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ORIGINAL PAPER

Atmospheric pollution in North Africa (ecosystems–atmosphere interactions): a case study in the mining basin of El Guettar–M'Dilla (southwestern Tunisia)

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Abstract Air quality transcends all scales with in the atmosphere from the local to the global with handovers and feedbacks at each scale interaction. Air quality has manifold effects on health, ecosystems, heritage and climate. New insights into the characterisation of both natural and anthropogenic emissions are reviewed looking at both natural (e.g. dust and lightning) as well as plant emissions. In the phosphate mining area (El Guettar–M'Dilla basin: Southwestern Tunisia), several diseases have been known as cancer, respiratory, allergies, cardiovascular, dental fluorosis, stress, etc. These diseases are directly related with the installation of the industrial sector of the CPG (from 1896) and the deforestation and the ecosystem degradation (fauna and flora).

Keywords Air quality · Anthropogenic emissions · Diseases · El Guettar–M'Dilla basin · Tunisia

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Introduction

The composition of the earth's atmosphere is unique in the solar system in being largely determined by biological processes in soils, vegetation and the oceans interacting with physical and chemical processes within the atmosphere. The physical surface–atmosphere exchange of most gases contributing major and trace constituents of the atmosphere is coupled to biological production processes and transferred through the surface–atmosphere interface. Thus, developing a mechanistic understanding of the production and destruction processes and their interactions with exchange processes is a core activity in understanding the Earth system.

"Clean air is considered to be a basic requirement of human health and well-being. However, air pollution continues to pose a significant threat to health worldwide" (WHO 2005). Air pollution can be defined as "when gases or aerosol particles emitted anthropogenically, build up in concentrations sufficiently high to cause direct or indirect damage to plants, animals, other life forms, ecosystems, structures, or works of art" (Jacobson 2002). Air pollution is not a modern issue and examples are available from antiquity and the middle ages (Stern 1968; Jacobson 2002). The state of air pollution is often expressed as air quality. This atmospheric pollution is a measure of the concentrations of gaseous pollutants and size or number of particulate matter. As previously stated, air pollution has implications for a number of contemporary issues including (these results are the findings of field):

- Human health (e.g. respiratory, cancer risk, allergy, cardiovascular illness, headache fatigue, kidney disease, stress, etc.) (Andronache et al. 2006) (Fig. 1)
- Ecosystems (e.g. crop yields, loss of biodiversity fauna and flora, etc.)

- Regional climate (aerosol and ozone exhibit a strong regionality in climate forcing, etc.)
- Change in diet.

Although air quality is a measure of the anthropogenic perturbation of the "natural" atmospheric state, it has to be considered in the wider context of the interactions with biogenic and other natural emissions that may have feedbacks with atmospheric composition and climate. The World Health Organization estimates that 2.4 million people die each year from causes directly attributable to air pollution, with 1.5 million of these deaths attributable to indoor air pollution (WHO 2002).

The physical exchange of most gases is coupled to several processes and transferred through the surface–atmosphere interface. Thus, developing processes and their interactions is a core activity in understanding the Earth system. The subject of this paper is much narrower than

