (lighting, cooking, production, mobility, comfort, communications, etc.) depends on the availability of energy services. In the 21st century, the **growth of the world's population**, industrial development and accelerated urbanization are also accompanied by a strong and rapidly expanding demand for energy. As a result, there is a continuous increase in energy **demand** and related services everywhere, from 5,500 Mtoe²⁷ in 1971 to 10,300 Mtoe in 2002. For the year 2030, this global energy growth would be estimated at 16,500 Mtoe (IEA²⁸ 2004).

As for global marketed energy production, it was estimated at 13,276 Mtoe in 2016 by Bristish Petroleum (BP), which already showed an 18% increase compared to 2006. This energy production is divided into 33.0% oil, 27.5% coal, 24.2% natural gas, 4.5% nuclear and 10.7% renewable energy (hydroelectricity 6.9%, wind 1.6%, biomass and geothermal 1.0%, biofuels 0.6%, solar 0.6%).

Since 1850, **fossil fuels** (coal, oil and natural gas) have played an important role in securing most of the world's energy supply. They are generally made up of mixtures of carbon-rich compounds from the fossilization of organic matter. The composition varies according to the complex and diverse origins of the deposits. The organic compounds resulting from the transformation processes are **toxic to living organisms**. In addition, the latter can generate new compounds with oxygen from the air, some of which are toxic in a live combustion reaction. The importance of this form of energy has led in recent years to the overexploitation of natural resources around the world, significantly changing our environment.

Indeed, **world energy consumption has continued to increase** since the industrial revolution, rising from 1,500 in 1945 to 13,511.2 Mtoe in 2017. It remains largely dominated by fossil fuels with 85.2% of contribution in 2017 and divided into 34.2% oil, 27.6% coal and 23.4% natural gas. According to the IPCC (2013), the trend continued in 2008 (Figure 5).

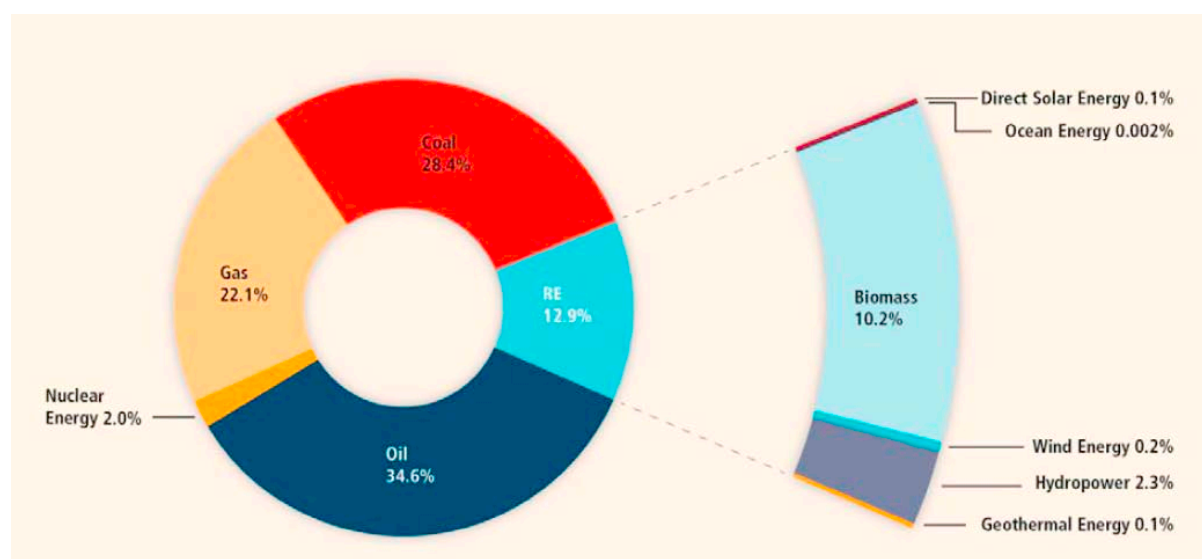


Figure 5: Proportion of various energy sources in the total global primary energy supply in 2008
(from IPCC, 2013)

²⁷ Mtoe means Megatonne of oil equivalent
²⁸ IEA means International Energy Agency

In addition, raw materials are subjected to various treatments leading to the final product to be marketed, are stored and transported often over long distances. The transformation process consists of extracting fossil fuels from the ground and carrying out appropriate treatments. Present in the subsoil and used for millions of years, these fuels are depleted with exploitation because they are in limited and non-renewable quantities.

By following the main stages of production and use of fossil energy sources, the following emissions can be distinguished (Landrieu, 1994):

■ Fuel extraction

Fossil fuel operations are generally preceded by major excavations, the destruction of ecosystems including fauna and flora, the appearance of subsidence or ravines, the alteration of the quality of water resources, the loss of biodiversity and drilling mud. These actions are accompanied by emissions into the atmosphere of deposit gases as well as those resulting from combustion processes or those stored in destroyed ecosystems.

■ Fuel preparation and transport installations

The preparation and especially the transport of fossil fuels requires heavy infrastructure (roads, ports, refinery pipes, storage,...) in specific areas such as coasts and valleys. Some operations (refining, others) emit gaseous organic compounds and toxic liquids (phenols, ammonia products,...) into the atmosphere. Also, the operation of the entire system requires energy that is often produced on site with the combustion of part of the fuel concerned. This option generates significant emissions of gases and toxic compounds into the atmosphere.

■ Fuel use equipment

The transformation of chemical energy from fossil fuels, the operation of machinery and power plants produce heat and generate significant emissions of gases and toxic compounds into the atmosphere.

■ Existence of leaks during fuel supply chains

Oil spills are often recorded in the oil sector. Offshore oil accidents (oil spills, pipeline ruptures) are significant (about 0.1% of the volume transported at sea). Atmosphere-ocean exchanges are often poisoned because rivers and oceans are loaded. Similarly, volatile hydrocarbon losses (0.3% of the total flow) occur during storage operations. Some of it, including methane, escapes into the atmosphere throughout the natural gas chain. Volatile matter also escapes into the atmosphere during coal mining operations. The storage and handling of coal leads to significant emissions of toxic materials (storage exposed to the wind, uncovered vehicles).

■ The final release of combustion products

Coal and crude oil contain sulphur, but the average shipment contains 1% of their weight in sulphur. In the presence of oxygen in the air, combustion produces nitrogen oxides

(**NO_x**) by oxidation of the organic nitrogen in the fuel or in the air. When combustion is incomplete, there are emissions of carbon monoxide (**CO**), unburned (**C** particle), polycyclic aromatic hydrocarbons (**PAHs**) and other volatile organic compounds (**VOCs**). In complete combustion, compounds of carbon dioxide (**CO₂**), water vapour (**H₂O**) and sulphur dioxide (**SO₂**). However, there are specific treatments that limit nitrogen oxide emissions. But the process also leads to the production of other solid waste. It should be noted that transport vehicles used at operating sites induce emissions of carbon monoxide and volatile organic compounds. During combustion, nitrogen oxides are produced with relatively high rates in engines.

Ultimately, the production and use of fossil fuels generate the emission of gaseous compounds, in particular **CO₂**, **CH₄** and **N₂O**. To date, their use remains the main source of anthropogenic **CO₂** emissions. In 2017, these emissions were 9.9 ± 0.5 GtC and accounted for 82% of the total (Le Quere et al., 2018). This continuous growth of CO₂ due to the use of fossil fuels continues to increase the greenhouse effect, and consequently global warming, which is reflected in the increase in the average temperature at the earth's surface.

1.8. Quick review of other energy sources and their advantages or disadvantages

Mastering the energy sector (from production to consumption) remains one of the major challenges of our century, especially in a context of sustainable development. This is the framework provided by Sustainable Development Goal (SDG)²⁹ “Ensure access for all to reliable, sustainable and modern energy services at an affordable cost”. To achieve this, it will be necessary not only to focus on all forms of energy, but also and above all to adopt relevant strategies to achieve SDG 13 “Take urgent action to combat climate change and its impacts”.

In addition to fossil fuel, other forms of energy (hydropower, biofuel, geothermal, biomass, solar and wind) have a role to play because of their 20% contribution to global consumption. In 2016, total global energy-related CO₂ emissions **were 33,432 Mt., up 13.6% from 2006 and 54.8% from 1990**. Clearly, **other energy sources also induce significant GHG emissions into the atmosphere**. In 2009, PICIR²⁹ demonstrated that by 2050, no more than 565 Gt of CO₂ should be emitted to keep 80% of the chances of being below 2°C. Each of the energy sources has advantages and disadvantages (Table 2).

²⁹ Postdam Institute for Climate Impact Research

Table 2: Advantages and disadvantages of the main energy sources

Energy sources	Advantages	Disadvantages
Fossil energy	<ul style="list-style-type: none"> • In stock • Acceptable cost 	<ul style="list-style-type: none"> • Limited, exhaustible stock • Demand and costs increase • Increasingly expensive exploitation • Significant pollution • Significant emission of CO₂ and other GHGs
Nuclear energy	<ul style="list-style-type: none"> • In stock • High energy power • Almost no GHG emissions • Possible increase in stock life expectancy 	<ul style="list-style-type: none"> • Limited, exhaustible stock • Radioactive waste difficult to recycle • Very dangerous in case of accident
Wind energy	<ul style="list-style-type: none"> • Unlimited • Clean energy 	<ul style="list-style-type: none"> • Flow energy • Difficult storage • Batch production • Heavy installation on large surfaces
Solar energy	<ul style="list-style-type: none"> • Unlimited • Clean energy • High development potential 	<ul style="list-style-type: none"> • Flow energy • Difficult storage • Batch production • High cost
Hydraulic energy	<ul style="list-style-type: none"> • High development potential • Clean energy • Mastered technology 	<ul style="list-style-type: none"> • Geographical constraints • Impact on the ecosystem • Heavy investments
Biomass	<ul style="list-style-type: none"> • Energy considered clean 	<ul style="list-style-type: none"> • Low energy efficiency • Risk of destabilization of the ecosystem (deforestation, degradation,...), increased land use competition
Geothermal energy	<ul style="list-style-type: none"> • In stock • Clean energy 	<ul style="list-style-type: none"> • Geographical constraints • Low energy efficiency

2. THE MAIN INTERNATIONAL AGREEMENTS RELATING TO GHGS

2.1 Introduction

Climate Change is the defining issue of our time and we are at a defining moment. From shifting weather patterns that threaten food production, to rising sea levels that increase the risk of catastrophic flooding, the impacts of climate change are global in scope and unprecedented in scale. Without drastic action today, adapting to these impacts in the future will be more difficult and costly.

The international community is constantly defining strategies and measures to limit global warming to less than 2°C.

2.2. The UN Intergovernmental Panel on Climate Change (IPCC)³⁰

The Intergovernmental Panel on Climate Change (IPCC) was set up by the World Meteorological Organization (WMO) and United Nations Environment to provide an objective source of scientific information. In 2013 the IPCC provided more clarity about the role of human activities in climate change when it released its *Fifth Assessment Report*. It is categorical in its conclusion: climate change is real and human activities are the main cause.

The *Fifth Assessment Report* provides a comprehensive assessment of sea level rise, and its causes, over the past few decades. It also estimates cumulative CO₂ emissions since pre-industrial times and provides a CO₂ budget for future emissions to limit warming to less than 2°C. About half of this maximum amount was already emitted by 2011. The report found that:

- From 1880 to 2012, the average global temperature increased by 0.85°C.
- Oceans have warmed, the amounts of snow and ice have diminished and the sea level has risen. From 1901 to 2010, the global average sea level rose by 19 cm as oceans expanded due to warming and ice melted. The sea ice extent in the Arctic has shrunk in every successive decade since 1979, with 1.07×10^6 km² of ice loss per decade.
- Given current concentrations and ongoing emissions of greenhouse gases, it is likely that by the end of this century global mean temperature will continue to rise above the pre-industrial level. The world's oceans will warm and ice melt will continue. Average sea level rise is predicted to be 24–30 cm by 2065 and 40–63 cm by 2100 relative to the reference period of 1986–2005. Most aspects of climate change will persist for many centuries, even if emissions are stopped.

There is alarming evidence that important tipping points, leading to irreversible changes in major ecosystems and the planetary climate system, may already have been reached or passed. Ecosystems as diverse as the Amazon rainforest and the Arctic tundra, may be approaching thresholds of dramatic change through warming and drying. Mountain glaciers are in alarming retreat and the downstream effects of reduced water supply in the driest months will have repercussions that transcend generations.

In October 2018 the IPCC issued a special report on the impacts of global warming of 1.5°C, finding that limiting global warming to 1.5°C would require rapid, far-reaching

30 Text extracted from : <https://www.un.org/en/sections/issues-depth/climate-change/index.html>

and unprecedented changes in all aspects of society. With clear benefits to people and natural ecosystems, the report found that limiting global warming to 1.5°C compared to 2°C could go hand in hand with ensuring a more sustainable and equitable society. While previous estimates focused on estimating the damage if average temperatures were to rise by 2°C, this report shows that many of the adverse impacts of climate change will come at the 1.5°C mark.

The report also highlights a number of climate change impacts that could be avoided by limiting global warming to 1.5°C compared to 2°C, or more. For instance, by 2100, global sea level rise would be 10 cm lower with global warming of 1.5°C compared with 2°C. The likelihood of an Arctic Ocean free of sea ice in summer would be once per century with global warming of 1.5°C, compared with at least once per decade with 2°C. Coral reefs would decline by 70-90 percent with global warming of 1.5°C, whereas virtually all (> 99 percent) would be lost with 2°C.

The report finds that limiting global warming to 1.5°C would require **“rapid and far-reaching” transitions** in land, energy, industry, buildings, transport, and cities. Global net human-caused emissions of carbon dioxide (CO₂) would need to fall by about 45 percent from 2010 levels by 2030, **reaching ‘net zero’** around 2050. This means that any remaining emissions would need to be balanced by removing CO₂ from the air.

2.3. The United Nations Framework Convention on Climate Change (UNFCCC)³¹

Climate change is a complex issue, which, although environmental in nature, has implications for many global issues such as poverty, economic development, population growth, sustainable development and resource management. The response to climate change requires a reduction in emissions. **In 1992, countries joined an international treaty** – the United Nations Framework Convention on Climate Change (UNFCCC) – to consider what could be done to reduce global warming and deal with any unavoidable temperature increases. With 197 parties, the United Nations Framework Convention on Climate Change (UNFCCC) enjoys almost universal adherence.

The UNFCCC provides a comprehensive **framework for the intergovernmental effort** to address the challenge of climate change

2.4. The Kyoto Protocol

When they adopted the United Nations Framework Convention on Climate Change (UNFCCC), governments knew that their commitments would not be enough to seriously address climate change. In 1995, in a decision known as the Berlin Mandate, the parties to the Convention began a round of negotiations to decide on stronger and more detailed commitments for industrialized countries. After two and a half years of intense negotiations, **the Kyoto Protocol was adopted in Japan on 11 December 1997**. The Kyoto Protocol has been ratified by 172 countries and has been in force since 2005. It sets a limit for the world's major economies on total greenhouse gas (GHG) emissions. An initial commitment period ran from 2008 to 2012. The **second commitment period** started on 1 January 2013 and runs until 2020. The Protocol now has 192 Parties.

31 Text extracted from : <https://www.un.org/en/sections/issues-depth/climate-change/index.html>

This text had set legally binding targets for significant reductions in GHG emissions for the industrialized signatory countries. These countries had collectively made a firm commitment to reduce their emissions by 5% compared to 1990 levels over the period **2008-2012**. These are Canada (-6%), Japan (-6%), France (0%), the European Union (-8%), New Zealand (0%) and Australia (-8%). It should be noted that this agreement concerned only six GHGs: carbon dioxide (**CO₂**), methane (**CH₄**), nitrous oxide (**N₂O**), hydrofluorocarbons (**HFCs**), sulphur hexafluoride (**SF₆**) and perfluorocarbons (**PFCs**).

The main measures suggested by the protocol concern energy, CO₂ emissions (transport, industry, energy production, housing) and those related to deforestation. Direct CH₄ and N₂O emissions from agriculture (livestock and crops) were neglected although this sector was the main source of GHG emissions in some countries such as Brazil, Argentina and New Zealand (30-50% of the national total). Reduction actions in agriculture were addressed through technological cooperation (bilateral and multilateral exchanges on agricultural practices, support for research programmes). The themes of 'agriculture' and 'climate change' were part of the adaptation measures. NAPAs³² had developed agricultural development strategies that had contributed to reducing vulnerabilities to the present and future impacts of climate change.

The conditions to be met by industrialized countries to account for GHG emissions related to the land use change (LUC)³³, assess potential soil and forest carbon sinks were specified. The **LULUCF**³⁴ component covers harvesting and forest growth, grasslands, forest conversion (clearing) and carbon-rich soils sensitive to the nature of activities. It represents a significant part of the GHG emissions balance sheet in some countries.

In France, for example, CO₂ emissions decreased by 7% between 1990 and 2006 by including LULUCF, but increased by 2% excluding LULUCF. Article 3.4 had allowed some countries to account for activities that contribute to carbon sequestration other than those covered by article 3.3 such as improving vegetation cover (forest management, agricultural land and pasture).

Similarly, the Clean Development Mechanism (CDM) has enabled industrialized countries to implement projects that reduce GHG emissions in developing countries (DCs). In return, these emissions reductions were accounted for by industrialized countries, thus meeting their own GHG emission reduction targets. This mechanism had promoted the cooperation of international mitigation financing instruments, particularly in agriculture. For example, several projects to treat pig manure and substitute fossil energy with agricultural biogas had been developed in India, Mexico, Chile and Thailand. However, the CDM has encountered difficulties in the agricultural sector. **A CDM project must prove the effective reduction of GHG emissions in an LDC before being eligible for 'carbon' credits.** Carbon sequestration did not automatically generate "carbon" credits because they were temporary, risky, poorly documented and difficult to measure. The CDM is one of the project opportunities seized by some African countries.

In December 2009 in Copenhagen, the 15th Conference of the Parties (COP) took place, which laid the foundations for the post-2012 period, marking the end of the first commitment period of the Kyoto Protocol. No agreement had been reached due to disagreements over emission reduction targets and financing for the poorest countries

32 National Adaptation Programmes of Action

33 Land use change

34 Land Use, Land Use Changes and Forestry

for low-carbon development. The final decision was **a non-binding roadmap** that would still keep the temperature below 2°C.

Interesting proposals had emerged to **reduce or prevent GHG emissions in agriculture** with better research cooperation on mitigation, adaptation, transfer of technologies, practices and processes. A work programme on methodological issues and agricultural policy approaches was discussed in order to fully include these aspects in the post-2012 regime. A global network such as “GRAG³⁵” had promoted significant investment and coordination in agricultural GHG mitigation research. In 2010, a work programme on agriculture addressed scientific, methodological and technical issues related to the implementation of mitigation and adaptation actions, making this sector one of the most important.

2.5. The Paris Agreement

The Paris Agreement follows the negotiations held at the Paris Climate Conference (COP21) of the United Nations Framework Convention on Climate Change. This agreement is part of the second commitment period of the parties to the UNFCCC and the Kyoto Protocol to continue the fight against climate change and to intensify actions and investments for a sustainable low-carbon future. It brought together for the first time all nations for ambitious climate efforts with increased support to help developing countries. Opened for signature on 22 April 2016 (Earth Day) in New York at United Nations Headquarters, it entered into force on 4 November 2016. On that day, the ‘double threshold’ (ratification by 55 countries representing at least 55% of global emissions) was reached. Since then, more countries have ratified the agreement and continue to do so, reaching a total of 183 of the 197 parties to the Convention as of 26 August 2019.

Under the agreement, parties committed to taking ambitious action to keep the global temperature rise below 2°C by the end of the century. It aims to increase the capacity of countries to cope with the impacts of climate change and to make financial flows compatible with low levels of GHG emissions. It is important to mobilise and allocate substantial financial resources. A new technological framework and capacity building are needed to support action by developing countries, especially the most vulnerable, within a framework of increased transparency for action and support.

All Parties shall submit Nationally Determined Contributions (NDCs) and strengthen their efforts with regular reporting of their emissions and implementation efforts. A global review will be conducted every five years to assess collective progress. In order to operationalize the agreement, a work programme has been launched to develop modalities, procedures and guidelines, some aspects of which are:

- Long-term temperature objective (art. 2);
- Global emissions cap and ‘climate neutrality’ (art. 4);
- Mitigation (art. 4) ;
- Wells and tanks (art.5);
- Voluntary cooperation/Founded and non-market-based approaches (art. 6);
- Adaptation (art. 7);

35 Global Research Alliance on Agricultural Greenhouse Gases

- Losses and damages (art. 8);
- Support for financing, technology and capacity-building (arts. 9, 10 and 11);
- Climate change education, training, public awareness, participation and access to information (art. 12);
- Transparency (art. 13);
- Implementation and compliance (art. 15);
- Global review (art. 14);
- Decision 1/CP.21.

The **Green Climate Fund** (GCF) is an entity responsible for the operation of the COP's financial mechanism. It is the most recent to enter the multilateral architecture for climate financing, adaptation and mitigation on an equal footing (50%). Operational since 2015, it is the largest multilateral climate fund and is designed to mobilize significant funding over time. All activities with low GHG emissions are eligible. Several projects have already been approved and others are under study.



2.6. Climate Summit in 2019

In September 2019, Secretary-General António Guterres will convene a Climate Summit to bring world leaders of governments, the private sector and civil society together to support the multilateral process and to increase and accelerate climate action and ambition. He has named Luis Alfonso de Alba, a former Mexican diplomat, as his Special Envoy to lead its preparations. The Summit will focus on key sectors where action can make the most difference—heavy industry, nature-based solutions, cities, energy, resilience, and climate finance. World leaders will report on what they are doing, and what more they intend to do when they convene in 2020 for the UN climate conference, where commitments will be renewed and may be increased.

3. CARBON AND NITROGEN CYCLES

3.1. Carbon flows in 'culture' and 'ecosystem'

Carbon dioxide CO_2 is one of the key elements of the earth's life cycle. Together with water vapour and light, it constitutes the first links of living matter. Initiator of life, it is also the final product of its degradation. Indeed, chlorophyll plants (crops, forests...) absorb a quantity of the CO_2 contained in the atmosphere through the process of photosynthesis (Figure 6). The amount of carbon thus assimilated for its operating needs (maintenance, growth and energy) is called **gross primary production (GPP)**.

