GAS EXCHANGE IN SOILS

See Aeration of Soils and Plants

GASES SINK

See Greenhouse Gases Sink in Soils

GEOLOGIC EROSION

A process that changes soil into sediment. It relates to movement and resistance of soil to the forces of water and wind that lead to detachment and transportation of soil particles, sedimentary rocks and various land formations.

GEOSTATISTICS

Applies the theories of stochastic processes and statistical inference to geographic phenomena. Geostatistics is a branch of statistics focusing on spatial or spatiotemporal datasets. Developed originally to predict probability distributions of ore grades for mining operations, it is currently applied in diverse disciplines including petroleum geology, hydrogeology, hydrology, meteorology, oceanography, geochemistry, metallurgy, geography, forestry, environmental control, landscape ecology, soil science, and agriculture (esp. in precision farming).

GIBBS FREE ENERGY

The thermodynamic potential for a system whose independent variables are the absolute temperature, applied pressure, mass variables, and other independent, extensive variables. The change in Gibbs free energy, as a system passes reversibly from one state to another at constant temperature and pressure, is a measure of the work available in that change of state.

Bibliography


GRAIN PHYSICS

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Synonyms
Grains; Kernel; Seeds

Definitions
Kernel. Kernel is the cereal fruit (botanically called caryopsis). It consists of three components: bran, germ,
and endosperm. The fruit can play role as a grain or a seed depending on its utilization.

**Grain.** This term includes cereals, pulses, and oilseeds. Grain, according to its economical utilization, is divided into food grain crops, feed (fodder) crops, and industrial crops. Grains are also divided on three groups depending on type of main component: cereal fruits (polysaccharides), legumes (proteins), and oil plants (lipids). **Seed.** Seed is a reproductive material of the cultivated plants. It is applied to obtain a new plant generation on a generative way.

### Introduction

Crops cultivation started ages ago at the time when *Homo sapiens*, who lived in tropical and subtropical forests, changed gathering the gifts of nature (leaves, fruits, and roots) for primitive hoeing. Archeologists found fossils from the first cultivated plants dated back to Early Neolithic Period (10,000–12,000 years ago). A hypothesis that people had started plowing in the Upper Paleolithic Period (40,000–50,000 years ago) was proven by the recent archeological studies (Gordeev and Butkovsky, 2005).

Wide range of cultivated grain species including cereals, pulses (grain legumes), and oil plants (oilseeds) are exploited all over the world. Among different types of cultivated plants cereals are basic part of the human diet from ages. The word “daily bread,” the most common product obtained from grain, has become synonymous with food. Grain and grain products are vital for human activities since the proverb says: “Bread is beyond everything.” One of the grain products is a whole grain which is usually called “kernel.” If the kernel has been cracked, crushed, or flaked, then in order to be called whole grain, it must retain nearly the same relative proportions of bran, germ, and endosperm as the original grain.

Wrigley et al. (2004) describe a lot of cultivated plant species, especially cereals and pseudocereals. The cereal group consists of a few species such as wheat, rye, triticale, barley, oats, and corn, whereas buckwheat, millet, rice, and sorghum are included to pseudocereals. This division is connected with the fact that pseudocereal kernels are gluminous. It means that the buckwheat grain is covered with flower glumes, while wheat grain is covered with flower glumes. Another group of cultivated plants are legumes that consist of ten crop species depending on specification. In Europe large-seeded annual plants (pea, soy, broad beans, lentil, pea-vine, haricot, chick-pea, spring vetch, feed lupine, etc.) are grown. Soy is referred both to leguminous. It is applied to obtain a new plant generation on a generative way.

### Physical properties of grain

Physical properties of grain are considered as features that are measured by instrumental methods. The properties are applying for estimation of grain quality depending on its destination. Using methods cannot change structure of the grain, thus they must be nondestructive. Grain physical properties depend on size and structure of a studied object or amount of matter in it. Grain is regarded as an anisotropic center since some of its physical properties are linked with the direction of observation.