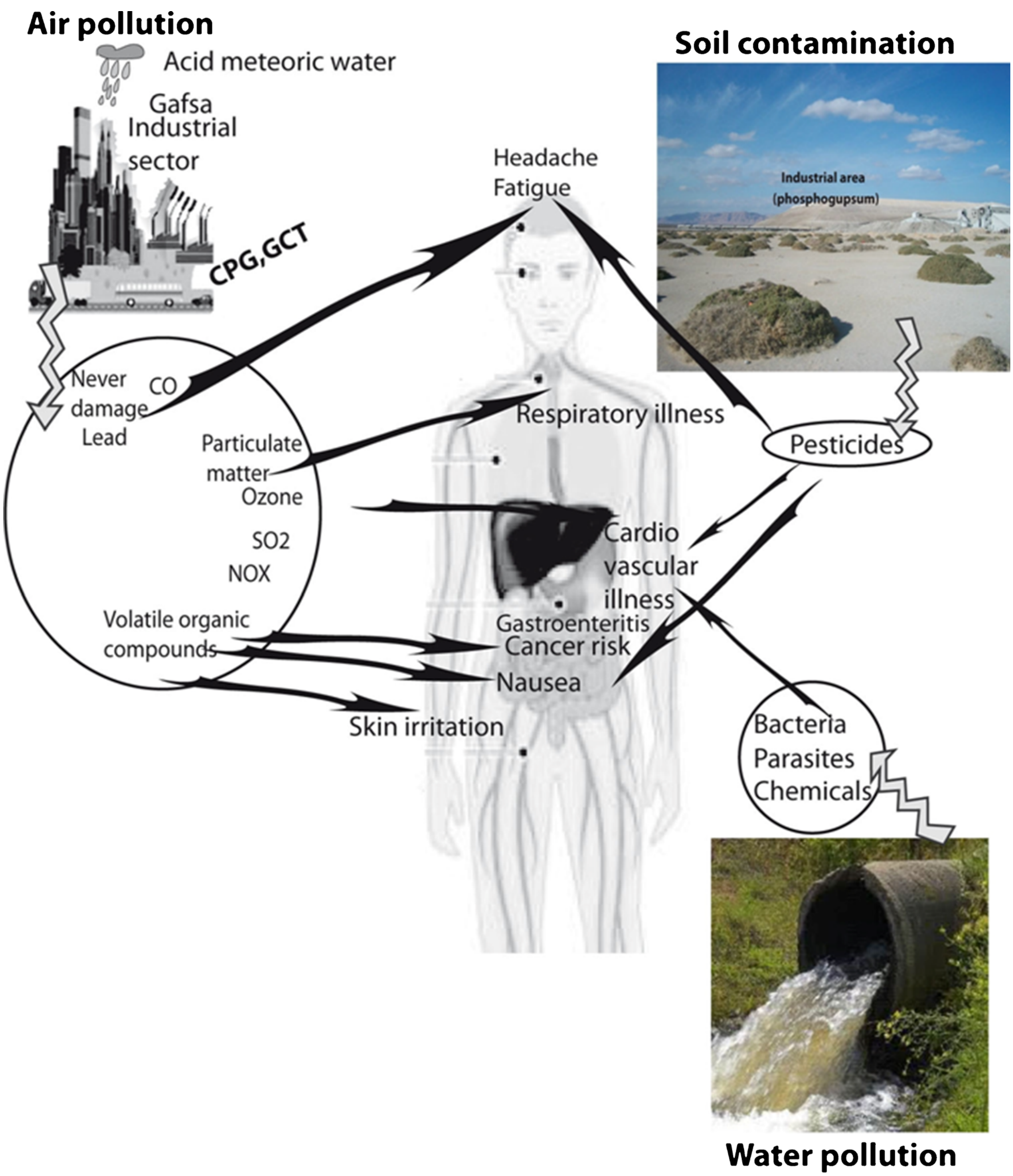

Fig. 1 Schematic conceptual model showing the various diseases in the human body of El Guettar-M'Dilla basin (southwestern Tunisia) (Andronache et al. 2006, modified)

the scope of these opening lines and is restricted to the trace gases and aerosols exchanged between the atmosphere and the earth's surface. However, as is clear from much of the international assessment of changes in atmospheric composition since the industrial revolution, these trace atmospheric constituents are changing the earth's climate (IPCC 2007), global biodiversity (Millenium Ecosystem Assessment 2005) and the biogeochemical cycling of major nutrients including nitrogen, carbon and sulphur. The earth's surface is a sink for some atmospheric trace gases and aerosols, and a source for many others, and for most, the surface–atmosphere interface represents a zone within which most of the overall control of fluxes occurs. An understanding of the rate controlling processes at this interface is therefore vital in describing the exchange process and understanding the global biogeochemical cycles. Applications of science in this field are necessary to quantify and model responses to human perturbation of many of the biogeochemical cycles (C, N, S, halogens and metals). These perturbations include changes in land use or emissions of trace gases to the atmosphere, through combustion and industrial activities.