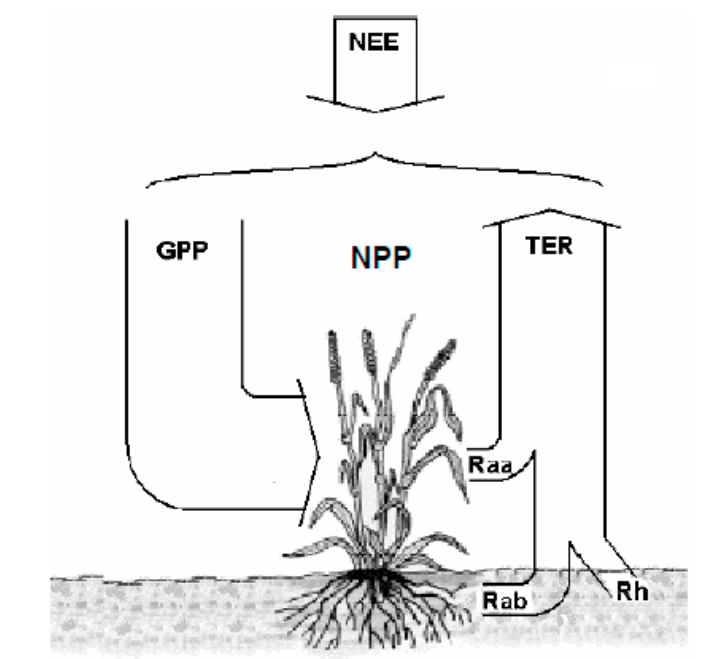


Figure 6: Representation of CO_2 flows exchanged between a culture and the atmosphere (Moureaux, 2008)

In addition, the ecosystem (plant and soil) will release CO_2 back into the atmosphere through the process of respiration. This flux refers to the sum of the respiration of the aerial parts of the plant (R_{aa}), that of the roots (R_{ab}) and the CO_2 emissions resulting from the decomposition of organic matter (R_h). The terrestrial ecosystem respiration (**TER**) represents the sum of these flows.

Net ecosystem exchange (NEE) represents the balance of these two important, but opposite flows (GPP and TER) between the atmosphere and the culture or ecosystem.

Some of the assimilated CO_2 called net primary production (NPP) is stored in vegetation. Apart from ecosystem-atmosphere exchanges, exports (**CExp**) (harvesting, harvesting, grazing...) or imports (**CImp**) of carbon (chemical or organic fertilizer, manure...) can take place.

The balance of **all carbon flows** (GPP, TER, CImp, CExp) refers to the **gross productivity of the Net Biome Production (NBP)**. Finally, the important terms are obtained by the following expressions:

$$\text{NEE} = \text{NPP} + R_h ; \quad \text{NEE} = \text{GPP} + \text{TER} ; \quad \text{NBP} = \text{NEE} + \text{CImp} + \text{CExp}$$

These equations form the **basis for designing techniques or methodologies to measure or estimate CO₂ exchanges between the atmosphere and a terrestrial ecosystem** (Ago *et al.*, 2016). By convention, incoming flows into the ecosystem are counted negative (with a - sign) and positive (with a + sign). The sign of NBP or NEE according to the authors determines the behaviour of the ecosystem over a given period, usually a year: carbon '**sinks**' if $NBP < 0$; '**source**' if $NBP > 0$ and in **equilibrium if $NBP = 0$** . Forests, oceans, meadows, savannahs behave like '**carbon sinks**' until they reach an equilibrium. As for agrosystems, they act as sinks, but also as carbon sources, depending in particular on the degrees of anthropogenic disturbances and their impacts on carbon flows.

3.2. The global carbon cycle

The global carbon cycle consists of carbon exchanges between the major reservoirs: the oceans, the atmosphere and terrestrial ecosystems (fossil resources, biomass and soil). It includes atmosphere-biosphere and ocean-atmosphere exchanges (Figure 7).

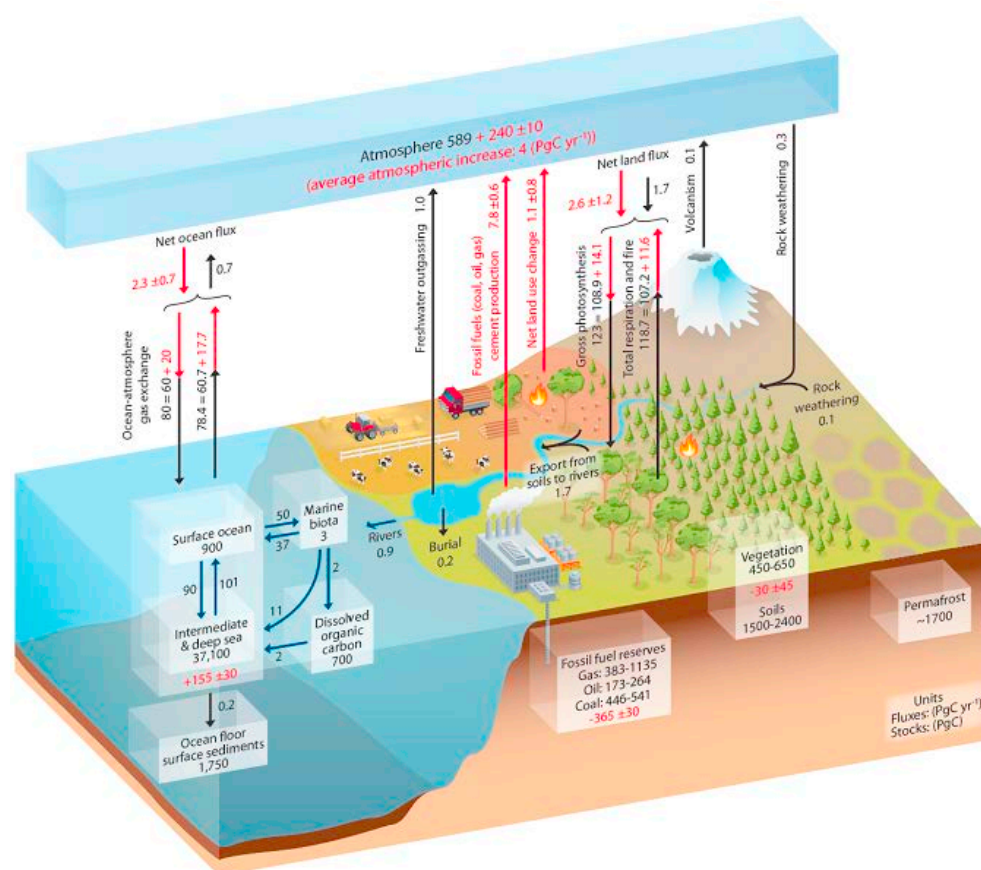


Figure 7: Representation of estimated carbon stocks and major disruptions to the global carbon cycle caused by human activities. The red arrows represent additional flows due to human activities, averaged over the period 2000-2009 and the arrows represent 'natural' flows at equilibrium (IPCC, 2013)

Carbon circulates in varying proportions between the different reservoirs. In particular, a double flow is observed between the atmosphere and terrestrial biomass: photosynthesis and respiration. Indeed, through the process of photosynthesis, chlorophyll plants absorb CO₂ contained in the atmosphere which they assimilate for their operating needs (maintenance, growth and energy). Some of this carbon is **transferred to living beings** (including humans) **that feed on plants** while the other part is incorporated into the

soil through the excrement and death of living beings. The carbon incorporated into the soil **then integrates the humus** via the activity of the micro-organisms. CO_2 emissions from terrestrial ecosystems are produced by respiration processes (heterotrophic and autotrophic). These two important flows of the same order of magnitude, but in opposite directions, are the driving forces behind the CO_2 exchanges between the biosphere and the atmosphere.

Some of the carbon in the depths of terrestrial ecosystems is transformed into hydrocarbons over tens of thousands of years, building up fossil energy reserves (gas, oil, coal). The oceans also absorb carbon, mainly by dissolution in the form of bicarbonate and by photosynthesis of marine flora.

It should be noted that some of the methane CH_4 emitted is oxidized once in the atmosphere and rapidly converted into CO_2 . **Methane (CH_4) generally comes from livestock farming, peat bogs, rice fields and landfills.**

In its natural state, the global carbon cycle is relatively in equilibrium. In recent decades, anthropogenic CO_2 emissions have been an important component of the global carbon cycle (IPCC, 2013). In 2017, the planet's total anthropogenic CO_2 emissions were estimated at 11.3 ± 0.9 Gt, of which 24% were absorbed by the oceans, 31% by terrestrial ecosystems and 45% remained in the atmosphere (Le Quere et al., 2018), further enhancing global warming.

3.3. The nitrogen cycle

The atmosphere is made up of about 78% nitrogen (N), one of the elements essential to the living because it is found in proteins. The nitrogen cycle consists of several processes combining the actions of a multitude of bacteria (Figure 8):

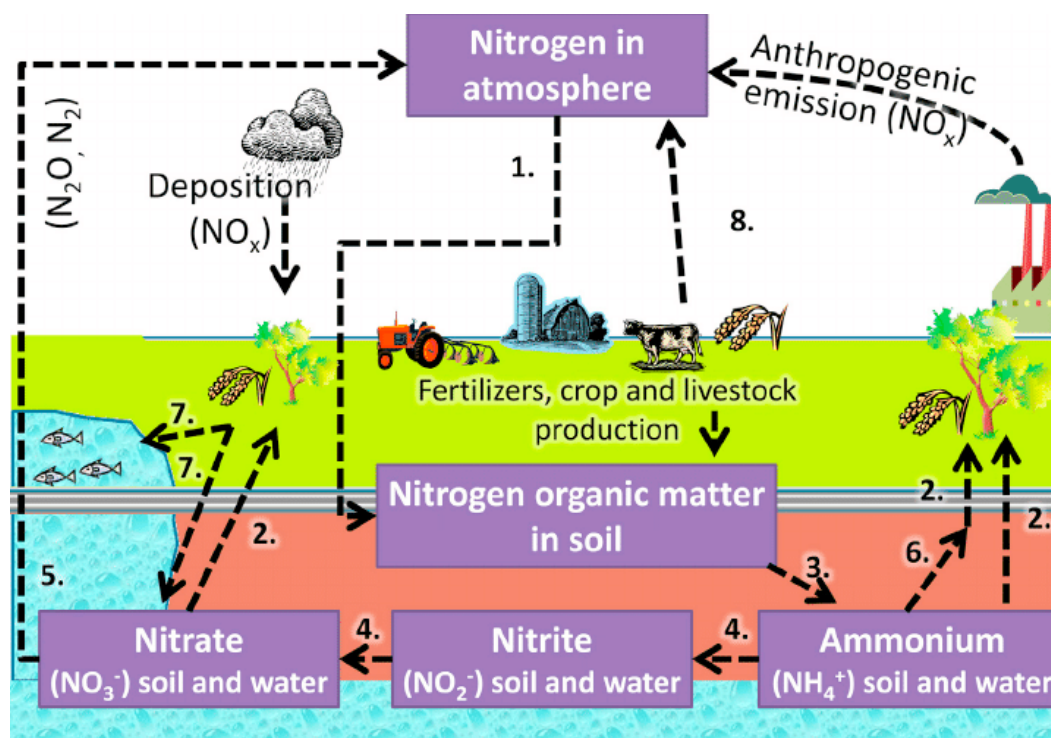


Figure 8: The nitrogen cycle: explanation of the various emissions into the atmosphere

- **The fixation of atmospheric nitrogen** (N_2) by plants **via bacteria** in the soil or legumes (soya, beans, cowpeas, vandas, lentils, cajanus, mucuna,...). It is converted into mineral nitrogen (NH_4^+) before being assimilated by living organisms. These plants, which are very rich in nitrogen, are used in human and animal feed (direct nitrogen flow). It should be noted that NH_4^+ adsorbed on clay-humic complexes or in solution in the soil is most often transformed into ammonia (NH_3). The nitrogen consumed returns to the soil upon the death of living things or through feces.
- **Nitrification**, a process that transforms the products of fixation (NH_4^+ , NH_3) into NO_x (e. g. nitrates, NO_3^-) in soils low in oxygen (O_2) thanks to certain bacteria, thus making nitrogen available to living beings.

Nitrification: $NH_4^+ + \text{(nitrosomas)} \leftrightarrow NO_2^- \text{ (nitrobacter)} \rightarrow NO_3^- \text{ (nitrates)}$

- Denitrification, which again produces atmospheric nitrogen in its molecular form (N_2) with carbon dioxide CO_2 and nitrous oxide N_2O as secondary products of this reaction.

Denitrification: $NO_3^- \leftrightarrow N_2O / N_2 \uparrow$ (nitrous oxide / dinitrogen)

However, these processes are **very slow** and the excessive use of nitrogen fertilizers and agricultural effluents could limit the assimilation processes of NH_4^+ ammonium, NH_3 ammonia and NO_3^- nitrates (the most common forms of ionization of nitrogen fertilizers).

4. THE MAIN SOURCES OF GHGS IN THE AGRICULTURAL SECTOR

4.1. Origin of GHG emissions

GHG emissions, mainly CO_2 , CH_4 and N_2O observed in agriculture, come from upstream, inside and downstream of farms (Figure 9).

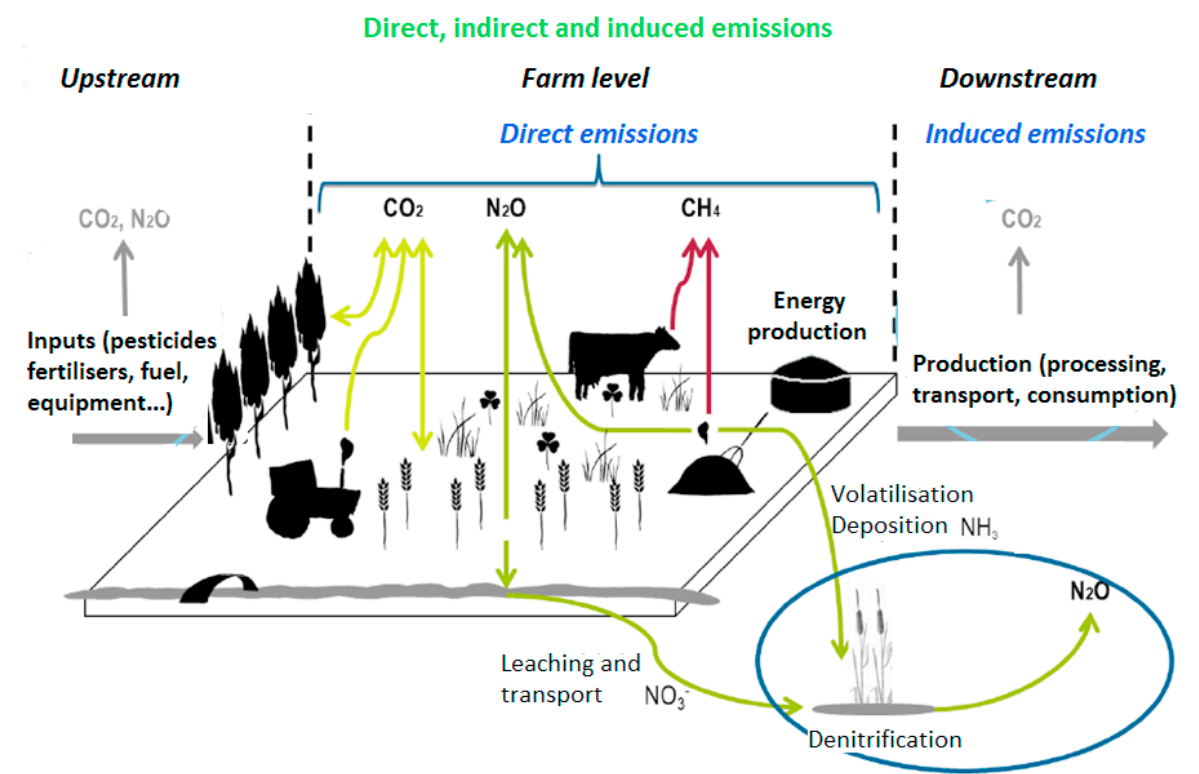


Figure 9: Main sources of GHG emissions in agriculture (Pellerin, 2017)

They mainly concern crop and animal production, the agri-food industries, the use of fertilisers, plant protection treatment and transport. In particular, the main areas of responsibility are **enteric fermentation** (CH_4), **nitrogen inputs to agricultural soils** (N_2O), **livestock manure management and storage** (CH_4 , N_2O), **biomass or agricultural waste burning** (CO_2 , CH_4 , N_2O), **phytosanitary treatment** (CO_2), **conversion of grasslands to agricultural land** (CO_2 , CH_4 , N_2O), **rice cultivation** (CH_4) and **transport** (CO_2).

In developing countries (particularly ACP countries), very few experiments, studies and measures are carried out on the assessment of GHG emissions in agriculture. Most analyses are more qualitative than quantitative (FAO, 2017). The reasons for the situation are multiple and concern:

- the inadequacy of research programs to evaluate practices;
- the lack of capacity of the various actors;
- the lack of significant financing in the sector. However, commendable efforts are increasingly being made and need to be supported. The quantification of emissions and impacts will help to better discuss mitigation and adaptation actions to be taken in the sector. Taking into account the cost-benefit analysis of the different practices would also be decisive at all the stages concerned.

In West Africa, average CH_4 emissions amount to 7,200,000 kg per season in rice crops (Djaby and Ozer, 2013). The Intensive Rice Growing System reduced CH_4 emissions, but increased N_2O emissions in high manure use systems. In Benin, about 68% of total GHG emissions come from agriculture (UNFCCC, 2013). In 2015, total agricultural emissions were estimated at 4,863.69 Gg CO_2 eq (PRBACC, 2018).

Enteric fermentation represents in Benin country the largest contribution to GHG emissions with 56.47% of the total. It is followed by cultivated soils (36.51%), manure management (3.97%), rice cultivation (1.96%), burning crop residues (0.83%) and urea application (0.26%). Considering the three main GHGs (CO_2 , N_2O and CH_4), methane emissions dominate significantly with 61.47% of the total compared to 38.27% for nitrous oxide and 0.26% for carbon dioxide. This importance of methane results from the importance of enteric fermentation and manure management.

4.2. Carbon dioxide CO_2

Carbon emissions in agriculture are mainly due to the use of machinery (fuel), agricultural practices and the conversion of natural ecosystems (forests, savannahs, grasslands, etc.) into agricultural plots.

4.2.1. Energy consumption

The operation of machinery and the heating of greenhouses or livestock buildings on farms consumes fuel (fossil energy), a source of CO_2 emissions. Emissions depend on the types of crops, regions, levels of development and mechanization of the agricultural sector. For example, in France, this item represents about 80% of CO_2 emissions in agriculture. In Africa, where the agricultural sector is less mechanized, it would be much weaker.

4.2.2. The different agricultural practices

The addition of organic or mineral fertilizers to the agricultural soil can promote the CO_2 emission (Fontaine *et al.*, 2003). In southern Ghana, McCarthy *et al.* (2018) highlighted the influence of management and land use systems on CO_2 emissions in agro-system soils. These authors reported the control of CO_2 emissions by mineralization and decomposition of organic matter.

In Benin, a comparative study of the impact of organic matter in market gardening revealed a positive influence on soil CO_2 emissions (Akpo, 2017). The author observed emissions of 0.51-0.71 g $\text{CO}_2\text{-C}/\text{m}^2/\text{h}$ for poultry droppings, 0.68-0.95 g $\text{CO}_2\text{-C}/\text{m}^2/\text{h}$ for small ruminant droppings and 0.32-0.42 g $\text{CO}_2\text{-C}/\text{m}^2/\text{h}$ for cow dung. In addition, the study showed no impact of mineral fertilization on soil CO_2 emissions.

In the same country, Dossou-yovo *et al.* (2016) observed an increase in soil CO_2 emissions with mulch (rice straw) and fertilization, up to 0.136g $\text{CO}_2\text{-C}/\text{m}^2/\text{h}$ from soil respiration measurements in rainfed rice plots. Direct seeding without tillage reduced emissions compared to manual tillage.

In Kenya, livestock grazing has reduced soil CO_2 emissions in the Lambwe tropical savannah (Ondier *et al.*, 2018).

In Belgium, the work of Buysse *et al* (2017) reported a loss of 1.05 ± 0.22 Kg C/m², or 17% of the 1 m deep stock after 12 years of crop rotation. These authors concluded that tillage is not necessarily a source of CO₂ emissions from the soil during inter-crop periods.

Another work in France at the Boigneville site showed an overall decrease in soil CO₂ emissions of 11% in 'SCT³⁶- superficial work' and 16% in 'direct seeding'. Indeed, tillage has an effect on the physico-chemical characteristics of agricultural soil. This operation consists in turning the first parts of the ground (especially 15 to 30 cm) with the following objectives:

- distribute the manure and soil improvers in the topsoil,
- weed control,
- bury crop residues, plant debris and organic inputs,
- make the surface layer very soft,
- improve the drainage of wetlands or drained areas,
- destroy intermediate crops and warm the soil.

Moreover, ploughing does not necessarily destocking soil carbon (Baket *et al.*, 2007). However, crop management such as residue disposal plays an important role in carbon storage. This sequestration capacity may change over time depending on the zones of the soil profile (Dimassi *et al.*, 2014). In agrosystems, soil and climate factors influence soil CO₂ emissions (Ago, 2016; Dimassi *et al.*, 2014). It is therefore too early to conclude on the carbon storage potential of farming practices only in a given region.

Faeces can contribute to CO₂ emissions depending on soil and climate conditions. In addition, TDM techniques can improve soil carbon stock, and even more so in no-till conditions (Arrouays *et al.*, 2002).

4.2.3. Soil and vegetation

The mineralization of soil organic matter and the respiration process of ecosystems are important contributors to CO₂ emissions. The conversion of natural ecosystems (savannahs, grasslands, forests, etc.) into agricultural land destocks carbon, accounting for 17% of global GHG emissions.

4.3. Nitrous oxide N₂O

N₂O emissions **come from the application of nitrogen to agricultural soils** necessary for the growth and harmonious development of crops. The farmer makes these nitrogen supplements in the form of organic fertilizer (manure, slurry, crop residues...) or synthetic minerals (product obtained from an industrial process between nitrogen and hydrogen). A distinction is made between **direct N₂O emissions** that arise directly from the soils when nitrogen is applied and **indirect N₂O emissions** that are N₂O emissions that arise after some of the applied nitrogen got lost from where it was applied due to volatilization and leaching.