Grain is also considered to be viscoelastic material as many other biological materials. This kind of materials has interesting properties that exhibit viscous behavior as the gradual deformation of molasses and latex. For example, wheat with 9.3% moisture showed high elastic behavior compared with wheat tempered at 22.5% moisture that showed a plastic behavior (Ponce-Garcia et al., 2008) as well as elasticity (like a rubber band or monocrystal that stretches instantaneously and quickly returns to its original state once a load is removed). Various materials exhibit viscoelasticity with the deformation depending on load, time, temperature, and humidity.

Since there is a necessity for continuous estimation of grain quality, the physical properties are divided into the following groups:

- **Mechanical:** Young’s modulus, ductility, moment of inertia, weight, specific gravity, hardness, density, mass, porosity, viscosity, volume, moisture, etc.
- **Thermal:** thermal transfer, heat conductivity, etc.
- **Acoustic:** velocity, emission, damping, etc.
- **Optical:** reflectance, refraction, luminance, refractive index, chromaticity, absorption, color, etc.
- **Electrical:** electric potential, capacitance, resistance, conductance, impedance, permeability of storage grain, etc.
- **Magnetic:** magnetic permeability, inductance

The grain has undergone handling and processing by using various means such as mechanical, thermal, electrical, spectral, and sonic techniques. For this reason, some information about basic physical properties of grain will be presented. Knowledge of these properties should construct the base of essential engineering data for designing of machines, determining of its efficiency control of processes or operation during food or feed production. Such basic information should have a sufficient meaning not only to engineers but also to other scientists who may exploit these properties and find new applications for final grain products.

To better understand some terms a few examples are given below. Grain mechanical damage that has not resulted from damage during development of the crop may be due to problems encountered at harvest, transport, subsequent storage, and processing. Grain mechanical damage is considered as a state of interruption of tissue continuity. It can be caused by external static, impact loading, or internal strain during intensive drying of wet grain or intensive wetting of dry ones. Mechanical damage of grain, which occurs in harvesting, threshing, and handling, can seriously affect viability and germination power of seeds, growth vigor, insect and fungi attack, and utility value of the final product. Decrease of viability is due to mechanical damage of the seed embryo,
especially during harvesting of cereals in the wetted region of cultivation, for example, in Scandinavian Countries.

Grain damage can be also caused by insect and/or fungus activity. Therefore, it is important to be familiar with normal, healthy cereal grains before trying to recognize physical defects of damaged ones. Causes of physical defects are not always obvious. Many of them result from pest infestation or disease infection that appeared earlier in the growing season.

All physical properties of grains/seeds originating from cultivated plants depend mainly on their humidity and temperature, which are very important. In fact, each biological material and the majority of its properties depend on temperature and water content inside the object and in its surrounding. Having acquaintance with the above-mentioned features provides insights into the physical structure of the cereal at both macroscopic and microscopic levels. Mechanical damage occurs wherever grain is subjected to the destructive action of internal or external forces, commonly in the form of impact, causing internal or surface cracks. One of the most often used properties of grain is hardness. Hardness of grain has been a subject of interest to millers, livestock feeders, breeders, and other agricultural scientists. According to literature (Mohsenin, 1978) biting and cutting the grain has provided a qualitative evaluation of grain hardness. A number of attempts have been made to find an objective and a qualitative method of the individual kernel hardness determination. One of these methods can be the SKCS apparatus (Single Kernel Characterization System, type 4100) made by Perten Instruments in Illinois (USA).

Mechanical properties such as strength, impact, and shear resistance are crucial for agricultural engineering to become acquainted with seed resistance to cracking during harvesting and handling conditions. The internal cracks in grain are caused very often by external forces (as impact), acting on grains during harvesting or handling processes. The second main reason of internal cracks originating are internal forces arising inside kernel as consequence of the fast changes of field conditions, temperature, and humidity of climate mainly, not the grains. The internal cracks are studied using soft X-ray and/or colorimetric techniques. X-ray investigations are carried out mainly in the Institute of Agrophysics of Polish Academy of Science (PAS) in Lublin, Poland, in Agrophysical Research Institute of Russian Academy of Agricultural Sciences (RAAS), St Petersburg, Russia, and in Czech University of Life Science (CULS) in Prague, Czech Republic. X-ray detection makes it possible to analyze position of cracks and also to quantify them inside the kernel. This method allows evaluating the physical state of the grain endosperm (Grundas et al., 1999). Studies, carried out in the above-mentioned institutes, have shown that moisture content influences on grain resistance to cracking. Natural processes like rain or dew cause sudden increase of grain moisture and it is a main reason of cracks formation in the endosperm.