The gases emitted from industrial area of the El Guettar–M'Dilla basin has been the typical example in the North Africa. Since Tunisia is considered as the most phosphate productive country in the world. The Gafsa south mining district in southwestern Tunisia is one of the most important producers of phosphate in the world. The exploitation of this district started at the beginning of the twentieth century a few years after the first discovery of this valuable resource in 1885 by the French amateur geologist, Philippe Thomas (1893). Since 1896, date of the foundation of the French phosphate company, the first excavation took place with a total production of 200,000 metric tons/a (CPG-GCT 2009). Currently, the merchant rock output rises to more that 8 million metric tons/a, placing Tunisia fifth in the word for phosphate production (CPG-GCT 2009). This production is ensured by the Tunisian phosphate company, "CPG", which operates seven open-pit quarries and one underground mine scattering within about 1,250 km^2 area around the mining basin of Gafsa "M'Dilla, Metlaoui, Moulares and Redeyef cities" (Boujlel et al. 2008). In order to meet the international standards of quality, the Tunisian phosphate undergoes several refining and enrichment procedures, such as mechanical separation (grinding, sieving, etc.), washing and floatation, which increase the P_2O_5 concentration in phosphate rocks from 12 to 29.5 % (Naeili et al. 2008). It is within this framework that the present study is undertaken, which aims to provide baseline information about (1) identification the sources of the atmospheric pollution and (2) explain the effect of this pollution to the ecosystem and the human health in the study area.

Study area

The study area, which covers a total surface of (≈1,000 km^2), is located in southwestern Tunisia, between the longitudes 6° 30′–7°00′ E and the latitudes 34°00′–34°30′ N. It is characterised by a semi-arid type climate with a mean annual precipitation of 170 mm, mean annual temperature of 21 °C and potential evapo-transpiration of 1,700 mm$year^{-1}$ (Hamed 2011). The drainage network is not very dense. It is composed of the El Kebir, Bayeïch, El Maleh, Majni, Lortess, As Sad, and Berda, non-perennial wadis that collect surface runoff from the surrounding hills of Gafsa, the North Chott ranges and the Algerian territories. The surface water of these wadis is carried to the large continental depression of Chott El Gharsa (El Guettar basin) and to the endorheic depression of Chott Djerid in the southern part of the study area (Mokadem et al. 2012a; Fig. 2).

Result and discussion

Anthropogenic aerosol emissions

Trace gases are produced by physical, biological and chemical processes of CPG sector on land and in the ecosystem. The natural cycles include emissions of a large variety of chemical species, which have been perturbed over the past decades by human activities, such as agriculture and deforestation. These gases emissions from this industrial activities, transportation and landfills have also led to the emissions of large quantities of pollutants into the atmosphere. This section summarises recent advances and highlights the main uncertainties remaining in the characterisation of surface emissions. This pollution has resulted in the reduction of stomata number (reduction photosynthesis and respiration activities) and thus reducing the contact surface of air-plant-human body. In our study, we identified several phone damage than deforestation (yellowing of leaves and sometimes their dead) (Fig. 3a–c), the appearance of nodules in the trunks of trees (Fig. 3d) and the appearance of a white layer in the soil due to the accumulation of the industrial dust, which gave a white cover for flora and fauna (Fig. 3a) (Mokadem 2012; Mokadem et al. 2012b). The chemical and physical complexity of terrestrial surfaces, illustrated in the Fig. 4 at the microscopic scale is greatly simplified in the parameterisations used in models. The simplification is necessary in part due to the nature of the flux measuring systems, which integrate the net fluxes over large areas of these surfaces and fail to reveal the microscopic scale of variability of the true exchange.

In our study, dead zones of the leaves have been identified either in the periphery or inside. After the bibliography, these two cases were due to an excess of SO_2 and NO_3. This trend may be regarded as representative for the regions in