N₂O emissions are also recorded at the livestock level. They are due to nitrification-denitrification processes during the stay of animals and the storage of excreta. Depending

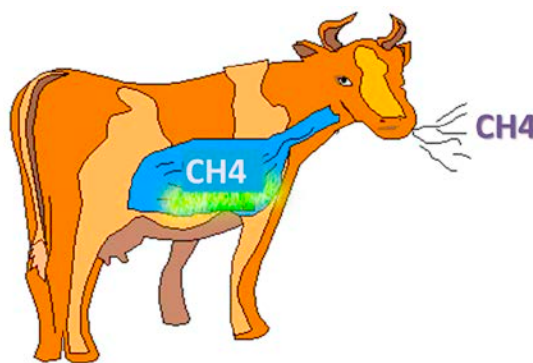
on the type of manure (slurry or manure), oxygen and humidity levels, these emissions are complex and varied. They are correlated to the quantities of nitrogen applied, the form of nitrogen supplied (urea, nitrate, ammonitrate), the form of fertiliser (solid or liquid), the technique used, the crop and the soil and climate conditions (soil type, humidity, temperature, wind, etc.). A study carried out by Solagro in 2003 showed that N_2O emissions in France would fall by 20% as the nitrogen surplus on agricultural soils was reduced.

The general trend is an increase in nitrous oxide emissions in SCT³⁷ with differences of 0 to 5 kg $\text{N-N}_2\text{O}/\text{ha}/\text{year}$ (Nicolardot and Germon, 2008; Oorts, 2006). The (higher) bulk density of the soil limits gas transfers by promoting denitrification. Another test in Boigneville reported small emissions from direct seeding compared to tillage with an average deviation of 0.5 kg $\text{N-N}_2\text{O}/\text{ha}/\text{year}$ (Oorts, 2006).

4.3. Methane CH_4

4.3.1. Ruminants

CH_4 emissions are produced by **enteric fermentation** (especially in **ruminants**), animal waste management and rice cultivation. Indeed, the particular mechanism of digestion of ruminants (cattle, sheep, goats) is responsible for methane emissions from agricultural sources. These are emissions after the fermentation of food ingested from the rumen (enteric fermentation), influenced by several factors such as race, genetic type, level of animal production, physical activity, composition and digestibility of the food.



For example, CH_4 emissions increase with age and production level (milk or meat) in cattle.

Animal feed plays a major role in methane emissions. Dry rations (containing more than 80% concentrated feeds made from cereals, hay or straw) reduce enteric fermentation. In all cases, it is necessary to distinguish between different livestock farming systems (e.g. intensive or grass-fed) and types of livestock because GHG emissions differ between farming systems and types of meat produced.

Cattle remain the most methane-emitting ruminants with an annual average of 62.3 kg of $\text{CH}_4/\text{animal}$. In West Africa, CH_4 emissions in 2017 from cattle alone were estimated at 24,534,442.8 kg (Djaby and Ozer, 2013). However, there are significant variations within the different species.

4.3.2. Animal manure management

The fermentation of animal manure (manure, slurry) also induces significant methane emissions. This often happens when excreta are piled up in anaerobic conditions. These emissions are often significant during housing periods. Liquid storage methods seem to be the most methane-emitting.

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It should be noted that manure and slurry do not cause identical emissions during storage because of their respective organic matter compositions. Indeed, manure can produce higher methane emissions under anaerobic conditions from the straw supply. Slurry stored in the pit is often in an anaerobic condition that is favourable to CH₄ emissions. For manure, emissions depend on the management of litter (accumulated or scraped) which may or may not cause the anaerobic conditions necessary for CH₄ emissions. Some of the emissions also come from cattle and pig droppings and, on a more modest level, from poultry.

4.3.3. Agricultural soils, especially rice fields

The research inventory showed low and negative flows, indicating the absorption of gas by the microflora of the soil that oxidizes it. This consumption seems to be higher in uncultivated soils than in cultivated and fertilized soils. However, the impact of tillage on methane flow has not been studied extensively. However, few differences in absorption capacities have been noted (Vanterea *et al.*, 2005). Another literature review had shown that TCSL soils oxidize methane with very small differences, in the order of 0.4 kg C-CH₄/ha/year (Nicolardot and Germon, 2008; Six *et al.*, 2002).

The rice field is another important source of methane production and emission. The availability of excess water limits the circulation of oxygen in the soil and promotes methane production.

5. THE DIFFERENT METHODS OF CALCULATING GHGS IN THE AGRICULTURAL SECTOR

In the agricultural sector, several methodologies are used to estimate GHG emissions, including those proposed by the IPCC. Inventory classifications, procedures and calculation rules are evolving, taking into account scientific advances. The '**guidelines**' were **published in 2006** and a very recent update was **published in 2019**. These guidelines are produced to support the preparation of national inventories for countries' reporting under the UNFCCC

The **methods are mainly based on emission factors** (EF), research results (field or laboratory), **statistics** and **models** (biophysical modelling).

In the assessment of CH₄ and N₂O emissions, **direct and indirect emissions** are taken into account. For CO₂, on the **other hand, changes in use are or are not included**. Nevertheless, some countries have adopted other specific provisions based on specific commitments.

The overall GHG balance in the agricultural sector is given by the following expression:

$$E = AD \times EF$$

Where:

- E is the emission expressed in Kg CO₂ eq/ha
- AD refers to activity data;
- EF refers to emission factors.



It should be noted that **default EF values have been published** in the IPCC guidelines... but they can also be determined for each crop according to the precision sought, ecosystem types and the specificities of the regions or countries.

There are **three main steps to** assess GHG emissions. It is about:

1. Identify the sources of emissions by socio-economic category (energy, agriculture, nature, transport, etc.)
2. Estimate emission factors (EFs) (default, culture, modelling,...)
3. Estimate inputs (regional or national economic statistics)

In addition, GHG flow measurements on site or in the field are carried out using relatively appropriate techniques and instruments. There are micro-meteorological devices, ventilation tunnels and automated statistical enclosures.

Several GHG balances have already been established in the agricultural sector, some examples of which are shown in Figure 10 and Table 3 below:

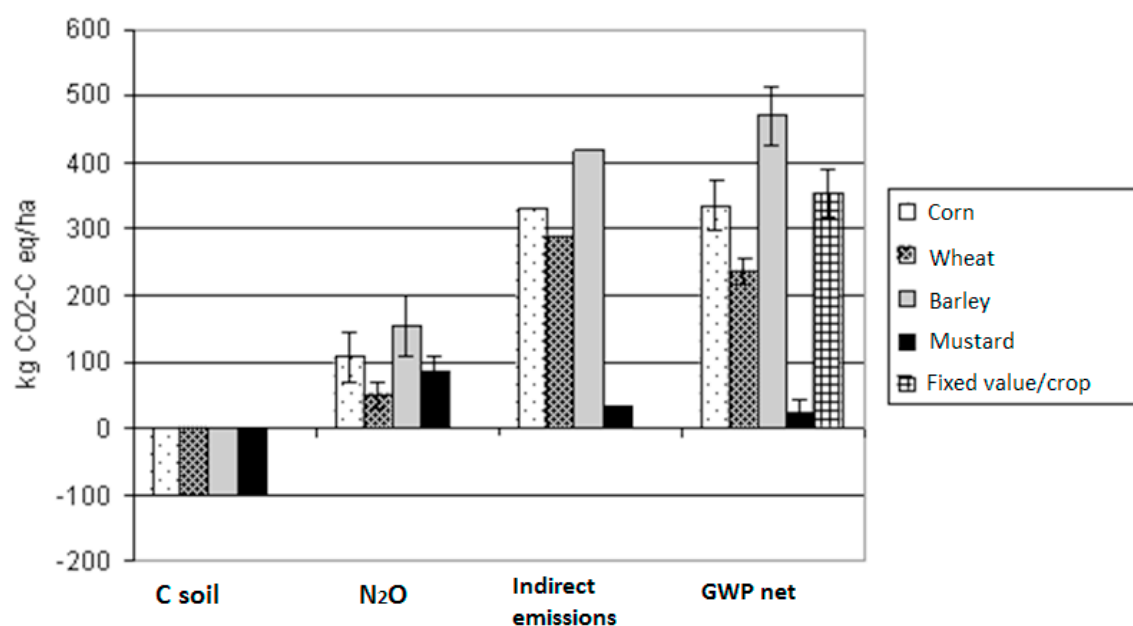


Figure 10: Annual GHG balance (350 ± 35 Kg CO₂-C eq/ha) at one rotation scale (Lehuger, 2006)

$$\text{Net GWP} = \Delta \text{stock C soil} + \text{N}_2\text{O} + \text{Indirect emissions}$$

Table 3: GHG balance (kg CO₂/ha/year) according to 3 tillage methods at the Boigneville site in France (Labreuche *et al.*, 2007)

Type of issue	Direct seeding	Superficial work	Plowing
Emissions related to crop management	2047	2323	2340
Emission/storage from the ground	-70	-136	11
GHG Emissions Balance Sheet	1978 (84,1 %)	2087 (88,8 %)	2351 (100 %)

Agriculture contributes significantly to the continuous increase in GHG concentrations, but remains one of the sectors most affected by global warming.

In the context of sustainable development, the implementation of appropriate mitigation, resilience and adaptation measures is essential. GHG emissions from the literature are much more obtained from indirect methods (estimates, models).

GHG emissions in agriculture **remain complex and difficult to understand**. Other factors also influence progress decisions, such as producers' difficulties in changing paradigms in terms of practices. Emphasis should be placed on scientific research to significantly contribute to refining GHG emissions measurements, to better understand the mechanisms controlling their trade and to reduce uncertainties in the results. Developing countries (ACP in particular), where statistical data, research projects on climate and its impacts are even more scarce, need both technical and financial support to reverse trends.



Chapter 4

Impacts of agricultural practices on air quality and mitigation strategies

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Training objectives:

From this chapter, the trainee be able to:

- Understand that horticulture contributes to GHG emissions at all stages of the supply chain.
- Be familiar with the main sources of GHG emissions in crop production and horticultural supply chains.
- Recognise that the relative importance of different sources of GHG emissions differs between different farming systems, crops, supply chains and due to factors such as whether or not a crop is irrigated, refrigerated or transported over long distances.
- Appreciate that agriculture and horticulture can contribute to climate mitigation efforts.
- Identify the most important opportunities on farms and in the wider food system for reducing emissions and increasing the amount of carbon that is stored in agricultural systems.
- Understand that the most suitable climate mitigation measures need to be identified on a case by case basis and in a location specific way.
- Appreciate the large potential of improving individual farm management in a holistic way to increase the efficiency of the system and reduce emissions.
- Understand the need for holistic approaches towards agricultural climate mitigation, food security, climate adaptation and other sustainability and development targets.

1. AGRICULTURAL PRACTICES AND GHG EMISSIONS

1.1 Introduction

Agriculture and horticulture are different from other industrial sectors in that they are linked to climate change in **three main ways**:

- 1) they emit greenhouse gases (GHGs) to the atmosphere, thus contributing to climate change;
- 2) they can contribute to combating climate change because they have the potential to lock up carbon in soils and biomass; and
- 3) they are already and will increasingly be impacted by a changing climate, e.g. by increasing droughts or extreme weather events.

Agricultural and food system activities contribute to climate change by releasing GHGs into the atmosphere at all stages of agricultural value chains, including cultivation, the production of inputs (e.g. mineral fertilisers), transportation, processing, packaging, storage, retailing, consumption and waste disposal.

It is estimated that the food system contributes **19-29% of total human GHG emissions** (Vermeulen *et al.* 2012). The majority of these emissions relate to agricultural production and land cover changes for agriculture (80-86% at the global level), while the production of farm inputs and further supply chain stages beyond farms (e.g. processing, packaging, refrigeration, transport, retail, waste disposal) account for the remainder (Vermeulen *et al.* 2012).

Livestock production is associated with a significant amount of global GHG emissions, where the main sources include emissions from ruminant animals, manure and its management, and the production of animal feed. However, because this manual focuses on the ACP horticultural sector, there will be no detailed discussion of livestock related sources of GHG emissions and their mitigation opportunities here.

1.2 On-farm sources of GHG emissions

The **three main GHGs** related to agriculture are carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4). Methane is particularly important on livestock and rice farms but typically does not represent a significant source of GHGs on horticultural farms where CO_2 and N_2O are more important. The following paragraphs present important sources of GHGs in crop production.

1.2.1 Emissions from soils

Agricultural soils have been a global net source of GHGs (Lal 2013). They can emit carbon from soil organic matter decomposition and N_2O and CO_2 related to the application of mineral and organic nitrogen, urea fertilisers and lime. GHG emissions from soils, in particular N_2O emissions, often represent **a large source of total GHG emissions from horticulture**.

For example, Iriarte *et al.* (2014) found that soil emissions accounted for 49% of emissions from banana cultivation in Ecuador (Figure 1). However, if other large emissions sources such as energy use for irrigation are also present the relative importance of soil emissions can be lower (Figure 3).

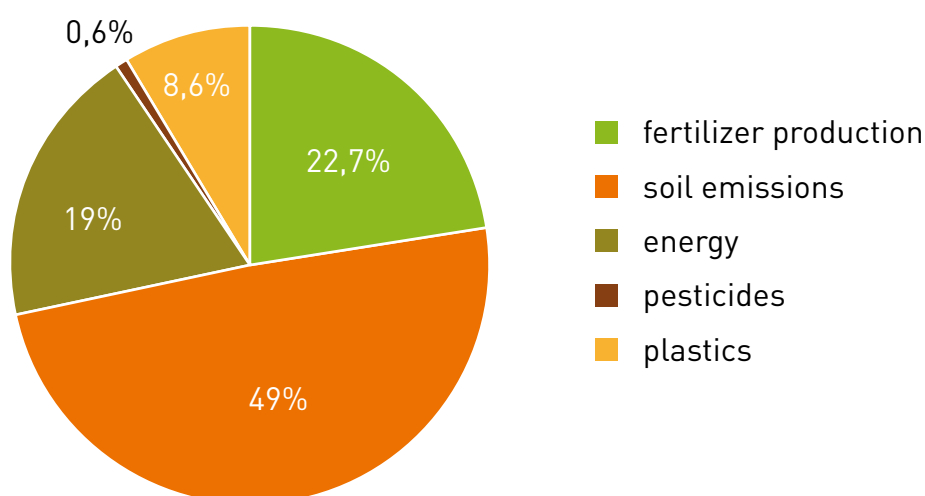


Figure 1: Percentage contribution of different processes to the farm gate carbon footprint of bananas. Case study from Ecuador. Source: adapted from Iriarte *et al.* (2014).

■ Loss of soil carbon

Agricultural practices can have negative effects on soils, including **loss of organic matter and associated GHG emissions**. Global soil carbon stocks are under threat: an estimated 25-75% of the original soil organic carbon pool has been lost from the soils of the world's croplands, grazing lands and rangelands (Lal 2011, Banwart *et al.* 2015). The loss of carbon from cultivated soils is **affected by land use, land use** change, vegetation cover and soil management, and its magnitude depends on climatic conditions, soil types, terrain and historic management (Lal 2011). Generally speaking, **soil carbon stocks are higher in more humid world regions** with higher rainfall (Banwart *et al.* 2015).

One of the main factors leading to this depletion of soil carbon is the conversion of land from undisturbed forests and grasslands to agriculture. Management practices that contribute to a loss of soil carbon include the removal of residues, mechanised and intensive tillage operations, short (or no) fallow periods, a reduction or absence of crop rotation systems, and nutrient depletion or imbalances.

Conventional soil tillage involves disturbing or inverting the soil profile by using ploughs, cultivators, discs, chisels or other equipment. The effects of conventional tillage on soil physical quality, soil erosion and degradation are often negative, and it **increases the mineralisation** of soil organic matter and thus CO₂ emissions from soils (Sanz *et al.* 2017). The effects of tillage on soil organic matter levels are determined by the depth, intensity and frequency of the disturbance (Paustian *et al.* 2000).

The **drainage of organic soils** (peatlands) for agriculture increases decomposition rates of the organic carbon and leads to significant emissions of CO₂ and N₂O (Smith *et al.* 2014). The amount of GHGs emitted depends on biophysical processes such as peat **decomposition and compaction**, nutrient availability, soil water contents and water table levels, all of which are affected by management practices (Murdiyarso *et al.* 2010). Therefore, although the conversion of natural and semi-natural land to agriculture (land use change) and drainage are the root causes of this loss of carbon, it is also important to consider how current management influences emissions after such land use change.

■ Direct and indirect N₂O emissions

The application of **nitrogen** containing materials to agricultural soils leads to both direct and indirect N₂O emissions. Adding mineral or organic fertilisers, plant residues, slurries, manures, etc. increases available nitrogen in soils and so leads to enhanced direct emissions of N₂O through microbial processes (*i.e.* directly from the soils that nitrogen is applied to). In addition, nitrogen inputs also lead to N₂O emissions indirectly through ammonia volatilisation, leaching and run-off of nitrogen from managed soils. Horticultural crops can leach large amounts of nitrogen (Goulding 2000).

On a tea estate in Kenya, N₂O emissions from nitrogen fertiliser application accounted for 27% of all emissions of tea cultivation, and N₂O emissions from crop residues contributed another 34% (Wiltshire *et al.* 2009) (Figure 2a). On a coffee estate, also in Kenya, N₂O emissions related to mineral nitrogen fertilisation contributed 39% of all emissions during cultivation (Figure 2b).

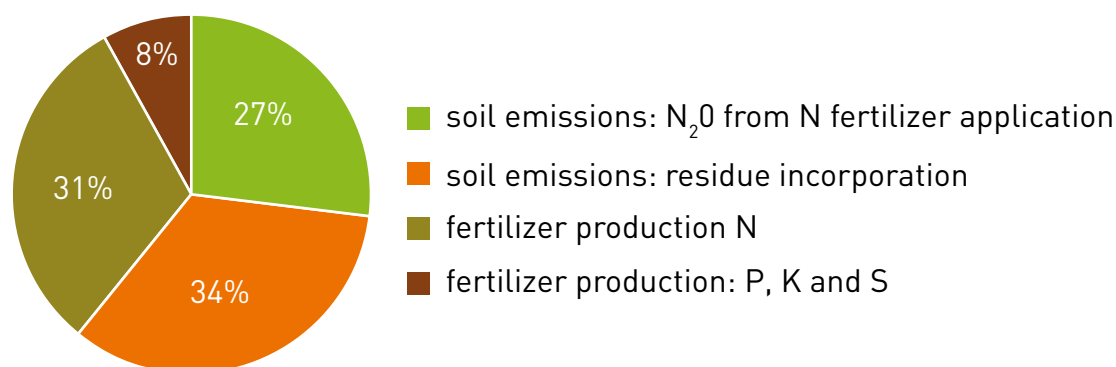
Ammonia volatilisation from animal manures and nitrogen fertilisers, most importantly urea fertilisers, also contributes to the formation of particulate matter which is an air pollutant with negative impacts on human health. It also leads to local and regional increases in nitrogen deposition which can contribute to the eutrophication of water courses and natural habitats.

■ CO₂ emissions from liming and the application of urea fertilisers

The application of both lime and urea containing fertilisers to soils leads to the emission of CO₂ as a result of chemical processes. **Liming** is used to reduce soil acidity levels and support improved plant growth in agricultural systems. After the addition of calcic limestone (CaCO₃) or dolomite (CaMg(CO₃)₂), the carbonate lime dissolves and releases

bicarbonate which then evolves into CO_2 and water. The application of urea fertilisers leads to the release of CO_2 which was previously fixed (from fossil sources) during the industrial manufacture of urea.

a) Tea carbon footprint



b) Coffee carbon footprint

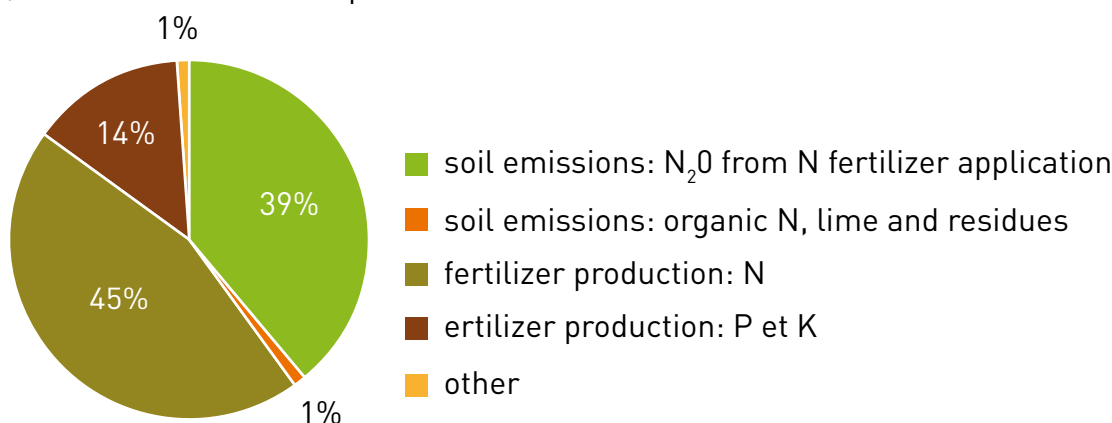


Figure 2: Percentage contribution of different processes to the farm gate carbon footprint of: a) tea and b) coffee. Case studies from Kenya. Tea: energy consumption, waste and the production of pesticides not shown due to their insignificant contribution. Coffee: "other" includes energy, pesticides, seeds and waste. Source: adapted from Wiltshire *et al.* (2009).

1.2.2 Energy use: field operations, irrigation, on-farm processing and storage

Farm management processes that use **fossil energy**, e.g. diesel, petrol or electricity, emit GHGs and so contribute to climate change. These management processes can include the preparation of soils for planting, ploughing, seeding, the application of mineral and organic fertilisers, the application of agro-chemicals, harvesting and irrigation. If on-farm processing and/or storage of harvested crops takes place this represents another source of energy use. Non-GHG air pollutants related to the production of electricity include for example sulphur dioxide (SO_2) emissions (especially in countries where the national energy mix is dominated by coal) and **NO_x** emissions (IPCC 2006). Energy generation also contributes to the **formation of ozone** which is one of the most damaging air pollutants for plants and an important contributor to global warming (Royal Society 2009).

Electricity: The generation of electricity via the combustion of fossil fuels like oil, coal or natural gas mainly causes CO_2 emissions but small amounts of CH_4 and N_2O are also involved. The electricity mix of the country or location in question will be important for associated GHG emissions: if the national energy mix is dominated by coal, then the GHG emissions per unit energy will be higher than if it contains more natural gas. This

is because coal combustion is more carbon intensive than the combustion of natural gas or petroleum. Renewable energy typically has lower GHG emissions per kWh produced than fossil fuels (Moomaw *et al.* 2011). Some countries generate most of their electricity using hydropower which then leads to very low emissions per kWh.