Results of research carried out by using X-ray methods showed also a significant difference in grain endosperm cracks between common wheat varieties. Natural wetting of dry grain (below 14% of moisture content) during rainfall, when wheat is standing in the field, is one of the reasons of cracking. Intensive drying of wet grain (above 15% of moisture content) in field or industry or in laboratory conditions is also the reason of cracking. In drier climate, premature ripening may occur due to stress connected with drought. In these conditions, grains are unlikely to reach full potential. The susceptibility of grain to mechanical damage is determined by genetic factors (e.g., grain hardness), environmental effects (climatic condition during pre-harvest period), and by the condition of grain storage (especially excessive humidity). The combination of these properties determines the utility value of grain material. The big effect of kernel humidity on its behavior is shown in next two literature examples: Al-Mahasneh and Rababah (2007) and Mohoric et al. (2009). Furthermore, mechanical properties of grain also change under biological factors, for example, insect pest infestation (Nawrocka et al., 2010) and fungi.

Shape, size, volume, surface area, density, porosity, color, and appearance are some of the physical characteristics of grain that are important in some problems connected with design of specific machines for harvesting and processing of raw materials or analysis of grain behavior during handling. What shape should be assumed for single grain in bulk material and which dimension should be employed in calculations are basic questions that have to be answered before selection of healthy grain or seeds from undesirable materials by preferred pneumatic or electrostatic devices. Knowledge about shape and size is also important for stress distribution in bulk material under load. Contact area is also vital for effective and safety transport of bulk material.

Knowledge of density and specific gravity of grains or seeds is needed, for example, in calculation of thermal diffusivity, in heat transfer, and in pneumatic and hydraulic handling. The irregular shape and porous nature of grains make problems in volume and density measurements.

Figure 1 shows the examples of grain impact. From a mechanical point of view, mechanism and the conditions of the running impact on grain play a big role in its damage (Stronge, 2000). The velocity of impact is not too high and the collision objects are rigid or viscoelastic bodies and very often is running noncollinear configuration of acting bodies. After rebound the kernel starts its rotation. An incidence of kernel is not on the center of the force transducer. This fact and the inclination of longitudinal axis of kernel are main reasons of a kernel rotation about a perpendicular axis.

Figure 2 shows the principle of scintillation sensor work, which is used for direct making of digital roentgenograms (Del Guera, 2004). The figure explains simultaneously a reason of “fuzzy contours” of roentgenogram. This phenomenon is caused by the difference in dimensions of image ($D_{image}$) and object ($D_{object}$), which depend
A strong influence on “fuzzy contours” and X-ray image resolution has thickness and properties of the sensor scintillation layer. This type of sensor is widely used in practice and its properties depend mainly on properties of the sensor scintillation layer. This type of sensor is used in the laboratory of CULS, Prague. An image of this kind of sensor and a roentgenogram made by it are depicted on Figure 3.

Near-infrared hyperspectral imaging (NIR HSI) is another method used to determine the physical properties of grain. It integrates conventional imaging and spectroscopy to attain both spatial and spectral information from an object. Hyperspectral images (hypercubes) are three-dimensional blocks of data, comprising two spatial and one wavelength dimension. It allows for the visualization of biochemical constituents of a sample, separated into particular areas of the image, since regions of a sample with similar spectral properties have similar chemical composition. It is currently unfeasible to obtain information in all three dimensions of a hypercube simultaneously (Gowen et al., 2007).

The NIR technique can be applied to determine moisture, protein, lipid and starch content, wet and dry gluten, and alveograph parameters of whole wheat in the laboratory (Miralbes, 2003) as well as on the field during harvesting (Maertens et al., 2004). It also allows for detection of single wheat kernels containing insects (Maghirang et al., 2003) and classification of healthy and fungal-damaged soybean seeds (Wang et al., 2003).