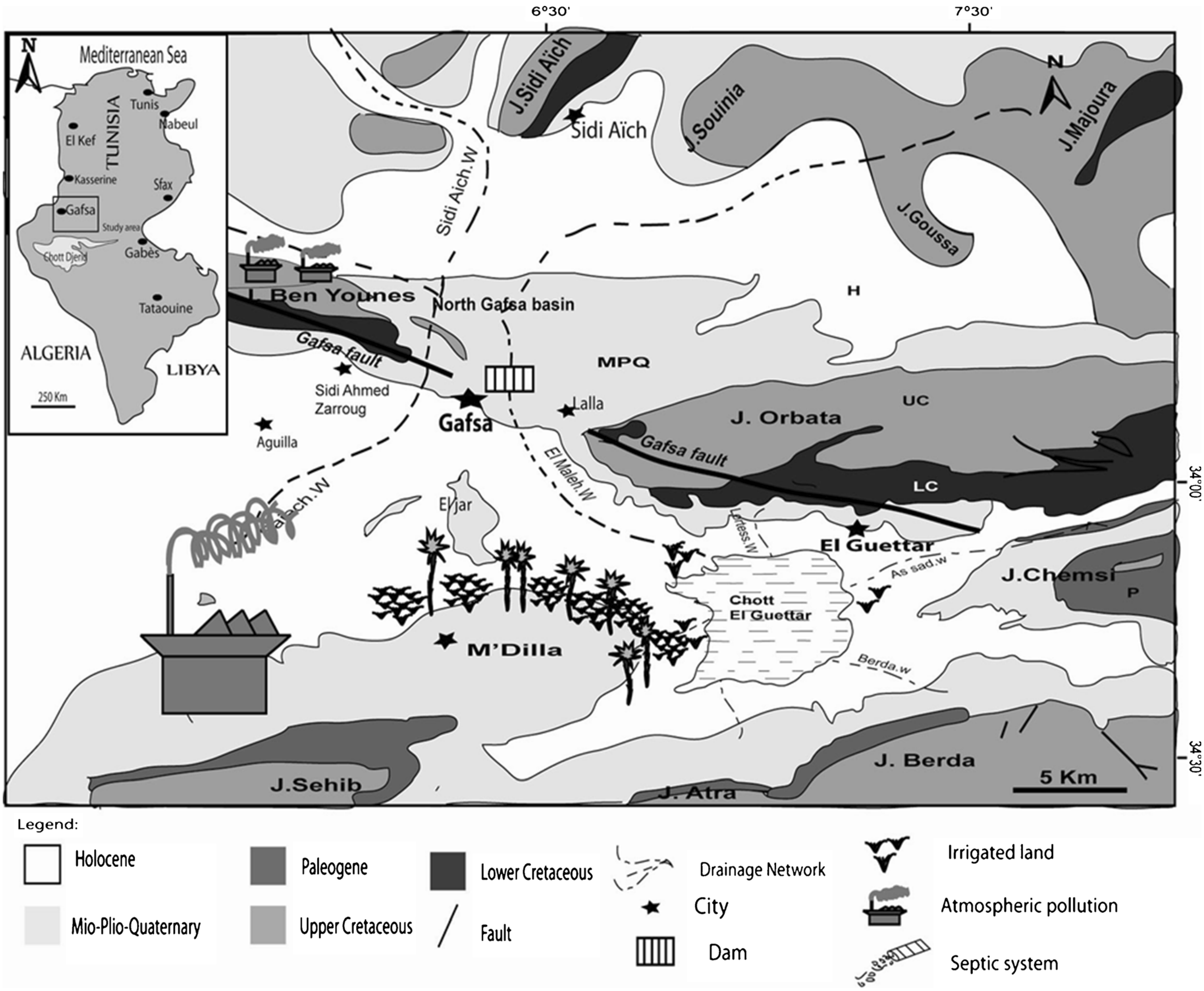

Fig. 2 Simplified geological map of El Guettar-M'Dilla basin and the localisation of industrial area (southwestern Tunisia)

which ambient SO_2 and NO_2 concentrations have increased from 1 year to another in this mining area. The deforestation in the study area is probably reflecting the growing concern over increasing sulphur and nitrogen emissions and deposition to ecosystems (Figs. 5 and 6). Sulphur dioxide dry deposition to vegetated surfaces is largely controlled by non-stomatal processes, but in many arid ecosystems and deserts of the world where vegetation is sparse, the nature and pH of soils determine the sink strength. Soil surface emissions of NO are the result of several industrial, biological and abiotic processes in the soil producing and consuming NO. Production and consumption of NO occurs predominantly via the biological nitrification and denitrification processes. Nitrification is the oxidation of soil NH_4^+ to NO_3^-, and denitrification is the anaerobic reduction of soil NO_3^- to N_2O and N_2. In nitrification, NO is formed as a by-product during the oxidation of NH_4^+ to NO_2^- and possibly also as a result of nitrifier reduction of NO_2^- leading to an NO production of 1–4 % of the NH_4^+ being oxidised (Skiba et al. 1997). The NO produced may be transformed within the soil profile by oxidation to NO_3^- or it may be released to the atmosphere following diffusion to the soil surface. In denitrification, NO occurs as an intermediate in the cascade of reductive processes, and in the soil profile, NO reduction may contribute to the formation of N_2O. Abiotic production of NO occurs from oxidation of nitrous acid (HONO) that has been produced by protonation of biologically formed NO_2^- (Venterea et al. 2005). This phenomenon is also observed in much of central and eastern England and the industrial regions of Germany, France, The Netherlands and Belgium (Tang et al. 2009).