Fuels: The combustion of fuels like diesel and petrol produces the direct emission of CO₂, CH₄ and N₂O. The combustion process is usually optimised so that the maximum amount of energy per unit of fuel is consumed, producing the maximum possible amount of CO₂. Therefore, the carbon content of the different fuels determines the amount of CO₂ emitted (IPCC 2006). CH₄ and N₂O emissions, in contrast, **strongly depend on the combustion technology**. Table 1 shows the GHG emissions from the production and combustion of different fuels as presented in Bochu *et al.* (2013). In addition, other air pollutants that contribute to local or regional air pollution are also emitted, including carbon monoxide, non-methane volatile organic compounds, SO₂, particulate matter and oxides of nitrate (NO_x) (IPCC 2006).

Table 1: GHG emissions in kg CO₂e per l, kg or m³ for four different fuel types. Source: Bochu *et al.* (2013).

	emissions from production and combustion
diesel	2.984 kg CO2e/l
petrol/gasoline	2.968 kg CO2e/l
natural gas	2.556 kg CO2e/m3
coal	2.801 kg CO2e/kg

The importance of GHG emissions from **fuel and electricity** use relative to other sources of emissions depends on how energy intensive the production system is and which other processes occur. Figure 1 shows a case study on banana cultivation in Ecuador (Iriarte *et al.* 2014). On the farm analysed in this study, energy consumption included diesel for irrigation, fuels for aerial pesticide applications and electricity use during on-farm processing; these energy uses together accounted for 19% of all life cycle emissions up to the farm gate. Another case study on banana cultivation in Costa Rica estimated that energy uses (mainly for aerial spraying) contributed 7% to all GHG emissions up to the farm gate (Luske 2010). The consumption of diesel can also be an important source of emissions in products such as grain legumes and fruit and vegetables (Sonesson *et al.* 2010).

Irrigation has been shown to contribute almost 40% of all energy uses up to the farm gate on vegetable farms in New Zealand (Barber & Pellow 2005). Basset-Mens *et al.* (2016) compared energy use and GHG emissions for apples and peaches produced in France and clementine produced in Morocco and highlighted the importance of national energy mixes for determining the amount of GHG emissions related to irrigation. Energy use for fertigation accounted for about 20% of all energy consumption but only 3-5% of GHG emissions for the crops in France. In Morocco, in contrast, electricity consumption for fertigation accounted for 39% of all GHG emissions. The reasons for this much higher percentage contribution in Morocco include a higher share of fossil fuels in the national energy mix (France: less than 10%, Morocco: 50%), the larger water requirement of clementine and the need to pump water from deep wells in a water scarce region. The energy and water needs for the three crops are shown in Table 2. Figure 3 shows an

example for potato cultivation in Zimbabwe, where irrigation accounted for 18% of all farm scale GHG emissions for small to medium farms and 28% of large commercial farms (Svubure *et al.* 2018).

Table 2: Water and energy requirements for the cultivation of apples and peaches in France and clementine in Morocco for representative systems. Source: Basset-Mens *et al.* (2016).

	apples (France)	peaches (France)	clementine (Morocco)
water, m3 ha ⁻¹	2767	7000	8000
energy, MJ ha ⁻¹	2988	7560	22830

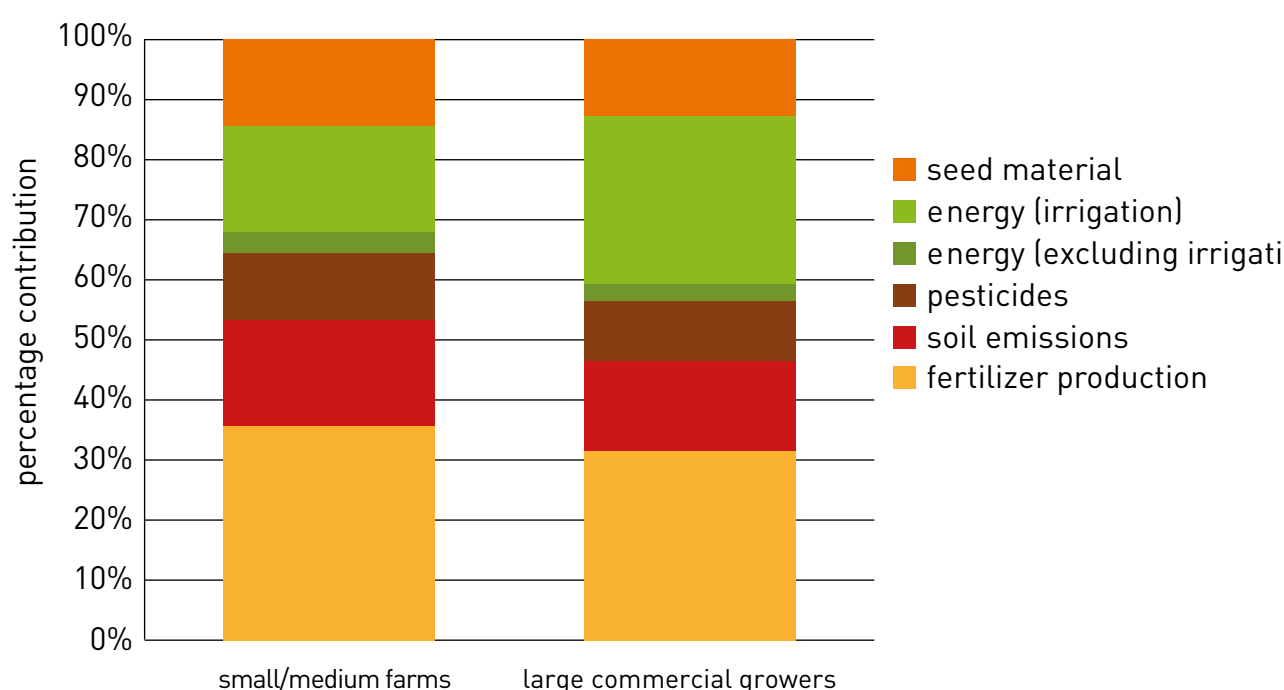


Figure 3: Greenhouse gas emissions from potato cultivation on small to medium scale farms and large commercial farms in Zimbabwe. Source: adapted from Svubure *et al.* (2018).

Storage of fresh produce can increase energy consumption considerably compared to produce that does not need to be stored.

This was illustrated in a case study that compared total energy use for apples for four scenarios (Milà i Canals *et al.*, 2007):

- apples produced and consumed within the same country in the European Union;
- apples produced and consumed in two different European countries;
- apples produced in New Zealand and consumed in Europe;
- apples produced in other southern hemisphere countries (e.g. Chile, Argentina, South Africa, Brazil) and consumed in Europe.

The authors calculated the energy needed to provide apples to consumers in April, August, October and January for these four scenarios. The results highlight the importance of the timing of consumption which is related to the length of storage: when apples are in season in Europe and have been stored for short periods, domestic apples have a lower energy use than imported apples; however, in the European spring and summer, total energy consumption overlaps for the four scenarios.

One reason for this is the length of storage for the European apples. Storage for 5-9 months in Europe increased energy consumption by up to 16% compared with a situation where no storage and no losses occur.

On-farm processing can include, for example, packaging, grading and washing, all of which may consume fossil energy.

1.2.3 Burning of biomass

The **burning of biomass** releases CO_2 to the atmosphere; however, because this CO_2 was recently fixed by the biomass that is being burned it does not usually get considered as a net source of GHG emissions. More important in the context of air pollution are the emission of the GHGs CH_4 and N_2O and other non- CO_2 emissions such as carbon monoxide and NO_x . Sulphur dioxide also plays a role in climate change. Hydrocarbons, non-methane volatile organic compounds and reactive nitrogen emissions (NO_x) related to the burning of biomass cause the **formation of tropospheric ozone** (Smith *et al.* 2008, IPCC 2006). The amount of GHGs emitted depends on the amount of biomass burned and the emission of each gas per kg dry matter burned.



Source : Sud-Ouest

1.2.4 Crop residues and N-fixing crops

Where crop residues are ploughed into the soil or left on the soil surface, they return nitrogen that was previously applied in organic or mineral fertilisers to the soil. Moreover, below-ground crop residues also contain nitrogen. These above- and below-ground nitrogen inputs lead to the emission of N_2O just like the application of nitrogen fertilisers. Similarly, N-fixing crops represent a source of nitrogen addition to the system and again this nitrogen causes the emission of N_2O .

If the residues are ploughed in during summer, the nitrogen they contain can be taken up by the next crop after mineralisation or lost by leaching, which can be a problem for residues containing high nitrogen contents, e.g. brassicas (Goulding 2000). Nitrogen that is lost to leaching can cause N_2O emissions via indirect pathways.

In the case study on tea cultivation in Kenya, Wiltshire *et al.* (2009) found a significant contribution of crop residues (including out grades) to total GHG emissions (34%) (Figure 2a).



Source : Wire.farmradio.fm

1.2.5 Organic wastes and landfill

Svanes & Aronsson (2013) analysed the carbon footprint of banana production in Costa Rica, using data from two case study farms. At these farms, harvested fruits are quality checked and cut into hands of 5-7 fingers each before packaging. During this processing, waste is produced in the form of banana stems, bananas and leaves. This waste is **landfilled** and **gives rise to CH_4** emissions due to the degradation of organic material. In the analysis by Svanes & Aronsson (2013) these CH_4 emissions were the main contributor to the farm gate carbon footprint (about 30% of all GHG emissions) (Figure 4).

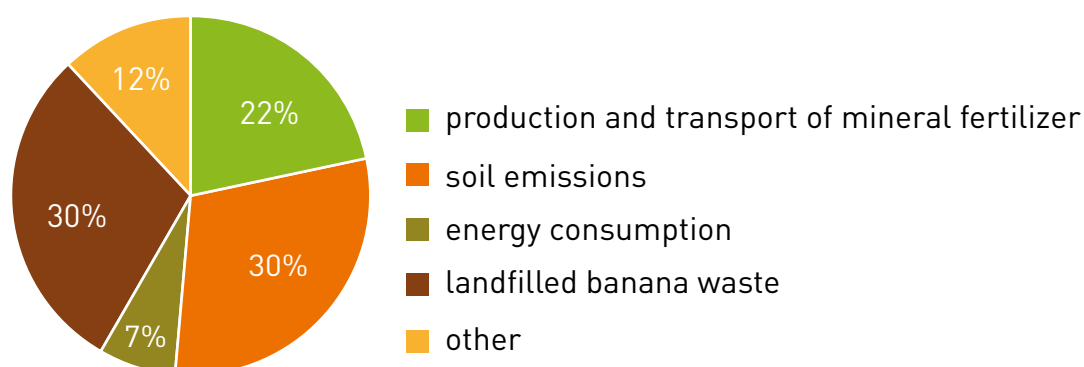


Figure 4: Percentage contribution of different processes to the farm gate carbon footprint of bananas. Case study from Costa Rica. Source: adapted from Svanes & Aronsson (2013).

1.2.6 Land use change

Land use change (LUC) is a change in the use or management of land by humans and includes the conversion of natural and semi-natural land to agriculture. There are six broad land use categories that are being distinguished by the Intergovernmental Panel on Climate Change (IPCC): forestland, cropland, grassland, settlements, wetlands,

and other land (e.g. bare soil, rock, ice). **The conversion from one land use category to another is called LUC.** Changes in management practices such as tillage practices within existing arable systems are not usually called LUC as they do not change the broad land use category.

LUC can lead to the emission of large amounts of GHGs due to **the release of carbon that was previously stored in above- and below-ground biomass and soils.** For example, tropical forests contain a lot of carbon that is stored in their soils and trees. If the trees are felled and the soil is disturbed due to the conversion to croplands or grasslands, a large part of this stored carbon is lost as the new land use type usually has lower carbon stocks in its biomass, soil and dead organic matter pools (Plassmann 2017).

The conversion of other habitats such as savannahs, wetlands or tropical shrubland also causes significant carbon emissions. Tropical peat lands, mangroves and **waterlogged organic soils in general typically contain very high carbon stocks.** The **drainage of these habitats** for agricultural use increases the decomposition rates of this stored organic carbon and releases CO₂ and N₂O (Smith *et al.* 2014). Global CO₂ emissions from drained peatlands account for about 25% of all emissions related to land use change (Birdsey *et al.* 2013), where Southeast Asia is the global hotspot for emissions from drained peat soils. In Indonesia, these emissions cause 60% of the national total. One of the most important drivers of the conversion of peat soils in both Indonesia and Malaysia is the expansion of oil palm production (Dommain *et al.* 2013). Less information is available for ACP countries; however, for example there are drained peat lands in Uganda that are being used to cultivate sweet potatoes, peas and legumes, maize and cereals (Dommain *et al.* 2013).

At the global scale, LUC is a significant source of GHG emissions: land use and land use change (mainly deforestation) accounted for 9-11 % of global anthropogenic GHG emissions in 2000 to 2010 (Smith *et al.* 2014). **Agriculture is the main direct driver of global deforestation** and causes about 70 to 80 % of all deforestation (Hosonuma *et al.* 2012). Both commercial and subsistence agriculture are important drivers but regional differences in their relative importance exist (Hosonuma *et al.* 2012).

LUC emissions are **usually included in product related carbon footprinting calculations** if the LUC happened on the farms analysed **up to 20 years prior to the assessment** (or a single harvest period for perennial plants, whichever is longer). Where LUC occurs it may account for a very significant proportion of the product carbon footprint (PCF) and dominate it (e.g. Plassmann *et al.* 2010). The magnitude and actual contribution to the PCF will depend on the type of habitat that was converted, the type of crop grown subsequently, and the intensity of other processes that emit GHGs. For example, one study found that LUC accounted for 98% of the PCF of cocoa from Ghana (Figure 5). On the cocoa farms in Ghana that form the basis of the analysis in Figure 5, most on-farm processes (harvesting, on-farm processing) were carried out manually and there was no application of mineral fertiliser. Another case study for pineapple produced in Costa Rica concluded that pineapples sourced from farms with recent LUC from primary forest have a ten times larger PCF than pineapples from farms without recent LUC (Ingwersen 2012).

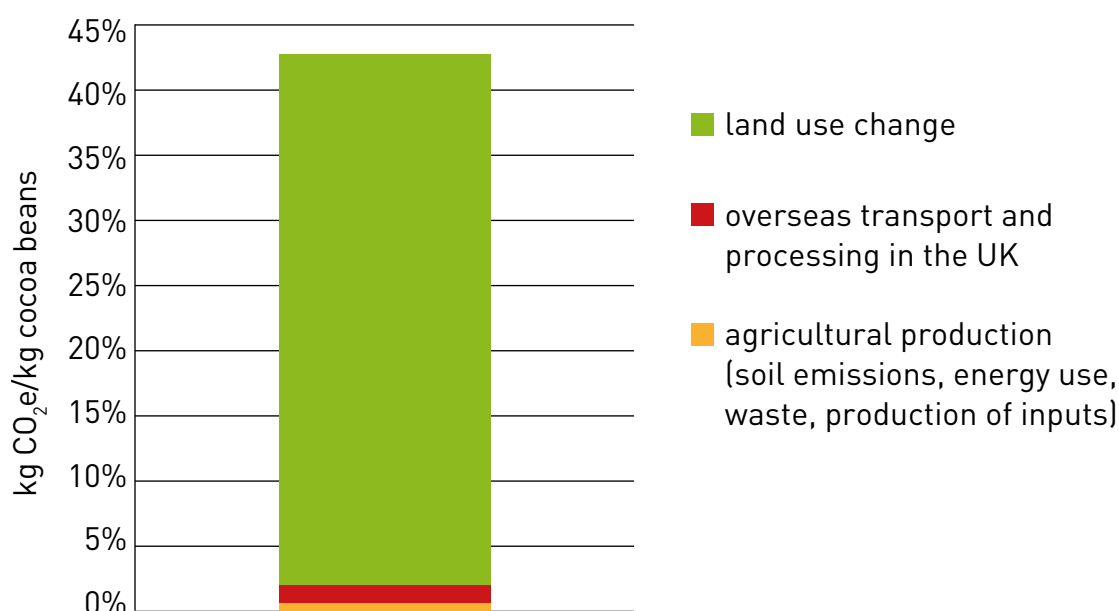


Figure 5: Greenhouse gas emissions related to the agricultural production of cocoa beans in Ghana, overseas transport to the UK and processing to cocoa powder in the UK (in kg CO₂e/kg cocoa beans), including land use change on farms in Ghana. Land use change emissions were modelled based on statistics that show that 60% of cocoa land in Ghana had been converted from forests in the last 20 years.

Source: adapted from Wiltshire *et al.* (2009).

1.3 Off-farm sources of GHG emissions

1.3.1 Production and transport of agricultural inputs

The manufacture of farm inputs such as mineral fertilisers, agro-chemicals, plastic packaging or seeds causes GHG emissions in the factories or on the farms where they are produced. After production, GHG emissions also arise due to the transport of such inputs from their point of manufacture to the farms. This transport can consist of different steps using different modes of transport, e.g. mineral fertilisers might be transported by ships to overseas markets, then by large trucks from the importing harbor to a wholesaler in the country of destination, and from there to the final consumer.

The emissions from the production and transport of inputs represent an indirect, upstream source of emissions for the farms that buy these materials. In product related carbon footprinting assessments that take a life cycle view, **these upstream emissions are included** because they are related to the product that is being cultivated on these farms. They often make a significant contribution to farm gate carbon footprints. For example, Table 3 shows the results of a case study on the production of pineapples on Mauritius where the production of mineral fertilisers accounted for 45% of all emissions. The production and transport of plastic mulches and agro-chemicals had a much lower contribution.

Table 3: Percentage of greenhouse gas emissions per kg of fresh pineapple produced on a case study farm on Mauritius, delivered to the airport. Adapted from: Plassmann & Edwards-Jones (2010).

inputs and processes		percentage contribution
production and transport of inputs:	mineral fertilisers	45.2%
	plastics (for mulching)	6.9%
	herbicides and ripeners	2.4%
energy consumption:	diesel	26.2%
	electricity	2.8%
soil emissions:		16.4%

Figure 6 summarises the results of three different studies that analysed the carbon footprint of bananas up to the point where the bananas leave the farm. The production of mineral fertilisers accounted for 23-36% and pesticides between 0.6-9% in these studies. This range in the relative importance of different emissions categories is typical in carbon footprinting analyses. It is due to a large inter-farm variability (due to different environments, climates, yields, management systems, efficiencies, etc.) and differences in the calculation methods applied in different studies. However, in the example in Figure 6, all three studies agree that the production of mineral fertilisers and soil emissions are the two main hotspots on banana farms.

Pesticides are relevant in the context of human and environmental toxicity impacts but the production of agro-chemical such as herbicides or ripeners (as in the example in Table 3) typically does not make a major contribution to total GHG emissions. Where large amounts of agro-chemicals are applied using machinery the more relevant impact for GHG emissions stems from the consumption of energy, as shown e.g. for apple production in France (Basset-Mens *et al.* 2016).

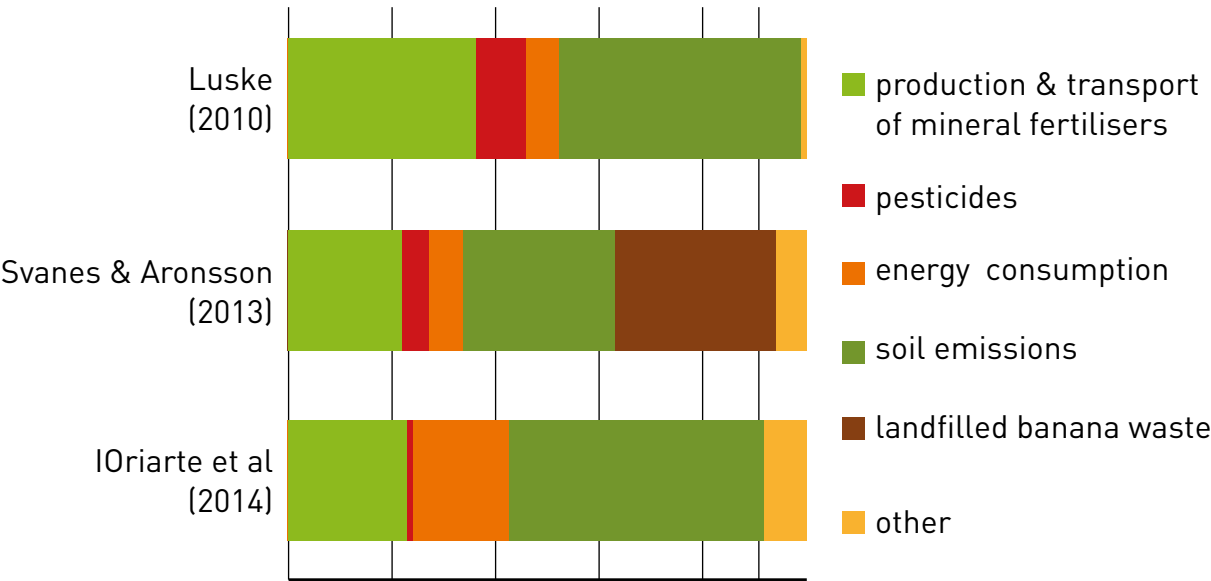


Figure 6: Percentage contribution of different processes to the total carbon footprint of banana cultivation (up to the farm gate) as analysed in three case studies in two countries (Luske 2010 and Svanes & Aronsson 2013: Costa Rica; Iriarte *et al.* 2014: Ecuador).

1.3.2 Transport of horticultural products from farm to market

The transport of harvested produce contributes to GHG emissions due to the use of fossil fuels and energy. Different modes of transport are related to different amounts of emissions. In Table 4, GHG emissions related to moving one tonne of goods over a distance of one kilometer are shown for several modes of transport. Transportation by ship usually has a comparatively low GHG burden whereas air freighting has the highest. Different sizes of trucks or ships can have different efficiencies and hence GHG emissions.

Table 4: GHG emissions (in kg CO₂e) related to moving 1 tonne of goods for 1 kilometer (t*km) for different modes of transport. Source: adapted from Edwards-Jones *et al.* (2008).

mode of transport	kg CO ₂ e/t*km
transoceanic tanker	0.005
transoceanic freight	0.011
freight train	0.038
truck, 32 t	0.157
truck, 16 t	0.316
van, < 3.5 t	1.118
freight plane	1.142

Figures such as those shown in Table 4 can be obtained from, for example, government publications or commercial and private databases. Care needs to be taken when choosing such emission factors for a particular study because they should be representative for the mode of transport, its efficiency, technology, and geography (Plassmann *et al.* 2010). Underlying assumptions (e.g. regarding the loading factor or whether return trips are presumed empty or not) and the inclusion or exclusion of the building and maintenance of the transport medium, roads and infrastructure are also important.

The importance of transport for the carbon footprint of different horticultural products depends to a large extent on their destination markets, how perishable they are and if they can be transported by ship or need to be air freighted over large distances.