TD-NMR technology (time-domain nuclear magnetic resonance) is widely used for various process and quality control, and R&D applications. Moisture and protein content of bulk cereal grain samples can be measured very quickly by a TD-NMR benchtop instrument at the harvest point. The same technique can be used to implement rapid quality control of incoming cereal grains at the food processing plant. TD-NMR can contribute significantly on the geometrical arrangement of X-ray apparatus.
toward quality improvement and can be a powerful tool for rapid analysis (Ghosh and Tombokan, 2009).

Conclusions
Physical measures to prevent some of the main causes for rejected grain samples are suggested. The physical condition of grain, which travels from field crop to commodity, is described. The simple method, used in the past to measure these quantities, have improved over time and nowadays that measure methods provide more information about studied objects. These methods are often noninvasive. Development of field measurement was caused mainly by a progress in information technologies and by the use of new physical principles. Nowadays more sophisticated and very sensitive methods for measuring individual properties of grain and seed are used. Very often optical properties of studied materials are preferred for their better characterization. These methods bring better knowledge about a material behavior on a cell level, and obtained results allow better utilization of studied materials.

Bibliography


Cross-references
Agrophysical Objects (Soils, Plants, Agricultural Products, and Foods)
Cereals. Evaluation of Utility Values
Grains, Aerodynamic and Geometric Features
Image Analysis in Agrophysics
Microstructure of Plant Tissue
Physical Properties as Indicators of Food Quality
Proton Nuclear Magnetic Resonance (NMR) Relaxometry in Soil Science
X-ray Method to Evaluate Grain Quality

GRAINS, AERODYNAMIC AND GEOMETRIC FEATURES

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Definition
Grains include cereals, pulses, and oilseeds. They are often referred to seeds that are reproductive materials of the cultivated plants (see Grain Physics). Aerodynamics is a field of dynamics that deals with the problems of gas flow and forces produced by the phenomena.

Introduction
The forces affect a solid during its movement in gaseous environment. The magnitude of the force is affected by the parameters of the solid (length l [m], air density $\rho$ [kg m$^{-3}$], coefficient of internal friction $\mu$ [kg m$^{-1}$ s$^{-1}$]) as well as air stream velocity $v$ [m s$^{-1}$]). Combination of above-mentioned components yields the Reynolds number
Re = (v · l) = (μ/ρ)[−] which is very important in the theoretical aerodynamic calculations.

In practice, air acts as a carrier both during transport, classification, as well as cleaning. The most usual is a system, where particles (grains) are transferred in a moving stream of air. Grain parameters like weight, size, and shape as well as moisture have an essential influence on its aerodynamic characteristics like critical velocity \( v_k \), coefficient of aerodynamic resistance \( k_s \), and coefficient of fineness \( k_0 \).

**Survey of literature**

Agricultural engineering has forced the investigation on the aerodynamic properties of the vegetables. Letoshnev (1949) considered in detail the problem of the aerodynamic properties in his textbook on the construction of agricultural machines. He referred there to Bezruczkin (1936), who as early as in the 1930s, reported the numerical values of the properties for the basic seeds. In his very important for agricultural physicists textbook, Mohsenin (1970) devoted a lot of attention to the problem of aerodynamics; he presented two methods of estimation of the aerodynamic properties of agricultural products: in a vertical air tunnel for terminal velocity determination in air and in vertical water tunnel for determining terminal velocity in water. He included also the results of investigations of the aerodynamic properties by Bilanski et al. (1962). The method of critical velocity estimation in the vertical air tunnel is commonly employed with various constructional modifications. Bogaczyński (1975) measured a dynamic pressure in a vertical air tunnel and estimated the coefficient of resistance and then the critical velocity for wheat, barley, and rye. Coates and Yazici (1998) described in detail a vertical wind tunnel used to determine the critical velocity and coefficient of resistance of cottonseeds. The aerodynamic properties of grain and straw materials were examined by Gorial and O’Callaghan (1990) and Zewdu (2007); weed seeds were investigated by Kahrs (1994). Jha and Kachru (1998) dealt with testing of the properties of makhana while Omobuwajo et al. (1999) examined African breadfruit seeds. In the following years the aerodynamic properties of pine nuts were studied by Faruk Ozguven and Kubilay Vursavus (2005), sunflower seeds were investigated by Gupta et al. (2007). A test stand and results of investigations on various coffee beans were presented in detail by Alfonso Junior et al. (2007).