Urban air pollution impairs human health, and plumes of large (mega) cities may influence air quality and climate on regional to global scales (Skiba et al. 1997). For these

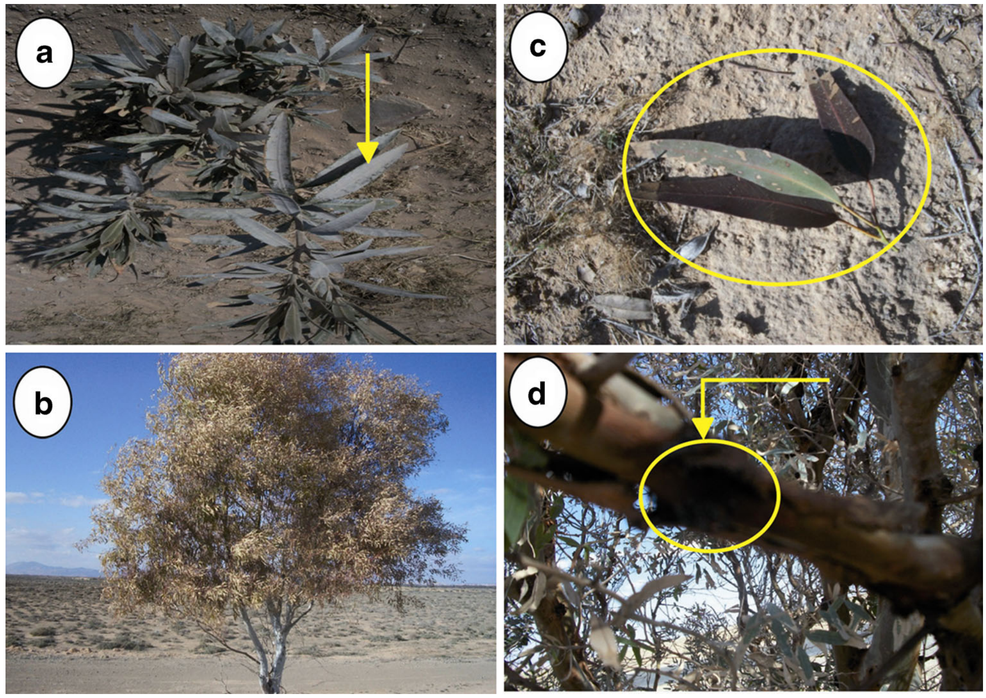

Fig. 3 Industrial effect. **a** Formation of a white layer covering the leaves. **b**, **c** Yellowing of leaves and sometimes their dead. **d** The appearance of nodules in the trunks of trees

reasons, radical chemistry in urban environments has received growing attention in the last years. The atmospheric chemistry in large cities is significantly different from rural and remote environments due to large emissions of NO_x, CO, volatile organic compounds (VOCs) and oxygenated VOCs. As a result, high levels of precursors and reactants of