Refrigerated **shipping** of pineapples from Ghana to Europe accounted for 22% of all emissions up to the UK supermarket distribution center (Figure 7) in the case study by Wiltshire *et al.* (2009). For coffee produced in Kenya and sold as instant coffee in the UK, Wiltshire *et al.* (2009) calculated that transport only accounted for 4.5% of all emissions while cultivation accounted for 74% and processing for 22%.

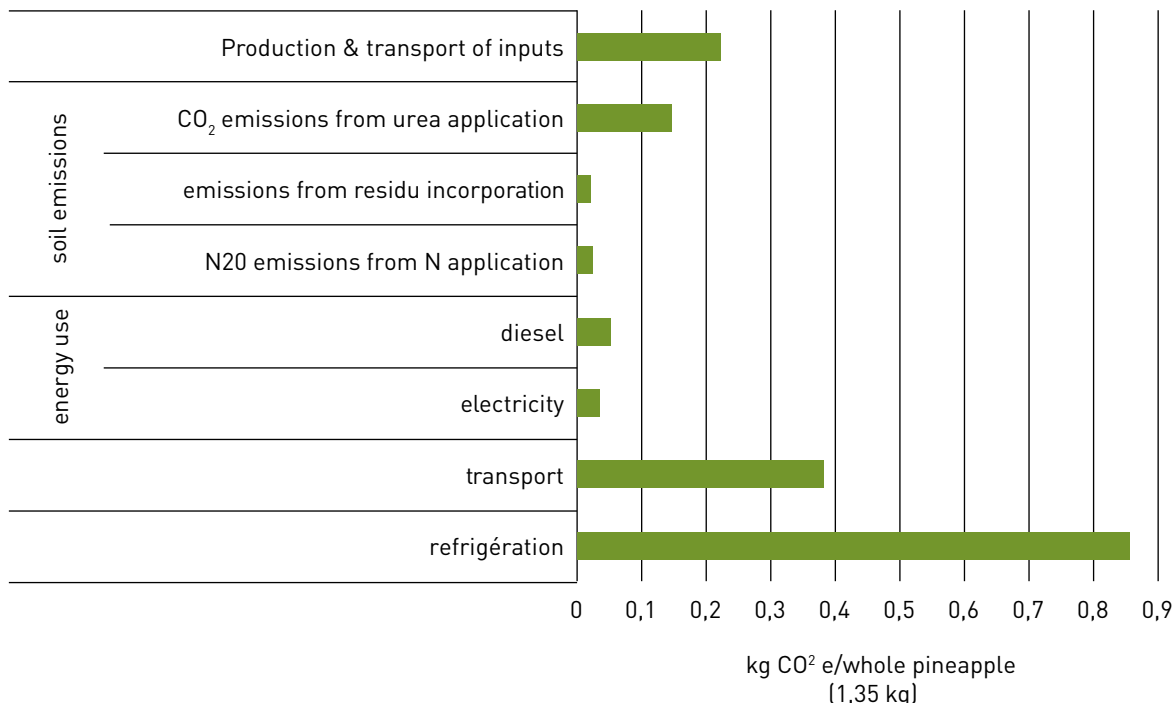


Figure 7: GHG emissions (in kg CO₂e) for a whole, fresh pineapple (1.35 kg) produced in Ghana and shipped to the UK (up to the UK supermarket distribution centre). Source: adapted from Wiltshire *et al.* (2009).

Air freighting is associated with a much higher carbon footprint than shipping (Table 4) so that air freighted produce typically has a comparatively high carbon footprint which is dominated by this transportation stage. For example, 57% of the climate impact of roses cultivated in Ecuador and transported The Netherlands by plane are due to the air freighting (Franze & Ciroth 2011); however, despite this impact the total carbon footprint of roses from Ecuador was still lower than roses produced within The Netherlands (due to the significant use of energy in Dutch glasshouses). The pineapples produced on Mauritius (Table 3) had a low carbon footprint at the farm gate which compares well with other fruit (0.26 kg CO₂e/kg of pineapple); however, due to the short shelf life of this particular variety and logistical demands on a small island like Mauritius they had to be air freighted to their markets in Europe. This air transportation added another 10.8 kg CO₂e/kg of pineapple, completely overshadowing all other emissions (Plassmann & Edwards-Jones 2010). Another case study on runner beans produced in Kenya and Guatemala and air freighted to the UK found that emissions from air transportation accounted for 89% and 91% of supply chain emissions, respectively (Sim *et al.* 2007).

1.3.3 Refrigeration

Refrigeration is a source of GHGs because of its energy consumption and – more importantly – because **refrigeration appliances often use substances that are very powerful GHGs**, including **hydrochloro-fluorocarbons** (HCFCs) and **hydrofluorocarbons** (HFCs). They are widely used in refrigeration, including cold storage, food processing, transport and industrial refrigeration. **The UN’s Montreal Protocol**³⁸ is a multilateral environmental agreement that regulates the production and use of these substances.

38 <https://www.unenvironment.org/ozonaction/who-we-are/about-montreal-protocol>

HCFCs contribute to the depletion of the ozone layer and climate change, and they will be phased out completely by 2020 in developed countries and by 2030 in developing countries. HFCs do not have a negative impact on the ozone layer but on climate change. Their impact on climate change is between 12 and 14,000 times greater than that of CO₂. The parties to the Montreal Protocol agreed to take action to reduce HFCs over the next couple of decades.

Because refrigeration typically involves the use of these substances with a very high climate change impact, it can contribute significantly to the carbon footprint of products that are cold stored or refrigerated during transport to retailers or consumers. An example for the latter is shown in Figure 7 which is based on a case study on pineapples produced in Ghana (Wiltshire *et al.* 2009). The harvested pineapples are cooled to 7°C during their transport to the export harbour and container shipping to Europe. Transportation (energy use) and refrigeration were the largest contributors to the carbon footprint per pineapple up to the UK supermarket distribution centre and accounted for 22% and 50% of all emissions, respectively.

1.3.4 Other sources of emissions

Packaging of fresh produce is another potential source of GHG emissions. For example, packing of bananas in Costa Rica and Ecuador accounted for between 8% and 19% of all emissions up to the destination port or retail in the country of consumption in Europe (Luske 2010, Iriarte *et al.* 2014). **Consumer shopping trips by car to the supermarket** can also contribute significantly to life cycle carbon footprints. For produce that is cooked, **the way that consumers prepare their food and the energy efficiency of the cooking equipment** are important.

Finally, **the amount of food that is lost or wasted** from farms to consumers' homes also has an impact on GHG emissions. Every food item that is lost or wasted is associated with emissions from its cultivation, transport, storage, packaging or other supply chain stages. Globally, **food loss and waste (FLW)** is an enormous source of emissions. **It is estimated that about one third of all food produced for human consumption is lost or wasted on a per unit weight basis**, and that this lost and wasted food represents about 8% of all global GHG emissions. **Fruits and vegetables account for the largest share of FLW on a weight basis.** In industrialised countries, FLW occurs mainly during retail and consumption, in low-income countries during production and storage. As an example, a case study in Uganda found that almost 15% of all cooking bananas produced in the country suffer postharvest deterioration, with 7.2% deteriorating completely and the rest deteriorating partially (Kikulwe *et al.* 2018).

2. MITIGATION OPPORTUNITIES AND OFFSETTING EMISSIONS

2.1 Mitigation vs. offsetting of emissions

Climate change mitigation means reducing or preventing GHG emissions on the one hand, and enhancing the removal of carbon from the atmosphere on the other hand (e.g. by planting forests).

All industrial sectors can and need to contribute to climate mitigation efforts, including agriculture and the entire food system. Climate mitigation includes activities such as

- increasing the use of renewable energies;
- increasing energy efficiency;
- changing our behavior and our demand for GHG emission intensive products;
- introducing new technologies such as electric cars.

Generally speaking, there are **three major opportunities** for achieving climate mitigation in agriculture and horticulture (Smith *et al.* 2008):

- 1) reducing emissions (e.g. by using nitrogen fertilisers more efficiently)
- 2) enhancing removals (e.g. by locking up carbon in soils or the tree biomass of agroforestry systems)
- 3) avoiding or displacing emissions (e.g. avoiding fossil fuel emissions by using bioenergy)

Companies can implement climate mitigation measures that lead to emissions reductions or removals within their own operations or supply chains. In contrast, carbon offsets represent GHG emissions reductions elsewhere. They fund external projects and activities that – for example – protect or restore forests, reduce emissions from industrial activities or increase the provision of renewable energy. The amount of GHGs that is saved by such projects is monitored by independent organisations which sell CO₂ reduction certificates. These organisations also define key requirements for credible offsetting projects and methodologies that project developers need to follow to generate saleable CO₂ reduction certificates, where the sale of the certificates funds the project.

One key requirement for credible carbon offsetting projects is that they would not have been implemented without this funding, i.e. it must be shown that the emissions reductions generated by the project are additional to measures that would have been implemented in the absence of the project. For example, if a government policy requires the implementation of certain climate mitigation measures, then companies would have to implement them in any case. This would mean that the project cannot be used to generate CO₂ reduction certificates (or 'carbon offsets') **because the emissions reduction would have happened without the extra funding**. This requirement for 'additionality' ensures that only those projects that actually lead to a reduction of GHG emissions will generate carbon offsets. **Two types of carbon markets** exist:

- 1) In the **regulatory carbon market**, offsets are sold to organisations and governments that need to comply with GHG emissions reductions targets set by the Kyoto Protocol or other regulatory initiatives (e.g. the EU Emissions Trading Scheme). For example, the Clean Development Mechanism allows

industrialised countries to purchase certified emissions reduction credits to meet their national GHG emissions reduction targets under the Kyoto Protocol. These credits can be earned through emission reduction projects in developing countries following strict rules.

- 2) The **voluntary market for carbon credits and offsetting** involves different organisations and providers of carbon offsets, e.g. the Voluntary Carbon Standard or the Gold Standard developed under the lead of the World Wildlife Fund (WWF). These standards may consider GHG emissions alone or alongside other environmental, social and economic benefits. Voluntary standards define the criteria that projects need to follow and then issue carbon offsets equivalent to the GHG emissions reduction by a project.

Carbon offsetting has been criticised for several reasons. One reason is that companies, organisations and individuals should rather reduce emissions from their own activities than paying for reductions elsewhere. Other reasons include doubts whether projects really are 'additional' and represent real climate mitigation benefits; **a single focus on GHG emissions only while disregarding other environmental impacts; possible negative impacts on local communities;** a potential lack of independent supervision; the potential for carbon leakage (where emissions savings in one place lead to increased emissions elsewhere); and issues around the permanence of carbon removals in forests. For a discussion of the 'ethics of carbon offsetting', see Hyams & Fawcett (2013).

An example of a company that combined both GHG emissions reductions and offsets to achieve carbon neutral certification is the Costa Rican coffee cooperative Coopedota (Birkenberg & Birner 2018). The cooperative used the independent standard PAS 2060 (Publically Available Specification) Specification for the demonstration of carbon neutrality³⁹ which defines requirements for achieving and demonstrating carbon neutrality. This process involves the quantification of all GHG emissions, the implementation of reduction strategies, and finally the compensation of the remaining emissions by carbon offsets.

2.2 Mitigation on farms

As the previous sections that describe different sources of GHG emissions on farms have shown, the relative importance of these sources can vary to some extent between production systems, countries, supply chains and individual farms. For example, if irrigation requires large amounts of energy, then this may account for a significant share of total GHG emissions; in contrast, if no irrigation occurs, then other farm processes may become more important, e.g. the production of mineral fertilisers or emissions from fertilised soils. Therefore, the best opportunities for reducing emissions need to be evaluated on a case by case basis.

2.2.1. *Balanced and efficient use of mineral fertilisers*

The production and application of mineral fertilisers often dominate GHG emissions up to the farm gate. Therefore, it is important to use these fertilisers efficiently and reduce any over-applications, e.g. by optimising the timing of application, choosing the most suitable type of fertiliser, applying appropriate rates, considering spatial variability within

39 <https://www.bsigroup.com/en-GB/PAS-2060-Carbon-Neutrality/>

and between fields and considering precision fertilisation (Smith *et al.* 2014). In addition, it is also important to consider the correct balance of different nutrients because this will increase their use efficiency and impact positively on yields. For example, Müller Carneiro *et al.* (2019) conducted a case study on mango production in Brazil and found that phosphorus was under-applied and potassium over-applied (compared to the local recommendation). Such an imbalance in plant nutrients can lead to reduced yields due to foliar burn as a result of too much potassium and low root growth and a reduction in flowering due to the under-application of phosphorus. Another option is to plant more nitrogen efficient cultivars, e.g. changing from clementine to mandarin (Basset-Mens *et al.* 2016), and the breeding of new crop cultivars that have the potential to reduce GHG emissions. Svanes & Aronsson (2013) estimated that switching to controlled release fertilisers in banana cultivation in Costa Rica could reduce N₂O emissions and lower the carbon footprint up to the farm gate by 9%.

2.2.2. *Energy consumption and efficiency*

GHG emissions related to irrigation can be reduced by making the irrigation system more efficient and matching irrigation events closely with plant needs in order to achieve the highest yield with the minimum water volume (Müller Carneiro *et al.*, 2019). This will reduce the total amount of water needed as well as energy requirements, which is especially important in water scarce regions.

The **source of the energy used** for irrigation also plays an important role as illustrated by Basset-Mens *et al.* (2016). In Moroccan clementine production, irrigation contributes significantly to the carbon footprint because irrigation water has to be pumped from deep wells and electric pumps are associated with high GHG emissions due to the large share of fossil fuels in the national energy mix. The Moroccan government is tackling the dual problem of water scarcity and high GHG emissions by searching for alternative practices that consume less water, improving access to water or shifting production to regions where water is more accessible.

Other possible options include **new dams, rainfall storage** or new power stations based on renewable energy (Basset-Mens *et al.*, 2016).

Further measures to increase the efficiency of irrigation include:⁴⁰

- choosing the most appropriate irrigation method for the soil, crop and region;
- minimising water pressure where possible;
- increasing pump and engine efficiency; considering using micro-irrigation systems that apply water near the bases of individual plants;
- applying water at appropriate intervals for the soil type;
- considering night time irrigation to reduce overall water use by eliminating day time losses through evaporation.

The consumption of diesel for field operations can be reduced by implementing several measures. For example, innovative solutions against pests and diseases can reduce the amount of agro-chemicals that are applied which also leads to reduced diesel consumption. In French apple orchards, new solutions that are being studied include

40 www.eolss.net/Sample-Chapters/C08/E3-18-04-01.pdf.

covering orchards with polyethylene plastic covers that reduce apple scab infestations or with insect proof nets which reduce infestations with codling moths (Basset-Mens *et al.* 2016). Other options include (O'Halloran *et al.* 2008): raising awareness for and training in fuel efficient driving techniques; engine and machinery maintenance; optimal load balancing and tyre settings; matching machinery and engine sizes to tasks; driving at the most fuel efficient speed and gears as recommended by the manufacturers; and the optimal planning of field operations. For cold stores, energy efficiency measures and renewable energy could be considered. Certain types of bioenergy and the use of solar or wind energy can also help reduce emissions.

2.2.3. Increasing soil carbon contents

The capacity of soils to store (or “sequester”) additional carbon depends on the balance between photosynthesis which fixes CO₂ from the air, the respiration of decomposer organisms that release CO₂ into the air, and the stabilisation of carbon in the soil. For climate change mitigation, increasing soil organic carbon contents is considered a low-cost option with a low land and water footprint and low energy use, i.e. a no regrets option with few negative externalities. Maintaining current soil organic carbon stocks should be the minimum target, especially in carbon rich soils like peatlands (FAO 2017).

While soils can contribute to climate mitigation by taking up atmospheric carbon **it is important to consider that they have a time limited capacity to do so until they have reached a new equilibrium** and that the any gains are easily reversible if management practices that foster carbon sequestration are discontinued (Paustian *et al.* 2000).

Measures that can maintain and increase soil carbon contents include:

- reducing physical erosion by wind or water;
- reducing the mechanical disturbance of soils;
- maintaining ground cover;
- raising the water content of organic soils;
- increasing the allocation of carbon below ground (i.e. greater root densities) (Banwart *et al.*, 2015).

Increasing the supply of organic matter can be achieved by returning residues, increased biomass production, application of composts, cover cropping, perennial crops, and increasing yields and residue inputs by increased fertilisation in low yielding systems.

Other options include **complex crop rotations**, integrated nutrient management, the application of biochar, and avoiding soil nutrient mining and soil compaction (Lal, 2013; FAO, 2017).

Agroforestry and other diversified systems, including integrating crops and livestock, are especially important in this context (FAO, 2017).

Responses to such measures vary between different climates and soil types. Therefore, the most suitable practices need to be chosen based on local conditions (FAO 2017). Additional benefits from increasing soil organic matter include improved soil and water quality, reduced erosion, better soil fertility and crop production (Paustian *et al.* 2000).

Minimal tillage, reduced tillage and no till systems often increase soil carbon contents because they reduce or avoid soil disturbance that leads to increased decomposition and erosion. However, this increase in soil carbon is not always evident in reduced tillage systems (Smith *et al.* 2008), and some studies found a change in the distribution of soil carbon across soil horizons but no net increase in total soil carbon contents (Sanz *et al.* 2017).

In addition, there is a risk of increased N_2O emissions in reduced/no till systems, especially in soils with restricted drainage and in wet climates (Rochette 2008). Further research is needed to **better understand the effects of reduced tillage** on soil carbon levels and net GHG emissions and how climatic factors and soil conditions influence them (Smith *et al.* 2008). It is important to consider local conditions, where no till farming and conservation agriculture are most suitable to well drained soils and terrains which are prone to runoff and erosion, crusting and compaction (Lal 2011).

In contrast, **no till farming is not suitable for sites where crop residues are removed, soils are clayey and often anaerobic**, springtime temperatures are sub-optimal and perennial weeds a serious problem (Lal 2011). In contrast to the uncertain climate mitigation benefits of reduced tillage related to soil CO_2 and N_2O emissions, a clear climate benefit results from the reduced use of agricultural machinery and therefore fossil energy.

The use of **cover crops, green manures and mulching** can increase soil organic carbon stocks, either on its own or in combination with reduced tillage. Cover crops promote the retention of soil and nutrients between crop cycles. If crop residues are retained, they tend to increase soil carbon because they are the precursor for soil organic matter (Smith *et al.* 2008). If burning of crop residues can be eliminated, this will not only increase the return of organic matter to the soil but also reduce GHG emissions and other pollutants from fire (Smith *et al.* 2008).

2.2.4. *Management of organic soils*

In the absence of oxygen under flooded conditions, organic soils accumulate large amounts of carbon because the decomposition of organic materials is suppressed. Drainage for agricultural use leads to the aeration of these soils which increases decomposition rates and releases CO_2 and N_2O . These emissions can be reduced at least to some extent by avoiding row crops and deep ploughing as well as maintaining a shallower water table. Where possible, water tables should be raised again, and any further drainage of such soils should be avoided (Smith *et al.* 2008).

2.2.5. *Increasing carbon stocks on farms*

Plants take up carbon as they grow, and so atmospheric carbon can also be locked up in new biomass on farms, e.g. in **agroforestry systems, shade trees, hedges, set aside strips or perennial horticultural crops like fruit trees or tree spices**.

For example, coconut plantations have been shown to take up 15-35 Mg CO_2 per hectare and year depending on the cultivar, soil type, climatic zone and management (Kumar 2013). However, for climate mitigation it is important that this biomass is maintained over long time periods and rotations. Possible additional benefits include reduced wind

erosion with positive effects on soil carbon levels, yield increases and greater resilience to climatic changes (Smith *et al.* 2014).

2.2.6. Improved farm management

Many case studies have found large differences in the environmental impacts of individual farms within the same country or region (e.g. Mouron *et al.* 2006). **This highlights the effects of individual management factors on the extent of GHG emissions** and other environmental impacts, and implies that the potential for improving the environmental performance of individual farms is large.

For example, Milà i Canals *et al.* (2006) found a 30-fold difference in energy consumption for the same field operations in apple orchards in New Zealand (e.g. mowing, thinning, pruning, harvesting) performed by different producers. One important mitigation opportunity therefore lies within the training, awareness raising and better understanding of the influence of management decisions on environmental impacts.

2.3 Mitigation downstream and upstream

Under the UN's Montreal Protocol, substances used in **refrigeration** that have a strong impact on climate change are gradually being phased out. Alternatives with lower impacts and greater energy efficiency are introduced to replace them, e.g. ammonia or hydrocarbons. **It is important that refrigerants are properly managed** and all equipment is handled, maintained and disposed of properly by trained personnel.

Another option to reduce the impact of long distance transport on the carbon footprint of fresh produce is the optimisation of **transport logistics**. In their case study on bananas produced in Ecuador and shipped to Europe, Iriarte *et al.* (2014) analysed two scenarios for overseas transportation. The worst case scenario was based on small reefer ships that are less efficient than larger container ships and typically return empty to their origin. The best case scenario assumed transportation in container vessels and that the vessels carry other produce on their return journey so that the GHG emissions from the return journey do not count towards the bananas' carbon footprint. Table 5 shows that improved transportation logistics can reduce the carbon footprint by 56%. Similarly, Svanes & Aronsson (2013) found that the carbon footprint of bananas produced in Costa Rica and consumed in Europe would be 45% lower if they were transported in larger, more efficient ships which did not return empty.

Other measures that lead to reduced emission from **transport** include optimal route planning, increasing the average load per trip, the choice of low carbon modes of transport, proper maintenance, using fuels that emit less CO₂ (e.g. biofuels or hydrogen), driver training to increase fuel use efficiency, vehicle sharing and backhauling (Garnett 2011, PCF Project 2009a).

Because of the **large emissions related to air freighting produce, shifting from air transport to shipping where possible is an option for achieving large reductions of the GHG emissions from long distance transport.**

For example, Stoessel *et al.* (2012) reported a case study on white asparagus cultivated in Mexico and Peru and consumed in Switzerland. In order to address climate change concerns, the amount of produce shipped instead of air freighted was increased

significantly which was made possible by improved logistics and storage techniques.

Table 5: Contribution of different supply chain stages to the overall carbon footprint of bananas cultivated on one farm in Ecuador and transported to Europe for two scenarios for overseas transportation. Figures are the averages of 2009-2011. Source: Iriarte et al. (2014).

	worst case scenario	best case scenario
cultivation	0.24	0.24
post-harvest fruit handling	0.002	0.002
packing	0.087	0.087
national transport	0.008	0.008
overseas transport	0.71	0.12
total	1.05	0.46

Refrigeration is also an important source of emissions related to **retailing and manufacturing**. Reduction opportunities include improved energy efficiency, the correct specification and appropriate use of equipment, developing new technologies, preventing refrigerant leakage and alternatives to refrigerants with a large climate impact (Garnett 2011).