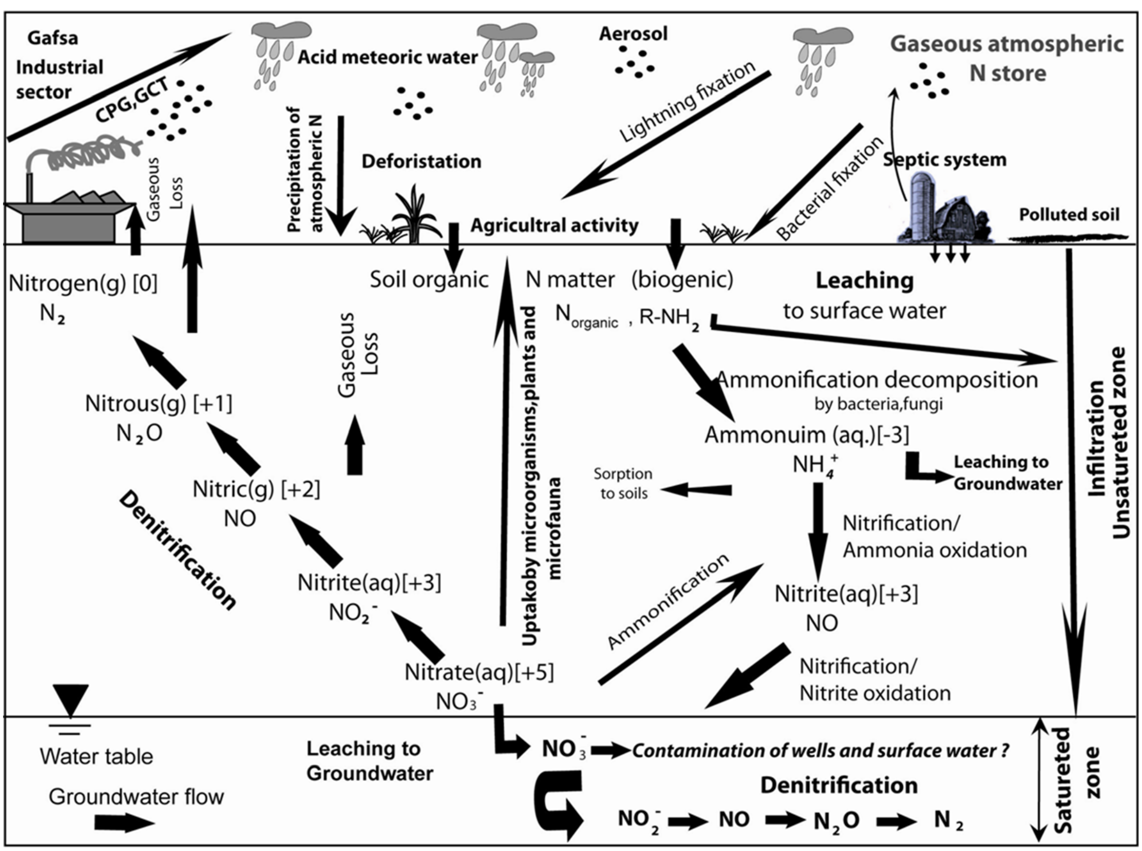

Fig. 4 The chemical and physical complexity of anthropic effect in groundwater in the study area

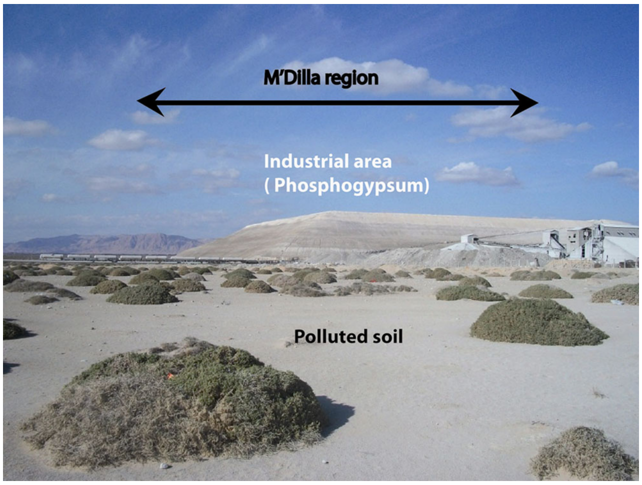

Fig. 5 Sulfur dioxide deposition to soils in the M'Dilla area

radicals are present with correspondingly large chemical turnover rates (Jagiella and Zabel 2007; Orlando and Tyndall 2001; Dillon and Crowley 2008; Hasson et al. 2004; Jenkin et al. 2007) the reactions:

$$CH_3C(O)O_2 + HO_2 - - \rightarrow CH_3C(O)OOH + O_2 \quad (1)$$

$$CH_3C(O)O_2 + HO_2 - - \rightarrow CH_3C(O)OH + O_3 \quad (2)$$

$$CH_3C(O)O_2 + HO_2 - - \rightarrow CH_3 + CO_2 + OH + O_2 \quad (3)$$

$$HO_2 + NO - - \rightarrow OH + NO_2 \quad (4)$$

$$RO_2 + NO_2 - - \rightarrow RO + NO_3 \quad (5)$$

Position of the human health in the study area

In the phosphate mining area, several diseases have been known as cancer, respiratory, allergy, cardio-vascular, dental fluorosis (Fig. 7), stress, etc. Due to the poverty of the population in this mining area, there is another serious damage due to alcoholism, smoking, and other family problems. After many studies in the mining area, this is the first to study cancer mortality mainly for children and workers of the CPG in Southern Tunisia (Hamed et al. 2010).