Energy management and efficiency are also important for shops, buildings, offices etc., and the use of renewable energy sources can also contribute to lowering overall GHG emissions from retailing and manufacture. Emissions related to **packaging** can be reduced by developing lighter packaging and bulk importing (Garnett 2011).

Finally, the end **consumer** often contributes a large share of the total life cycle GHG emissions of food products (e.g. Milà i Canals et al. 2008, PCF Project 2009b). Raising consumer awareness about GHG emissions related to their shopping trips, cooking methods, energy efficiency, and food waste can all help reduce these emissions.

Effectively reducing **food losses and wastes** (FLW) will require an integrated supply chain approach because many possible options will only have the desired effect if other parts of the supply chain are also improved.

For example, improving cold storage to reduce post-harvest losses can only be effective if farmers have access to markets and transport infrastructure. Various measures are being discussed to reduce FLW. Many of these apply to the post-harvest stages, are technological (e.g. improved cold storage), involve new policies or target changing consumption behavior. With regard to easily perishable products like many horticultural crops, options include: establishing and maintaining infrastructure to reduce their deterioration; improved storage, processing and transportation; or national programs to improve cold chains (Lipinski et al. 2013, HLPE 2014).

3. NEED FOR HOLISTIC ASSESSMENTS AND A SYSTEMS APPROACH

Because agricultural production includes different sources of emissions and different GHGs, it is **important to consider all practices and the net effects of any mitigation measures** on all GHGs in order to avoid unintentional burden shifting from one process or GHG to another.

For example, no till systems can have a positive impact by increasing soil organic carbon levels; however, N₂O emissions might increase at the same time so it is important to consider the net balance of these GHGs when assessing overall climate mitigation benefits. Similarly, if a more nitrogen efficient variety caused less GHGs during its cultivation but had a shorter shelf life resulting in more wastage, the need for chilling or more packaging, this could lead to increased emissions at other stages of the supply chain.

At the farm level, the systems approach called '**conservation agriculture**' combines several practices mentioned previously by fostering the retention of crop residues as surface mulch, including cover crops in the rotation, and implementing minimum soil disturbance. These practices can improve soil fertility, reduce erosion risks, conserve soil moisture, and contribute to climate mitigation by increasing soil **carbon levels** (although the latter is associated with some uncertainty) (Sanz *et al.* 2017).

Agroecological farming practices are another integrated approach to increasing yields, enhancing on-farm fertility and adapting to the effects of climate change by fostering positive biological interactions and synergies between different parts of the agricultural system. At the same time, such systems can achieve wider benefits such as improved human nutrition, creating new jobs and increasing farmer incomes (Pretty *et al.* 2006, De Schutter 2010).

Climatic changes are already evident in many regions of the world, and crop yields already being negatively affected by increasing droughts, extreme weather events, changing seasons, etc. Agriculture will need to contribute to climate mitigation by reducing the amount of GHGs released, but at the same time it is equally important to consider how agricultural systems can adapt to climate change and become more resilient.

Climate mitigation and adaptation need to go hand in hand, and approaches are needed to consider both in order to maximise potential synergies and reduce trade-offs. Soil conservation practices, conservation agriculture, agroforestry, silvo-pastoral systems, agroecology, climate smart agriculture and other approaches can combine climate mitigation and adaptation and other food security, development and conservation targets (e.g. diversification of farmer incomes or the protection of pollinators).

An increased focus on integrated landscape approaches is recommended for tropical agriculture to contribute to climate mitigation targets, food security and the increased provision of ecosystem services such as carbon sequestration or biodiversity protection (Harvey *et al.* 2014). For a case study on the combined benefits of coffee-banana intercropping on climate mitigation and adaptation, farmer livelihoods and risks in Africa, see van Asten *et al.* (2015)⁴¹.

Taking a holistic approach to the interconnected challenges in the land use sectors, including climate change, food security, land use, sustainable food production, healthy

41 <https://cgspace.cgiar.org/bitstream/handle/10568/69017/CCAFSpbCoffee-Banana.pdf>

diets and biodiversity conservation, is also important because of the large potential for trade-offs and synergies. Explicitly identifying and acknowledging these trade-offs and synergies in governance and policy making can help overcome barriers to the implementation of best practices. Land management decisions are made at multiple levels (e.g. farms, regional and national levels, different sectors and government departments), and the involvement of all relevant stakeholders is needed for effective decision making (IPCC 2019).

Finally, **our entire food system needs to become more sustainable**. This includes changes not only to crop and animal production but to entire supply chains, our consumption behavior, food losses and wastes, and a shift of our diets towards less GHG and resource intensive diets.



Chapter 5

Case study

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Training objectives:

After reading this chapter, you will be able to:

- analyse a true-to-life scenario
- determine common direct or indirect, on- and off-farm sources of greenhouse gas emissions based on theoretical knowledge acquired
- propose a series of appropriate solutions to reduce the greenhouse gas emissions related to the products produced on the case study farms
- develop an action plan to address the main greenhouse gas emissions hotspots.

1. A CASE STUDY: WHY, HOW?

Working on the description of a hypothetical case will never replace your professional experience forged in the field and through contact with the everyday lives of farmers. However, from an example drawn from situations already encountered, it is possible to acquire **methodological principles** to analyse the situation and determine the nature and origin of problems that may be encountered by farmers; and to be able to propose **workable solutions** that are efficient, cost-effective and compatible with sustainability goals.

How to use this case study?

A case study should not be used to propose a ready-made 'recipe' with ingredients that will always result in the same solutions to recommend to farmers. On the contrary, it should enable you to **understand the complexity of situations that may exist and that require a case-by-case approach**, with appropriate solutions suited to each situation and to the resources available locally. **It must help the farmer to understand the why of their problems, and to determine themselves how a lasting improvement in the situation is possible**, by weighing up the costs and benefits of each theoretical solution.

1.2. How can you use this case study ?

The case study has **four parts**, reflecting the four steps to be completed in the exercise:

- 1) Scenario:** By reading the text, information can be identified that is relevant to understanding a situation that a horticultural business may encounter (in this case, concerning the emission of GHGs related to horticultural production).
- 2) Situation analysis:** To identify causes and propose solutions for the business, analyse the situation as described and identify practices that are likely to result in large GHG emissions.
- 3) Identification of appropriate solutions:** This will involve carrying out an inventory of solutions that would be appropriate to address each problem, identified separately; then observing, for each solution, whether it is: (1) effective; (2) profitable; (3) accessible; (4) sustainable.
- 4) Proposal of an action plan for the business:** This means drawing up an implementation strategy, incorporating the selected solutions, to improve the situation in a sustainable manner to reduce GHG emissions.

To fully benefit from this case study, you should **follow the guidelines** and perform each step as a personal exercise, referring to the theoretical aspects described in this *Handbook*, and consulting the relevant websites and resources provided.

At each step, you will see instructions, then a solution. You will see the following message:

“Have you completed your part of the exercise? Well done! Now compare your results with the proposed solution, identify the differences, and try to see why your results differ from this proposal. But perhaps you have thought of a new and/or a better proposal? Write your analysis of the results, and your personal perception, in a few lines: this will help you to retrace the reasoning behind your strategy at the end of the exercise”.

Tip before you start:

Print the pages of this chapter to make your work easier.



2. PART 1: BACKGROUND

Instructions:

Read carefully this account describing a horticultural business. Identify, in the situation described, the key elements that contribute to the emission of GHGs and other air pollution problems.

If necessary, print this page to re-read it several times.

(Disclaimer: this is a fictional case; any resemblance to actual situations, people or business names is entirely coincidental.)

2.1. Case narrative

For more than 10 years now, following the death of his father, who was a vegetable farmer as was his grandfather before him, Dieudonné Shamba has been the manager of the family business FRUITVERTS sarl. It is a medium-sized business (around 15 ha) on the outskirts of a large town, near some villages where a good number of his vegetables are sold all year round. This business produces some of its products (mainly green beans and cherry tomatoes) on site, but it also works with several small-scale farmers nearby, who provide it with fruit (mangoes) and some vegetables (okra, cabbage, peppers, tomatoes, amaranth, etc.) throughout the year. In its packaging station, it sorts and packs products for regional and export markets. Some of the tomatoes bought from local producers are also processed on site (dried) and packaged. The business is barely 30 km away from its main local market (in town) and from the large port from where its premium products (mangoes, fine green beans and cherry tomatoes) are shipped to Europe.

At FRUITVERTS, there are two growing areas. The part of the farm (8 ha) that is furthest from the coastline has the highest soils, which are fairly flat and divided into large squares separated by irrigation ditches. Until now, the soils, although sandy-clay, were fertile enough to accommodate crops to be grown for export. Green beans for the French market are produced there (6 ha) between September and March/April, and cherry tomatoes (2 ha) for the Dutch market, with the same crops being grown on the same plots every year.



Figure 1 - Crops grown on uplands (beans and cherry tomatoes)

The other soils, which are sandier (around 7 ha) slope gently towards the coast. They are interspersed with ditches hollowed by erosion. As they were considered to be less fertile, various vegetable crops (especially tomatoes, peppers and okra) for neighbouring markets are grown on the slope. The crops are distributed in small areas of a few acres, formerly separated by hedgerows that have mostly now disappeared. The small beds occupy land from the top to the bottom of the slope, where a large pond serves as a reservoir of water to irrigate these crops. On the slope, Dieudonné has planted a few trees to contain the soil and provide some shade for his nurseries. As far back as he can remember, Dieudonné has always known this division of crops. The surrounding villages are spread out along the coastline on the main road towards the town. Each villager has a small orchard of mango trees and some square beds where vegetables (tomatoes, melons, aubergines, etc.), maize, sorghum and groundnuts are grown, depending on the season.



Figure 2- Bed grown by a smallholder

For the past two or three years, Dieudonné has found, when looking at his accounts, that the income he generates from his farm has fallen sharply. However, the sale price has tended to rise in line with the expansion of the villages and the large town, where there is a high demand for fruit and vegetables. It is clear that, on the whole, it is his production that has fallen. His business has produced far fewer beans and cherry tomatoes (these are the crops where the yield has fallen the most), and he has also experienced a reduction in product quality, with a lower share of the total production suitable for export. For the other vegetables (tomatoes, okra and peppers), the fall in production has not been as dramatic, but it does not achieve the levels seen in previous years, despite repeated purchases of fertilisers and plant protection products. Unfortunately, the smallholders have not been able to offset the shortfall in his yield, even though they have been encouraged by him to produce as much as possible by increasing their surface area, and even though they have received compound fertiliser and plant protection products. They have increased their production area by converting semi-natural vegetation such as shrublands to new plots nearby. The collection of the fruit and vegetables that the smallholders supply is inefficient, with some bruising of the fresh fruit and vegetables during the trip, in part due to poor logistics that increase the time spent on the road and unsuitable packaging that does not protect the produce enough. Some storage of

the green beans and cherry tomatoes is necessary on Dieudonné's farm before they are exported; however, this storage is not cooled, and this leads to some loss of produce, quality and market value.

To produce his green beans and cherry tomatoes, Dieudonné has carefully prepared his land with his tractor, ploughing to 30 to 40 cm to dig in weeds and residues from previous crops (including maize grown in the wet season). Dieudonné has not been sparing with inputs, either. He has not hesitated to increase the quantities of NPK fertiliser spread (100-100-300), in addition to the fresh manure he works in when ploughing. He is careful to treat his crops several times a season with plant protection products (insecticides, fungicides) in order to increase his yields. For the past two years, he has even applied selective herbicides (atrazine) to beans, tomatoes and even maize to keep his soil clean and limit competition from weeds.

He applies peat in order to improve the soil's pH. Finally, over the past five years he has also increased the inflow of irrigation water, so that the beans and tomatoes take full advantage of his fertilisers and plant protection treatments. He has therefore installed a larger pumping unit on the pond to be able to irrigate the green beans and tomatoes more frequently by filling the channels winding across his fields with water. Nothing works.

His plants are sometimes attacked by diseases (e.g. fusarium wilt) that are treated with fungicides, but generally the leaves of his beans and tomatoes tend to be very dark green. On the other hand, during periods of great heat they tend to wilt more quickly. Dieudonné uprooted a few plants, but he did not find any traces of gall nematodes or rot on the collar. He does not understand what's going on.

Dieudonné's efforts are clearly not paying off. He is struggling with decreasing yields and increases his use of inputs in an attempt to counteract this trend. This has resulted in increasing GHG emissions from his farm and his produce. He needs the help of a specialist. Can you help him?

- On a sheet of paper, try to **sort and list the problems** described (without reading further).
- Make a list of **observations, analyses and actions** that would be required to offer a diagnosis.

2.2. Analysis of the situation described

Have you completed your part of the exercise? Well done! Now compare your results with the proposed solution, identify the differences, and try to see why your results differ from this proposal. But perhaps you have thought of a new and/or a better proposal? Write your analysis of the results, and your personal perception, in a few lines: this will help you to retrace the reasoning behind your strategy at the end of the exercise.

Proposed solution

■ Key information from the account given

- Yields have been declining in recent years.
- The business is also experiencing a reduction in product quality, with increasing shares of lower quality vegetables that are not suitable for the export market.

- At the same time, the use of inputs, in particular mineral fertilisers, pesticides and irrigation, has increased.
- The reduction in yields is mainly due to a decline in the farm's soil fertility which is caused by a number of inappropriate practices: over-use of inputs, a lack of appropriate crop rotations, inappropriate irrigation, soil compaction, a high soil pH, poor management of organic matter inputs, soil erosion due to a lack of protective structures such as hedgerows, negative impacts of the pesticides applied on soil life, etc.
- Mineral fertilisers are over-applied and both the amounts and the ratios of the different nutrients to each other are not according to crop needs and best practice recommendations.
- Fresh manure is applied during land preparation.
- Pesticides are applied several times per season and in large amounts. No integrated pest management is implemented.
- Large quantities of water are applied during irrigation.
- Hedgerows and trees have largely disappeared from the farm.
- Soil erosion by wind and water leads to a loss of productive soil.
- Peat is used in order to correct the soil pH.
- The smallholder farmers who supply the business have been encouraged to also increase their use of inputs but were equally unsuccessful in increasing their output.
- The smallholders are even encouraged to increase their production area. They have done this by converting previously unused land from semi-natural vegetation to agricultural production.
- The logistics of transporting produce from the smallholder farms to Dieudonné's farm is organised in an inefficient way.

■ Observations, analyses and measurements to suggest

- Try to identify the main sources of GHG emissions on this farm by considering typical sources of emissions both on-farm (e.g. energy use for field operations, fertilised soils) and off-farm (e.g. during the production and transport of external inputs to the farm).
- The following suggestions are targeted at understanding why yield levels are declining. If yield levels can be improved again while current levels of input use are maintained or even reduced the carbon footprint per unit of output will go down:
 - Create a soil profile over 50 cm.
 - Observe the colour of the soil.
 - Observe the presence of tunnels in the soil and of other soil fauna.
 - Perform a soil analysis to establish the nutrient content.
 - Measure the organic matter content.
 - Measure the soil's pH.
 - Measure the soil's electrical conductivity.

■ Results of analyses, measurements and observations

- The use of inputs is too high compared to the yields that are achieved.
- Both mineral and organic fertilisers are used inefficiently and inappropriately.
- Energy use related to irrigation is high, in particular since the installation of the new pumping unit and the increase in the amount of irrigation water used.
- Increasing use of inputs coupled with decreasing yields means that the efficiency of input use is going down. This inefficiency leads to high GHG emissions per hectare and a high product related carbon footprint (kg CO₂e/unit of produce). The product related carbon footprint has increased in recent years.
- It also leads to other negative environmental impacts (e.g. leaching of nitrogen to groundwater bodies and pesticides polluting the atmosphere and irrigation water) and negatively impacts the business’s economic situation.
- The smallholder suppliers are converting semi-natural land to horticultural production and increasing input use.
- Figure 3 shows the percentage contribution of the different sources of GHG emissions on Dieudonné’s farm and the smallholders’ farms (hypothetical example based on the description of the farms).
- Yield levels are declining, increasing the product related carbon footprint. The results of the soil analysis can help tackle this issue. Observations related to the soil analysis:
 - By creating a soil profile over 50 cm, the depth of the surface horizon (horizon A) is limited to 20–30 cm at most. A gap area is observed at around 30 cm (darker horizon above a much lighter horizon).
 - It is observed that the soil is brown, or even dark brown (colour due to the clay and organic matter present).
 - Very few tunnels can be observed in the soil, and few insects and few earthworms.
 - Residues from previous, poorly decomposed, crops are observed.
 - Soil analysis (in mg/kg):

N	P (P ₂ O ₅)	K (K ₂ O)	Ca (CaO)	Mg (MgO)
688	339	834	4,445	388

Analysis of organic matter content (result: **OM = 4.60%**).

Soil pH measurement (result: **pH_{water} = 8.8**).

Electrical conductivity measurement (result: **EC = 3.56 dS/m**).

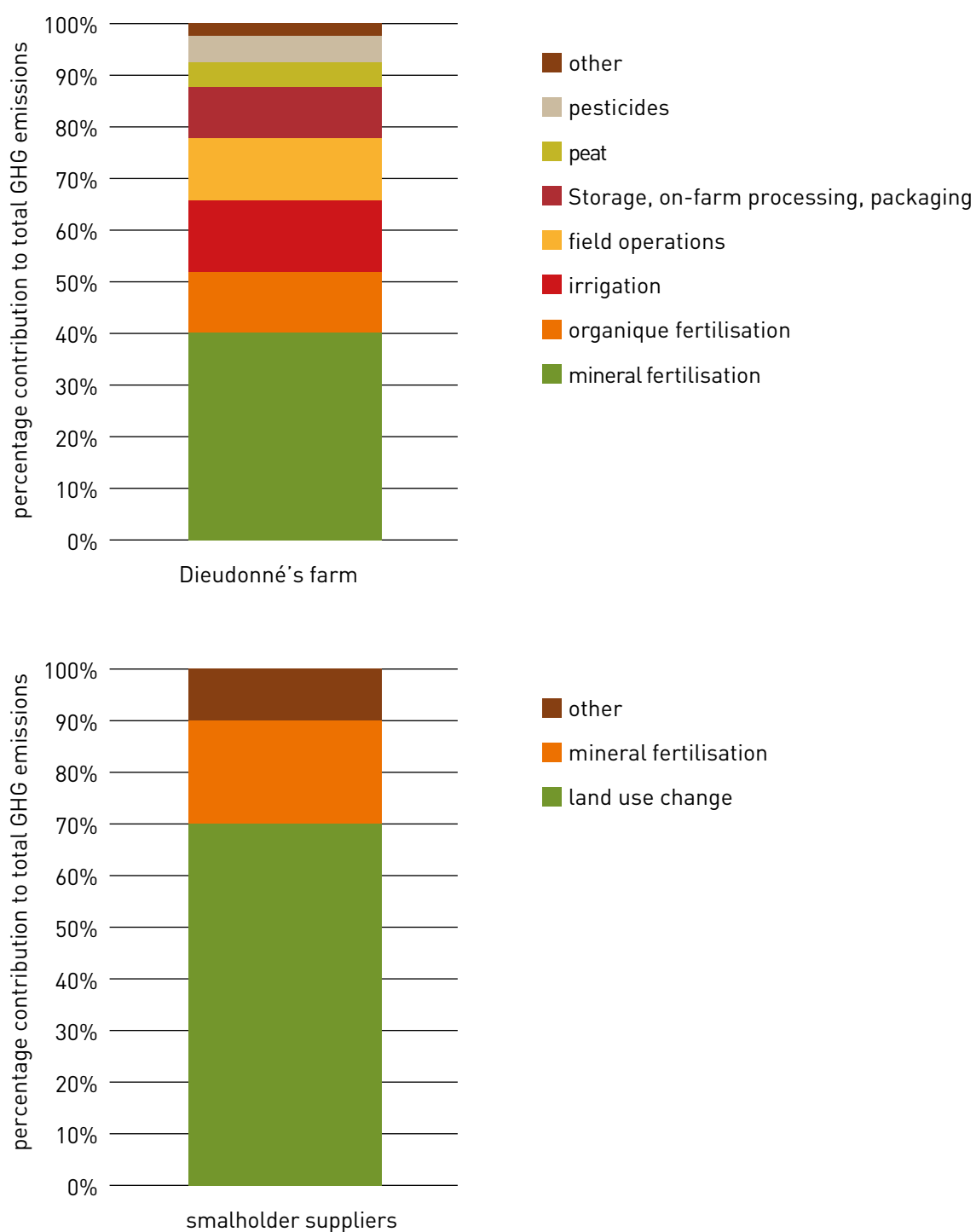


Figure 3- Percentage contribution of the different sources of greenhouse gas (GHG) emissions on Dieudonné's farm (top) and the smallholders' farms (bottom).

My supplementary analysis (free space):

[illegible]

3. PART 2: CASE ANALYSIS

Instructions for case analysis

Instructions:

To help Dieudonné, the causes of his business's high product carbon footprint and low productivity need to be analysed. Work with two tools: a table and a root-cause analysis diagram.

Begin by completing the table (if necessary, add more rows and columns). When the table is complete, create the root-cause analysis in the form of a diagram (a flowchart, as shown in the example). Start by putting the problems identified in the boxes at the top and indicating the probable cause(s) in the boxes below.

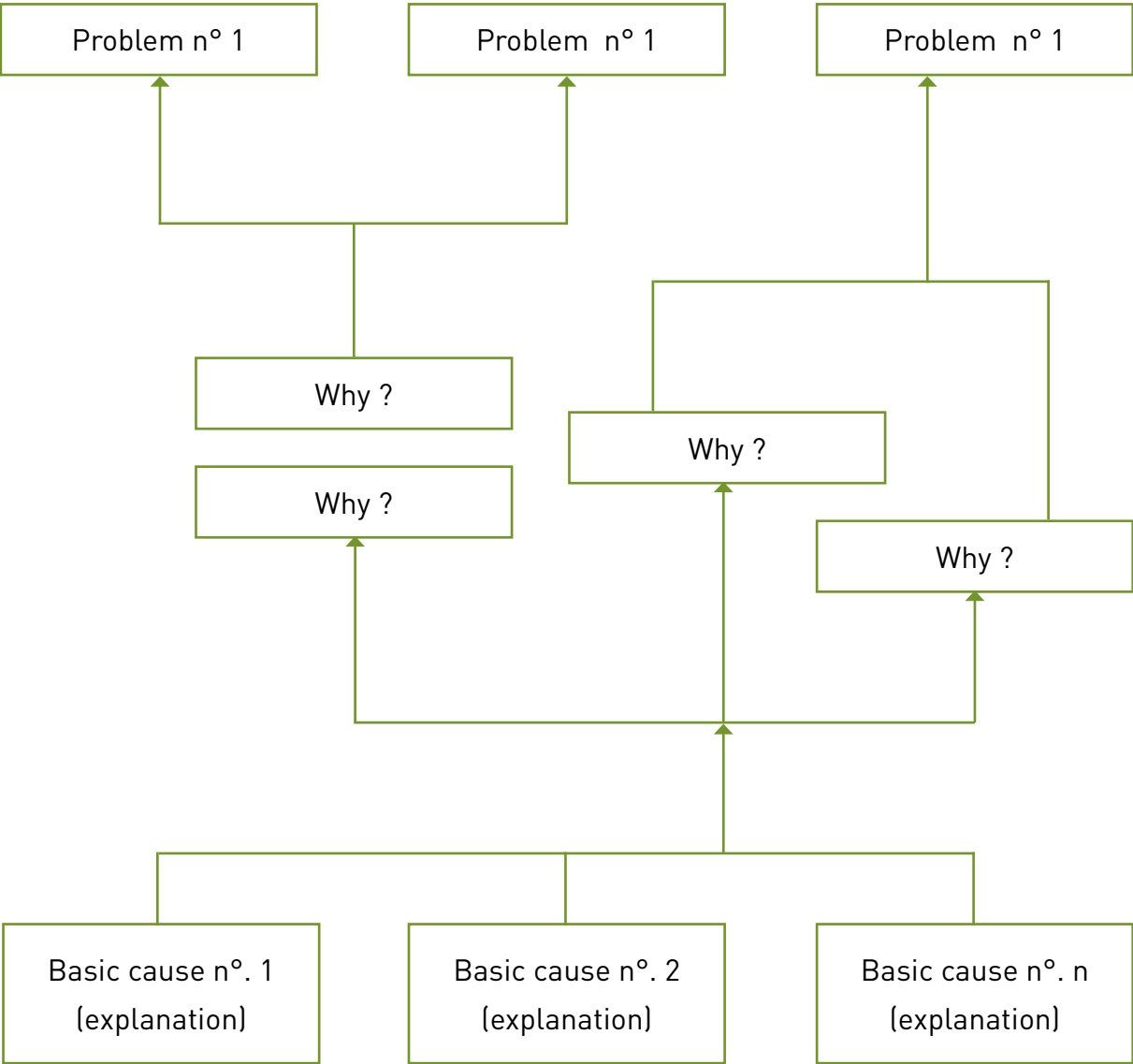


Tableau (exemple à imprimer et à compléter)

Problem identified (finding, observation)	Tentative explanation	Identification of probable cause(s)

Root-cause analysis (example of a diagram to create and complete)

Begin with the findings (problems observed), then go back to the sources (sometimes multiple) that explain the origin of each problem. At the root there will be a number of deeper, more widespread causes.



3.2. Root-cause analysis: proposed result

Have you completed your part of the exercise? Well done! Now compare your results with the proposed solution, identify the differences, and try to see why your results differ from this proposal. But perhaps you have thought of a new and/or a better proposal? Write your analysis of the results, and your personal perception, in a few lines: this will help you to retrace the reasoning behind your strategy at the end of the exercise.

Proposed solution: table

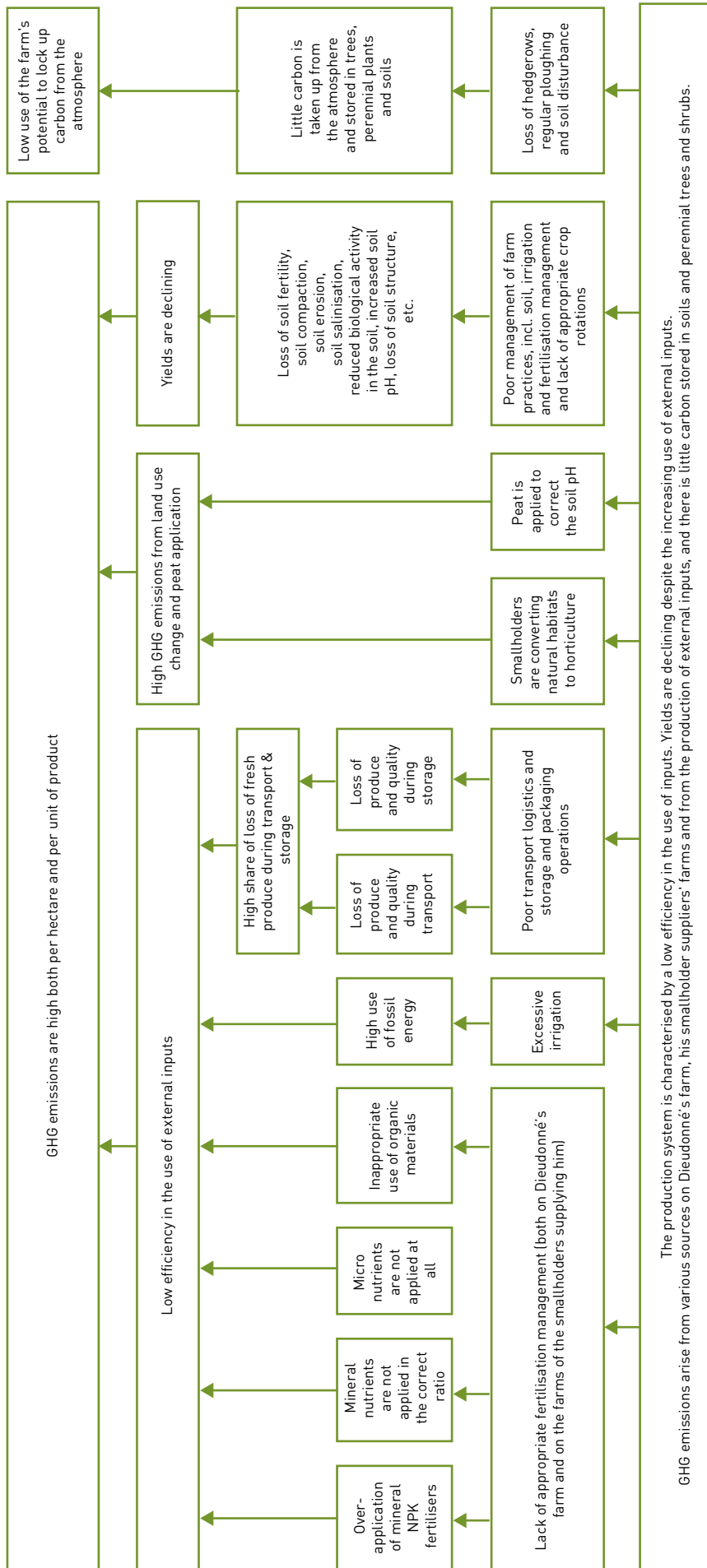
Problems identified (finding, observation)	Tentative explanation	Identification of probable cause(s)
The carbon footprint per unit of product has increased	The carbon footprint of Dieudonné's and his smallholder suppliers' products has increased due to declining yields and increasing input use.	The increase in the product carbon footprint is due to two main factors: 1) the intensity of input use has increased which leads to more GHG emissions from the production, transport and use of these inputs in absolute terms (per hectare); and 2) at the same time, the harvested yield has declined. The combination of these two factors means that the product related carbon footprint has gone up because more inputs produce less outputs , i.e. the system has become less efficient.
GHG emissions related to mineral fertilisation are high	<p>Dieudonné's mineral fertiliser management is inappropriate and excessive.</p> <p>He has increased the quantities of mineral fertilisers applied because of the observed decline in yields.</p> <p>His fertilisation practices are characterised by the over-application of nutrients.</p> <p>He applies NPK fertilisers only.</p> <p>He applies mineral fertilisers shortly before irrigating his fields.</p>	<p>Dieudonné is applying excessive amounts of mineral fertilisers. He applies more nutrients than needed to replace the nutrients that are exported with each harvest.</p> <p>He is also not getting the balance of the different nutrients right (e.g. too much potassium in relation to nitrogen and phosphorus) and does not include any micro-nutrients (e.g. calcium and magnesium) that are needed to produce healthy crops and high yields.</p> <p>Due to the over-irrigation on his farm and the poor timing of irrigation events, Dieudonné risks losing some of the nutrients applied due to leaching.</p> <p>Overall, his fertilisation is very inefficient. The excess of application and poor fertilisation practices mean that the GHG emissions related to the production, transport and use of mineral fertilisers are high in relation to the yield achieved, leading to a high carbon footprint per unit of output in addition to high absolute GHG emissions per hectare.</p>

Organic fertilisers are used inappropriately	Dieudonné applies organic fertilisers but not according to best practice. This means that they do not contribute as much as possible to increasing yields, and the GHG emissions that arise due to organic fertilisation are too high for the yields that are achieved.	Fresh manure that has not fully decomposed is applied and incorporated into the soil before growing beans and tomatoes which is not recommended. The heavy use of pesticides negatively impacts soil life so that the decomposition of the organic matter is slowed down which means that it cannot contribute to soil fertility as much as it could.
Energy use related to irrigation and field operations	The irrigation system requires fossil energy for pumping water from the pond to the fields, and tractors and other farm machinery consume diesel.	Fossil energy use is high on Dieudonné's farm because he pumps a lot of water for irrigation and carries out field operations such as ploughing and fertiliser applications. As he over-applies mineral fertilisers he uses more energy for fertilisation than necessary.
Little on-farm carbon sequestration in soils, trees and hedgerows	Dieudonné experiences problems with soil fertility and soil organic matter contents. His flat upland soils are prone to wind and water erosion. The farm does not make use of its potential to lock up carbon from the atmosphere in soils and trees.	Dieudonné's soils are prone to wind and water erosion due to a lack of protective structures such as trees and hedgerows. On-farm carbon sinks can lock up carbon from the atmosphere and include soils, trees and hedgerows. However, Dieudonné removed the hedgerows that used to separate fields and loses soil carbon due to erosion.
Smallholder suppliers convert semi-natural vegetation to expand their cropping area	The smallholders that supply Dieudonné face declining yields and are encouraged to increase their production area.	The smallholders increase their production by converting semi-natural vegetation such as shrublands to agricultural plots. This conversion causes the emission of large amounts of GHGs because carbon that was previously stored in above-ground vegetation and soils is released to the atmosphere upon conversion.

<p>The smallholder production system releases large amounts of GHGs</p>	<p>The carbon footprint of the fruit and vegetables produced by the smallholders for Dieudonné is high.</p>	<p>The smallholder production system shares several problems with Dieudonné's farm.</p> <p>The smallholders have been encouraged to increase their use of inputs, including mineral fertilisers and pesticides. However, yields are declining and soil fertility is going down.</p> <p>This means that the production system is inefficient at converting external inputs into yields, leading to a high carbon footprint per unit of product.</p> <p>The high use of pesticides also causes environmental and air pollution problems and has negative impacts on soil fertility levels.</p>
<p>Relatively high GHG emissions from logistics</p>	<p>Transportation of fresh produce from the smallholders to Dieudonné's farm is inefficient and characterised by comparatively high GHG emissions.</p>	<p>The transport is carried out whenever fresh produce has been harvested, and there is little coordination between the different smallholders.</p>
<p>Significant losses of fresh fruit and vegetables during transport and storage</p>	<p>A significant share of fruits and vegetables sourced from the smallholders arrives at Dieudonné's farm with bruising and a loss of quality. More produce gets damaged and lost during storage. Such losses represent a waste of resources and the GHG emissions associated with the cultivation of this produce were for nothing.</p>	<p>The reasons for the loss of produce and produce quality include:</p> <ul style="list-style-type: none"> - mechanical injury due to rough handling and rough roads; - delays in transporting fresh produce due to transport bottlenecks, bad weather or poor coordination of logistics; - unsuitable packaging materials that do not adequately protect the fruits and vegetables during transport; - lack of cold storage for the most perishable products.

<p>Packaging and processing release GHGs</p>	<p>Due to the consumption of fossil energy, the packaging station releases GHGs and other air pollutants.</p>	<p>The emissions related to sorting and packaging products contributes to GHG emissions mainly by consuming fossil energy. The packaging station consumes large amounts of energy, suggesting inefficient processes. Packaging materials also have their own carbon footprint (i.e. GHG emissions related to the manufacture and transport of the materials).</p>
<p>Large carbon losses result from the use of peat to correct the soil's pH</p>	<p>Dieudonné applies peat in an attempt to correct the soil's pH which is too high.</p>	<p>Dieudonné's poor management of irrigation is the main cause for soil salinization which in turn has led to an increase in the pH. Now the pH is so high that it causes problems for some of the crops he grows. He applies peat in order to reduce the pH again although this material is not recommended for this purpose and therefore has little positive effect.</p>
<p>Overuse of pesticides leads to the pollution of the atmosphere, soils and water bodies</p>	<p>Pesticides are not used sparingly and only when needed but are applied in large quantities to all crops, even when no pests or diseases are present.</p>	<p>Pesticides can contribute to air pollution because they enter the atmosphere via drift during application or volatilisation from crops and soils. Volatile organic compounds released from pesticides into the atmosphere can react with other chemicals to form ozone which is one of the most damaging air pollutants for plants and an important contributor to global warming. Pesticides can also disrupt the soil flora and fauna which contributes to a loss of soil fertility, reduces soil water infiltration and increases soil erosion, and pollute soils and water bodies (e.g. via runoff into aquatic environments).</p>

Proposed solution: root-cause analysis



My supplementary analysis (free space):

This image shows a full page of a document template designed for handwriting practice or general note-taking. It consists of approximately 28 evenly spaced horizontal dotted lines across the entire width of the page. The background is plain white, and there are no margins, headers, footers, or other markings present.

4. PART 3: SEEKING APPROPRIATE SOLUTIONS

4.1. Instructions for seeking solutions

Instructions:

To help Dieudonné, we must offer him appropriate solutions for addressing each problem identified. Work in two stages: briefly list the possible solutions to each of the problems in a table. Then check if these solutions are effective, profitable, accessible and sustainable (for each solution, evaluate these four criteria and give each one a score between 1 and 4).



Table 1 (example to complete)

Problems identified (finding, observation)	Proposed solution(s) (add some explanations)
The carbon footprint per unit of product has increased	S1:
GHG emissions related to mineral fertilisation are high	S2: S3:
Organic fertilisers are used inappropriately	S4: S5: S6:
Energy use related to irrigation and field operations	S7:
Little on-farm carbon sequestration in soils, trees and hedgerows	S8: S9:
Smallholder suppliers convert semi-natural vegetation to expand their cropping area	S10:
The smallholder production system releases large amounts of GHGs	S11:
Relatively high GHG emissions from logistics	S12: S13:
Significant losses of fresh fruit and vegetables during transport and storage	S14:

Packaging and processing release GHGs	S15: S16:
Large carbon losses result from the use of peat to correct the soil's pH	S17:
Overuse of pesticides leads to the pollution of the atmosphere, soils and water bodies	S18: ...

Table 2 (example to complete)

Suggested solutions	Effective	Profitable	Affordable	Sustainable	Score
S1	4	2	3	4	13
S2	2	3	4	1	10
S3	4	4	1	2	11
S4	4	2	4	4	14
S5	...	...	...	...	...
S6	...	...	...	...	...
S...	...	...	...	...	...
Sn	...	...	...	...	...

(1: Poor; 2: Average; 3: Good; 4: Excellent)

4.2. Seeking appropriate solutions: proposed outcome

Have you completed your part of the exercise? Well done! Now compare your results with the proposed solution, identify the differences, and try to see why your results differ from this proposal. But perhaps you have thought of a new and/or a better proposal? Write your analysis of the results, and your personal perception, in a few lines: this will help you to retrace the reasoning behind your strategy at the end of the exercise.

Proposed solution: table

Problems identified (finding, observation)	Proposed solution(s)
<p>The carbon footprint per unit of product has increased</p>	<p>S1: Review current management practices to identify all the reasons that contribute to a decline in yields and adopt best management practices to improve yields again without increasing the use of inputs or even decreasing it where appropriate.</p> <p>Product carbon footprints (PCFs) are an estimate of the amount of GHGs emitted during the production of a product, in this case horticultural crops. They are expressed per unit of yield and are therefore an indicator of the efficiency of the system. Because all the GHG emissions that arise are related to the unit of output, e.g. per kg of tomatoes, the result of a product carbon footprinting analysis is influenced by the productivity of a farming system. If a system is very efficient at converting all the inputs (e.g. mineral fertilisers) to outputs and energy is used efficiently, the result is a lower product carbon footprint than for an inefficient system. The higher the output is in relation to the inputs, the lower the PCF will be. In order to lower the carbon footprint of a product it is therefore important to maximise yield levels at any given intensity of input use, i.e. to increase production efficiencies.</p> <p>On Dieudonné's farm, there are several issues that lead to reduced yields despite him increasing the amount of inputs used. These include poor soil fertility management, over-application of mineral fertilisers, the lack of an appropriate crop rotation, soil salinization, soil compaction, a loss of soil fauna and flora, and a poor management of soil organic matter. For more details on these issues, please consult the COLEACP training manual on sustainable soil management.</p> <p>If Dieudonné can adopt the principles of conservation agriculture, improve his fertiliser management and soil fertility and apply best practices all around, then his yields will increase again and the product carbon footprint will go down.</p>
<p>GHG emissions related to mineral fertilisation are high</p>	<p>S2: Review the current fertilisation management and adopt good agricultural practices for each of the crops cultivated.</p> <p>Dieudonné must review his fertilisation management in order to make it more efficient and appropriate. He should consider best practices, e.g. considering the right balance of mineral and organic fertilisers (including micro-nutrients), the right amount of nutrient applications to match yield expectations and avoid over-fertilisation, and the right timing of applications. He should review the best practice recommendations that may exist locally for the different crops that he grows as different crops may have different requirements in terms of the amount of nutrients needed, the ratio of the different nutrients, and requirements for important micro-nutrients.</p> <p>He should make a fertilisation plan that includes appropriate organic fertilisation and consider both organic and mineral fertiliser applications when identifying the amount of nutrients that need to be applied. He might also want to consider split applications to increase the efficiency of fertilisation where appropriate.</p> <p>Mineral fertilisers (in particular nitrogen fertilisers) typically represent a GHG emissions hotspot from crop production because of the GHGs released during the industrial manufacture of the mineral fertilisers, their transport from their factories of origin to farms, and the GHG emissions that arise from fertilised soils after application. If Dieudonné can maintain the same yield as now or even increase it with lower but improved mineral fertiliser inputs, then the GHG emissions per unit of product will go down due to the improved efficiency of fertilisation.</p> <p>S3: Review the timing of mineral fertiliser application in relation to irrigation events.</p> <p>Dieudonné needs to review his irrigation practices and timing so he can minimise the amount of nutrients lost to leaching. This will improve the efficiency of fertilisation and might allow him to reduce overall application rates.</p>

**Organic fertilisers
are used
inappropriately**

S4: Improve the management of organic matter by incorporating well decomposed organic matter into the soil a long time before growing beans and tomatoes. Make a fertilisation plan that takes into account both organic and mineral nutrient sources.

The application of organic matter is part of integrated soil fertility management. It provides benefits in terms of nutrient retention, soil fertility, soil structure, soil fauna and flora. Organic matter also provides nutrients to the growing plants. Dieudonné's current management of organic matter inputs is not optimal. He should apply well decomposed organic matter and incorporate it a long time before planting tomatoes and beans. If he does this, he will more fully benefit from the application of organic matter and improve the fertility of his soils. This will help in making the production system more efficient, increase yields again and so reduce the carbon footprint per ton of produce.

**Energy use related
to irrigation and
field operations**

S5: Increase the efficiency of irrigation, match irrigation events and the amount of irrigation applied to crop needs, and consider improving the energy use efficiency of the pumps. Also monitor energy uses for field operations like ploughing or fertiliser applications and improve their fuel efficiency.

Dieudonné has to apply irrigation because of a decrease in the amount and frequency of rainfall due to climate change. Because the pumps consume considerable amounts of fossil energy, irrigation is related to the emission of GHGs and other air pollutants, and it is important to make the irrigation system more efficient in order to save energy and reduce GHG emissions. Improved efficiency is also important to minimise the amount of water needed per unit of yield which is particularly important in areas that already experience water stress and water scarcity.

Increasing the efficiency of irrigation might require improved maintenance of the equipment, matching irrigation events more closely with crop needs (both in terms of the amount of water applied and the timing of irrigation events), considering night time irrigation to reduce evapotranspiration, or changing to a drip irrigation system. Renewable energy sources for powering the irrigation pumps (e.g. solar) can reduce the use of fossil energy for running the pumps. Another possible option could be to consider rainfall storage systems so that the water does not have to be pumped to further away field from the pond.

Another benefit of improving the irrigation management is reduced salinization and resulting positive impacts on soil fertility and yields. Maintaining plant cover and improving the organic matter content of the soil can improve the water holding capacity of the soil and so help reduce the need for irrigation.

Field operations like ploughing by tractor also use fossil energy and release GHGs and other air pollutants such as carbon monoxide or particulate matter. Dieudonné should make sure that he uses farm machinery in the most fuel-efficient way possible.