Relation of atmospheric pollution–groundwater in the study area

The study of Hamed (2009) in the mining basin of Moulares shows that there is a close relationship between the two parameters. Air pollution causes a degradation of air and therefore a degradation of function input (rainfall = acid rain) (Fig. 4) and a subsequent degradation of deep waters that are only for direct consummation or indirect consummation in the food or in the respiration. This study also shows the effect of discharges of laundry phosphates that are discharged in a haphazard way into the water system (drainage network) of the mining basin. The various types of relationships have been summarised in Fig. 4.

Better understanding of the processes that link the chemical and biological properties of aerosols with cloud formation and droplet growth has indicated a need for better knowledge of the organic components. Although transport or organic C, and deposition to the earth's surface, has not been regarded as quantitatively important for ecosystem health, organic N has the potential to add to the known effects of inorganic N wet deposited from the atmosphere especially in remote areas. Studies of precipitation chemistry have highlighted our lack of knowledge of the organic nitrogen constituents (both gaseous and particulate) in the atmosphere. Recent reviews (Neff et al. 2002; Cornell et al. 2003) have indicated that the contribution of water-soluble organic nitrogen (WSON) in precipitation to wet deposition may be up to one third of the total, yet little is known about the chemical composition, form or sources of this material. Initial skepticism about the nature of WSON has to some extent been dispelled (Cape et al. 2001), but the broad range of possible composition and emission

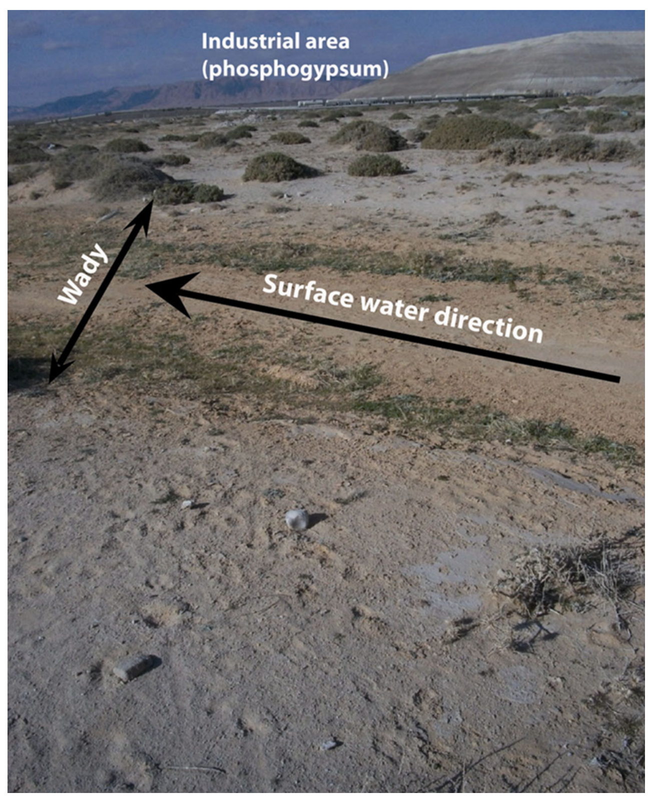

Fig. 6 The industrial impact in the soil in the M'Dilla area

Fig. 7 Dental fluorosis in M'Dilla basin

sources means that the transfer pathways are still somewhat uncertain. It is known, for example, that biological processes interconvert inorganic and organic nitrogen in forest canopies (Fang et al. 2008), but it is not clear how much biological activity may occur in the atmosphere or on the surfaces of sampling equipment. The presence of both gaseous and particulate WSON in the atmosphere implies that dry deposition is an important but unquantified pathway for transfer of organic nitrogen to the earth's surface.