Little on-farm carbon sequestration in soils, trees and hedgerows	<p>S6: Identify options for improving soil organic carbon levels and reducing the risk of wind and water erosion.</p> <p>At the moment, the farm does not provide many carbon sinks: there are not many trees or hedgerows and the soil is prone to erosion by wind and water. However, there is potential to lock up carbon from the atmosphere in trees and soils and thereby contribute to climate mitigation efforts.</p> <p>Agricultural soils can store large amounts of carbon if they are managed to increase soil organic matter levels. This can be achieved by improving the structure of the soil, introducing cover crops, green manures or mulching, and improved soil organic matter management. Dieudonné could change to a system with no or minimal soil preparation and leave crop residues on the field to cover the soil. This would lead to a saving of energy for field operations (ploughing) and potentially increase soil carbon levels.</p> <p>The excessive use of pesticides can negatively impact the soil flora and fauna which can lead to reduced infiltration rates and increased run-off and hence erosion.</p> <p>S7: Increase on-farm carbon sinks such as trees and hedgerows.</p> <p>Dieudonné could also plant more hedgerows and shade trees. These perennial plants take up carbon from the atmosphere and increase on-farm carbon stocks, thus contributing to climate change mitigation efforts. Establishing hedgerows and trees can also reduce wind and water erosion. At the same time, perennial plants, agroforestry systems and improved crop rotations also offer other benefits beyond carbon storage, e.g. the provision of habitats for beneficial insects or birds that can help reduce pesticide usage or increase pollinator populations; reduced soil erosion; provision of nutrients via crop residues; or protection of crops from increasing temperatures and heat stress. All these measures can help improve the productivity of the farm and – all else being equal – reduce the product carbon footprint. If appropriate, shade trees could also be species that produce an extra income, e.g. fruits or timber.</p>
Smallholder suppliers convert semi-natural vegetation to expand their cropping area	<p>S8: Review the smallholder production system in a holistic way in order to identify ways of improving yields on the existing area and eliminating the need to expand into semi-natural vegetation.</p> <p>The conversion of semi-natural or natural land to agriculture releases large amounts of GHGs because carbon that was previously stored in vegetation and soils is lost upon conversion. The clear felling or burning of forests is of great concern in this regard but it is equally important to protect grasslands, shrublands or wetlands from conversion. Preventing such land use change can contribute significantly to climate change mitigation efforts.</p> <p>In this case, preventing the expansion of the area cultivated by the smallholders should be possible without any negative consequences for the smallholders. By reviewing and improving their management practices, e.g. their excessive and inappropriate use of mineral fertilisers and poor soil fertility management, it should be possible to increase yields again on their existing production area. Dieudonné should work together with his smallholder suppliers to help them improve their practices so that the produce he buys from them has a lower product carbon footprint. He should stop encouraging them to increase their production by expanding their production area.</p>

The smallholder production system releases large amounts of GHGs

S9: Review the smallholder production system, in particular their fertilisation management, and support them in adopting best management practices. The smallholders have increased their use of external inputs, in particular mineral fertilisers and pesticides, in order to counteract the observed decline in yields. However, yield levels have not improved, and it is necessary to identify the reasons for this. A fertilisation management plan should be developed in order to eliminate over-applications and increase the efficiency of nutrient inputs. Improved fertilisation can increase yields and improve product quality and maintain or increase current yields at lower fertiliser application rates. The fertilisation management can be improved by considering crop specific nutrient requirements and determining the optimal application rate and ratio of macro- and micro-nutrients as well as the best timing of application during the crop cycle. Organic materials should also be considered because they contain nutrients and help improve soil fertility.

Relatively high GHG emissions from logistics

S10: Identify options for improved logistics for the transport of fresh produce from the smallholder farmers to Dieudonné's farm and to the export harbour. The optimisation of transport logistics can reduce fossil fuel usage and hence GHG emissions. Opportunities for improvement include: optimal route planning so that as much produce as possible is picked up from the smallholders in one trip (instead of making several trips); proper maintenance of vehicles and fuel efficient driving techniques; vehicle sharing with other farmers or businesses so that the number of empty trips is reduced; and planning the timing of the trips so as to reduce their overall number (i.e. when the maximum amount of produce can be picked up in one trip).

If the smallholders deliver their produce to Dieudonné instead of him picking it up, the smallholder should work together to ensure that one trip delivers several farmers' fruits and vegetables. Market information is needed to plan the timing of harvesting and subsequent logistics so that the produce arrives at its markets at the optimal time.

Significant losses of fresh fruit and vegetables during transport and storage

S11: Review the causes for bruising, spoiling and loss of quality during transport and storage, identify options for improvement and train personnel accordingly. Consider investing in cold storage facilities.

Post-harvest losses represent a waste of resources, and all the GHG emissions and resources used during their cultivation will have occurred to no avail. Reducing post-harvest losses therefore helps reduce the carbon and environmental footprint of the produce that does reach further supply chain stages and ultimately the consumer. Options for reducing post-harvest losses include:

better planning of transport logistics to reduce transit times

improved packaging materials that protect fresh vegetables and fruits from bruising, moisture loss, pathogens or high temperatures

avoiding rough handling during transportation and in pack houses and storage units

cold storage facilities

training of all staff involved to create awareness of this issue

Packaging and processing release GHGs	<p>S12: Increase the energy efficiency of the packaging and sorting station. Understand which processes consume most fossil energy and start with these. Consider options for switching to renewable energy sources. Identify low carbon sources of packaging materials.</p> <p>The first step in improving the energy management of the packaging and sorting station is to understand which processes consume most energy. Focusing on these main processes first, try to understand if the equipment used is efficient in its energy use. If not, consider options for improvement, e.g. upgrading to more energy efficient equipment, improved maintenance and improved handling. Consider switching to renewable energy sources if possible, e.g. wind or solar.</p> <p>Packaging materials have a carbon footprint related to their production and transport from their place of manufacture to the farm. Ask your supplier for information on the carbon footprint of their products to encourage them to implement reductions. Consider switching to alternative materials bearing in mind the potential impact on the total weight when transporting produce to its markets and whether the new packaging provides at least the same amount of protection of the produce against spoiling, bruising and loss of quality.</p>
Large carbon losses result from the use of peat to correct the soil's pH	<p>S13: Do not use peat to correct the soil pH. Identify other options for improving the soil structure and correct the pH.</p> <p>The use of peat to try and correct the currently too high soil pH is not recommended. The drainage of peat lands and the extraction and subsequent application of peat in agriculture lead to large GHG emissions because peat contains high carbon contents. This carbon is lost to the atmosphere when peatlands are drained and the peat decomposes. The protection of habitats that contain high carbon stocks (e.g. wetlands, peat lands) is a very important contribution towards the protection of our climate. It is also necessary to protect their plant and animal life.</p> <p>Dieudonné should consider appropriate alternatives that are more effective for improving the soil pH and do not threaten important natural habitats.</p>
Overuse of pesticides leads to the pollution of the atmosphere, soils and water bodies	<p>S14: Introduce integrated pest management to reduce the use of pesticides and find alternatives with lower environmental impacts.</p> <p>Pesticides can add to air pollution, e.g. via drift during aerial spraying, volatilisation from crops and soils, or due to wind erosion of soils. They also affect biodiversity and soil life in a negative way and can enter water bodies and pollute water used for irrigation.</p> <p>Dieudonné should reduce the amount of pesticides applied and adhere to recommended doses. He should implement the principles of integrated agriculture, re-introduce more crops into his rotations and mix different crop varieties. He should also consider possible alternatives to the use of pesticides, e.g. manual removal, using traps, removing pest breeding sites, using native crop species that are more resistant to local pests, and using biological controls (e.g. resistant crop varieties or ensuring healthy populations of natural predators such as birds). A healthy soil can also help by making the crops more resistant.</p> <p>Integrated pest management aims to reduce the use of chemical pesticides by employing such alternatives first, and pesticides only when these alternatives are ineffective. Ground spraying leads to less pesticide drift than aerial applications. Dieudonné should introduce buffer zones, e.g. trees that can act as windbreaks, that can absorb pesticides and so prevent drift into other areas.</p>

Proposed solution: analysis of the solutions

Suggested solutions		Effective	Profitable	Affordable	Sustainable	Total score
S1:	Review current management practices to identify all the reasons that contribute to a decline in yields and adopt best management practices to improve yields again without increasing the use of inputs or even decreasing it where appropriate.	4	4	3	4	15
S2:	Review the current mineral fertilisation management and adopt good agricultural practices for each of the crops cultivated.	4	4	3	3	14
S3:	Review the timing of mineral fertiliser application in relation to irrigation events.	2	2	4	3	11
S4:	Improve the management of organic matter by incorporating well decomposed organic matter into the soil a long time before growing beans and tomatoes. Make a fertilisation plan that takes into account both organic and mineral nutrient sources.	4	3	2	4	13
S5:	Increase the efficiency of irrigation, match irrigation events and the amount of irrigation applied to crop needs and consider improving the energy use efficiency of the pumps. Also monitor energy uses for field operations like ploughing and improve their fuel efficiency.	3	3	2	4	12
S6:	Identify options for improving soil organic carbon levels and reducing the risk of wind and water erosion.	3	3	2	4	12
S7:	Increase on-farm carbon sinks such as trees and hedgerows.	3	2	2	4	11
S8:	Review the smallholder production system in a holistic way in order to identify ways of improving yields on the existing area and eliminating the need to expand into semi-natural vegetation.	4	4	3	4	15
S9:	Review the smallholder production system, in particular their fertilisation management, and support them in adopting best management practices.	4	4	3	4	15

S10:	Identify options for improved logistics for the transport of fresh produce from the smallholder farmers to Dieudonné's farm and to the export harbour.	2	3	3	3	11
S11:	Review the causes for bruising, spoiling and loss of quality during transport and storage, identify options for improvement and train personnel accordingly. Consider investing in cold storage facilities.	3	3	2	3	11
S12:	Increase the energy efficiency of the packaging and sorting station. Understand which processes consume most fossil energy and start with these. Consider options for switching to renewable energy sources. Identify low carbon sources of packaging materials.	2	2	2	3	9
S13:	Do not use peat to correct the soil pH. Identify other options to improve the soil pH.	2	2	2	4	10
S14:	Introduce integrated pest management to reduce the use of pesticides and find alternatives with lower environmental impacts.	2	2	2	4	10

(1: Poor; 2: Average; 3: Good; 4: Excellent)

Based on the scores, four priority areas stand out:

- Priority 1: S1 – S2 – S4 – S8 – S9 (scores of 13 to 15)
- Priority 2: S5 – S6 (scores of 12)
- Priority 3: S3 – S7 – S10 – S11 – S13 – S14 (scores of 10 to 11)
- Priority 4: S12 (score of 9)

My supplementary analysis (free tables to complete): other problems identified and/ or other suggested solutions

Problems identified (finding, observation)	Proposed solution(s) (add some explanations)
.....	S... :
.....	S... : S... :
.....	S... : S... :
.....	S... : S... :

Other suggested solutions	Effective	Profitable	Affordable	Sustainable	Score
S... :					
S... :					
S... :					
S... :					

(1: Poor; 2: Average; 3: Good; 4: Excellent)

Classify all of your solutions based on a score that enables you to identify the actions that would be a priority to implement. It is most important for interventions to be consistent and strategic. Some steps should precede others.

5. PART 4: ACTION PLAN PROPOSED

5.1. Instructions for presenting an action plan

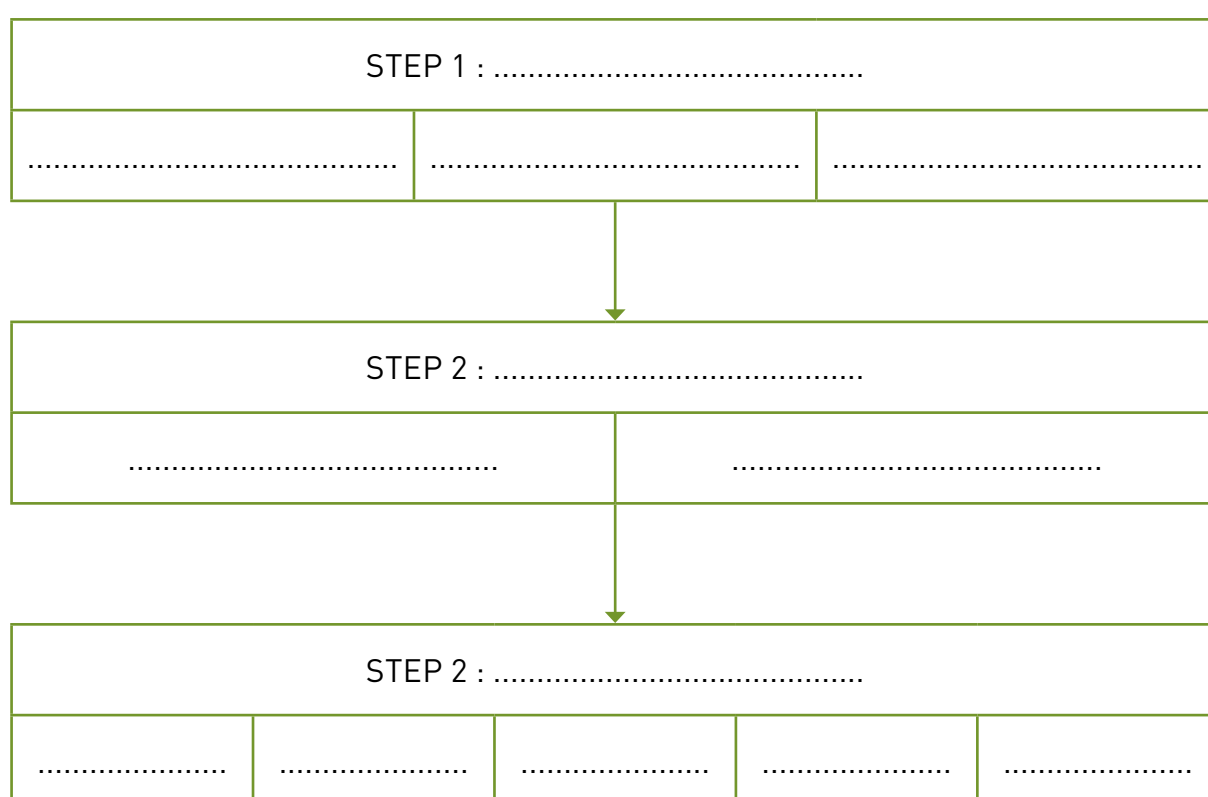
Instructions:

To help Dieudonné, propose an action plan for implementing the solutions, starting with those considered to be priorities. Work with a diagram (like the example) to indicate the strategy for implementing the interventions.



Action plan diagram (example diagram to use)

Indicate in the diagram the N steps to follow (general description of the objective) and the N actions to be carried out in each stage (based on the solutions considered to be priorities). In this example diagram, four steps are used:



Create your own diagram and propose a full action plan. Then review the proposed solutions and compare them with your diagram.

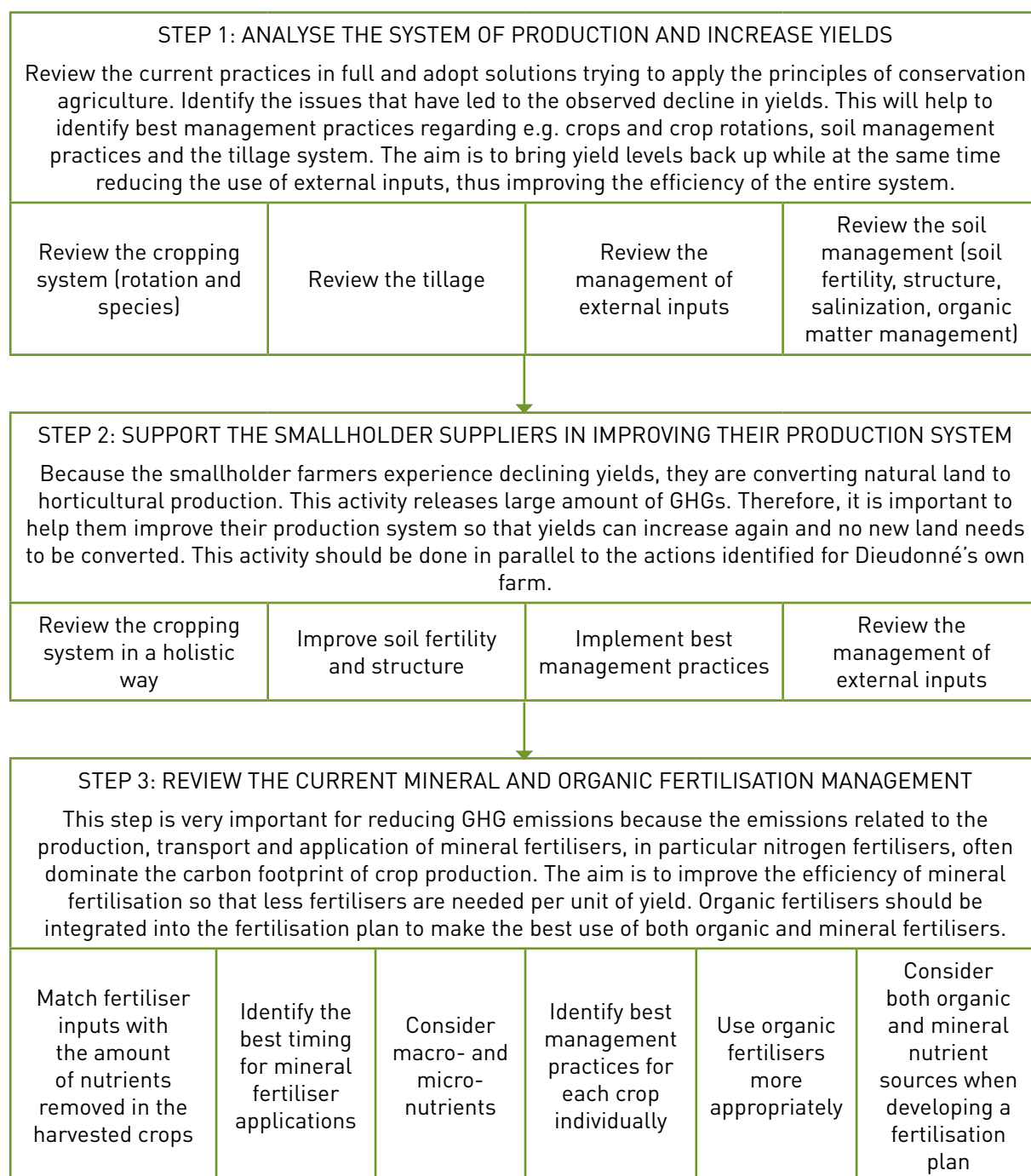
5.2. Preparation of an action plan: proposed result

Have you completed your part of the exercise? Well done! Now compare your results with the proposed solution, identify the differences, and try to see why your results differ from this proposal. But perhaps you have thought of a new and/or a better proposal? Write your analysis of the results, and your personal perception, in a few lines: this will help you to retrace the reasoning behind your strategy at the end of the exercise.

Proposed solution: proposing solutions

The action plan should be created taking into account the priorities identified; however, focusing on one element to achieve an effect can address another problem at the same time. Therefore, if we focus on the priorities of the proposed solution:

- Priority 1: S1 – S2 – S4 – S8 – S9 (scores of 13 to 15)
- Priority 2: S5 – S6 (scores of 12)
- Priority 3: S3 – S7 – S10 – S11 – S13 – S14 (scores of 10 to 11)
- Priority 4: S12 (score of 9)



STEP 4: REVIEW ENERGY USES RELATED TO FIELD OPERATIONS AND IRRIGATION MANAGEMENT

This will improve the efficiency of energy uses and so reduce the emission of GHGs and other air pollutants by reducing the total amount of energy consumed. Identify all processes that use energy and improve the efficiency of these processes. Start with the irrigation system because of its large energy consumption.

Increase the efficiency of the irrigation system

Improve the water holding capacity of the soil so less irrigation is needed

Use renewable energy where possible

Better match irrigation events with plant needs to save water and energy

STEP 5: INCREASE SOIL CARBON STOCKS AND PLANT TREES AND HEDGEROWS

Improving soil organic matter contents is not only good for soil fertility, reducing soil erosion and improving the water holding capacity of the soil but also contributes to climate change mitigation by locking up carbon from the atmosphere. Trees and hedgerows also lock up carbon and can provide shade, habitats for pollinators and even additional products.

Improve the management of the soil to increase soil carbon stocks

Add well decomposed organic matter

Establish cover crops and consider no or minimal tillage

Re-establish trees and hedgerows

STEP 6: IMPROVE THE MANAGEMENT OF THE TRANSPORT, PROCESSING AND PACKAGING OF FRESH PRODUCE

Improved logistics will reduce energy consumption for the road transport of fresh fruit and vegetables, leading to reduced emissions of GHGs and other air pollutants.

Optimise route planning

Train drivers in fuel efficient driving techniques

Properly maintain vehicles

Increase the energy efficiency of the packing and sorting station

STEP 7: REDUCE THE AMOUNT OF PRODUCE LOST DUE TO SPOILING

Improved post-harvest management reduces the amount of fresh produce lost due to spoiling and increases the share of high quality produce. Reducing post-harvest losses reduces GHG emissions because the lost produce represents a waste of resources and of the emissions during its production.

Plan logistics to reduce transit times

Use improved packaging materials

Avoid rough handling

Cold store easily perishable produce

STEP 8: STOP USING PEAT TO CORRECT THE SOIL pH AND REDUCE THE USE OF PESTICIDES

The use of peat releases large amounts of carbon. It also has negative impacts on important natural habitats where the peat is extracted. Other options for improving the soil pH exist and should be used instead. Integrated pest management helps reduce the amount of pesticides used to protect air, soil and water bodies.

Identify appropriate alternatives to correct the soil pH	Apply well decomposed organic matter to improve the soil structure and improve the pH	Adopt integrated pest management practices and reduce the use of pesticides
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Adopt integrated pest management practices and reduce the use of pesticides

My supplementary analysis (free space):

[illegible]



Frequently used abbreviations and acronyms

FREQUENTLY USED ABBREVIATIONS AND ACRONYMS

AASQA	Associations Agréées de Surveillance de la Qualité de l'Air
EEA	European Environmental Agency
CVA	Cerebrovascular accident
UNECE	United Nations Economic Commission for Europe
ABL	Atmospheric Boundary Layer
CNES	National Centre for Space Studies
VOC	Volatile Organic Compound
EC	European Commission
EPA	Environmental Protection Agency
FPD	Flame Photometric Detector
GHG	Greenhouse Gas
Gt	Gigatonnes
IASI	Infrared Atmospheric Sounding Interferometer
IPPC	Integrated Pollution Prevention and Control
KH	Henry's constant
BAT	Best Available Techniques
NPD	Nitrogen Phosphorus Detector
WHO	World Health Organisation
UN	United Nations
P	Vapour pressure
PM_x	Particulate Matter < x µm
PM_{2.5}	Particulate Matter < 2.5 µm
PM₁₀	Particulate Matter < 10 µm POP: Persistent Organic Pollutant
ppb	parts per billion
ppt	parts per trillion
GWP	Global Warming Potential
S	Solubility
TSP	Total Suspended Particulates
UV	Ultraviolet
ELV	Emission Limit Value
UV	IOELV Indicative Occupational Exposure Limit Values



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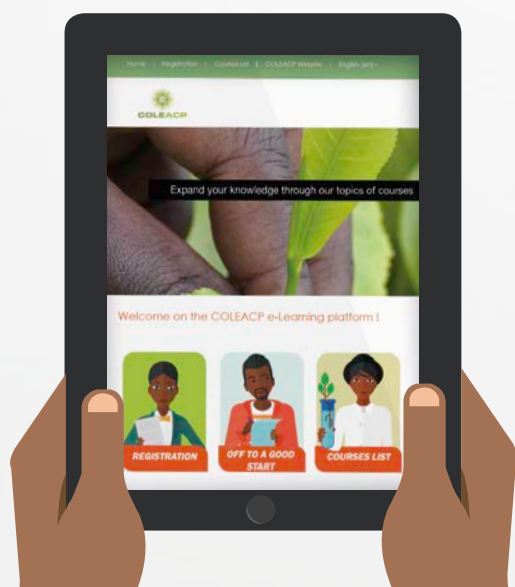
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