Ozone and the local interaction

Ozone is a gaseous, phytotoxic secondary air pollutant with widespread effects on human health, vegetation and materials. It is also a greenhouse gas, third behind CO_2 and CH_4 in importance. Its deleterious effects on plants pose a large-scale risk to crop production and forest vitality in many regions of the Northern Hemisphere (Fowler et al. 1999; Cape 2008), which have been widely studied in Europe and North America (e.g. Hayes et al. 2007; Karnosky et al. 2007); there is also evidence of ozone impacts in Asia, North Africa and Latin America (e.g. Ashmore 2005). Ozone deposition to external surfaces of vegetation is important as a removal pathway for ground level ozone but is of little consequence for plant effects. The primary potential for injury to vegetation requires stomatal uptake of ozone molecules (Fig. 8) followed by reaction with the internal plant tissue generating highly reactive oxidants that interfere with physiological processes (e.g. Matyssek et al. 2008). As ozone is a strong oxidant, it can also react with leaf cuticles and other external plant surfaces or with volatile compounds emitted by vegetation, and non-stomatal ozone deposition is a substantial fraction of the total flux. In addition to vegetation, ozone molecules may be deposited at any surface providing a chemical sink or acting as a surface for heterogeneous decomposition (Cape et al. 2009). Quantifying the stomatal uptake rates is central to understanding the ozone-induced risk to vegetation, but the non-stomatal deposition needs to be quantified to correctly partition the total deposition flux.

In recent years, flux measurement techniques have been extended to the urban environment to quantify emission fluxes of trace gases such as CO_2, N_2O, SO_2, CO and VOCs. But after the Tunisian revolution of the January 14, 2011, there is a radical upheaval to the extent that there was a reduction of these gases. Thanks God for this great revolution that has affected all domains without exception, hoping that we would go into the international standard for the release of greenhouse gases. In my opinion and like that

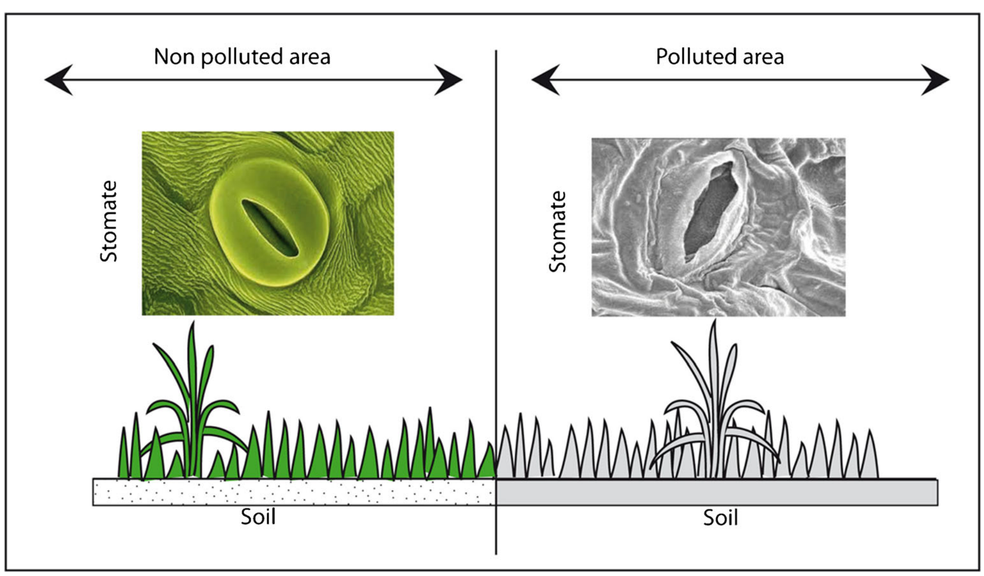

Fig. 8 Impact of industrialisation on vegetation in the study area

most of the scientists, the global effect of climate change results from local and regional effects.

Conclusion

Agriculture is a major source of emissions to the atmosphere, which, relative to the industry, have been regulated substantially less (Aneja et al. 2008). Until now, the policy requirements for food security from agriculture have moderated the willingness to limit emissions of trace gases from this sector. More and more, however, it is recognised that the production should be within the limits of sustainability, limiting pollutant emissions to surface or groundwater and to the atmosphere of reactive nitrogen compounds, greenhouse gases, persistent organic pollutants, phosphorus and odour. Agriculture is a collection of diffuse sources with many uncertainties in the emissions. Greenhouse gas emissions and ammonia are uncertain because the emissions depend on farm management practices, soil type, fertilizer use, type of crop or animal breeding, size and location of the farm, etc. This makes quantification of the sources and successful targeted measures and policies for control very difficult.

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