**Methodology**

The method of estimation of a particle (grain) critical velocity \( v_k \) consists in a placement of the particle in a vertical air stream (Figure 1) and keeping it in an equilibrium state.

A glass pipe 2 equipped with a charging mechanism 3.4 for grain supply at its bottom part, a supporting sieve and air inlet is used for observation of the grain behavior. The air stream is generated by a fan 6, driven by an electric motor 7. The yield of the fan is controlled by the change of rotational speed of the motor (by autotransformer 8). Pitot tube 1, arranged in the upper part of the glass pipe 2, is connected with a compensating micromanometer 5, measuring dynamic pressure \( p_{\text{dyn}} \) in \( \text{Pa} \). When the tested grain is in an equilibrium state, dynamic pressure \( p_{\text{dyn}} \), described by Equation 1 can be measured:

\[
 p_{\text{dyn}} = \frac{v^2}{2 \cdot g} \quad \text{[Pa]},
\]

where

\( v \), air velocity \([\text{ms}^{-1}]\),

\( g \), specific gravity of air \([\text{Nm}^{-3}]\),

\( g \), acceleration gravity \([\text{ms}^{-2}]\).

After transformation of the equation, critical velocity \( v_k \) may be evaluated:

\[
 v_k = \sqrt{\frac{2 \cdot g \cdot p_{\text{dyn}}}{g}} \quad \text{[m s}^{-1}]\).
\]
In the equilibrium state, the weight of grain $G$ [N] located in the vertical air stream is compensated by the resistance force $R$[N], expressed by Newton equation:

$$R = k_s \cdot S \cdot \rho_{dyn} \ [N],$$  \hspace{1cm} (3)

where

- $k_s$ coefficient of aerodynamic resistance $[-]$,
- $S$ lifting surface $[\text{mm}^2]$.

From the equation, the coefficient of aerodynamic resistance $k_s$ can be assessed:

$$k_s = \frac{G}{S \cdot \rho_{dyn}}.$$  \hspace{1cm} (4)

The ability of a particle to resist against air stream is defined by the coefficient of fineness. It can be derived from the dependence between the resistance force, weight of particle, and its acceleration:

$$a = \frac{R}{m} = \frac{k_s \cdot S \cdot \rho_{dyn}}{m} = \frac{k_s \cdot S \cdot \rho}{2 \cdot m} \cdot v_k^2 \ [\text{m s}^{-2}],$$  \hspace{1cm} (5)

where

- $a$, acceleration $[\text{m s}^{-2}]$,
- $m$, mass of grain $[\text{mg}]$,
- $\rho$, air density $[\text{kg m}^{-3}]$.

The quantity $k_s \cdot S \cdot \rho/2 \cdot m$ is called a coefficient of fineness $k_0$:

$$k_0 = \frac{k_s \cdot S \cdot \rho}{2 \cdot m} \ [\text{m}^{-1}].$$  \hspace{1cm} (6)

A lifting surface, necessary for the calculations is determined with an optical device (Figure 2) consisting of light sources (1), set of lenses (2), set of flat mirrors (3), screen with scale (4) enabling magnification of perpendicular projection of a tested grain (5) by the factor of 29.7. When we have the outlines of three perpendicular projections, we can measure and estimate the length, width, and thickness of a grain.

The method of setting of grain and the exemplary contours of three orthogonal projections presents Figure 3.

The largest of the three perpendicular projections is assumed as the lifting surface. After planimetry of the obtained outline of measured surface, its size can be estimated with a high accuracy. Size and shape of the lifting surface depend on the species and variety of tested grain. Some examples of lifting surfaces of tested grains are shown in Figure 4.

**Aerodynamic characteristics**

Aerodynamic characteristics were developed for the basic grains including: rape, seeds of chosen leguminous plants, maize, buckwheat, amaranth, and grass seeds.
Lifting surface, weight, and length of a tested dry grain affect both critical velocity and coefficient of fineness. In all investigated cases high regularity has occurred. The critical velocity increased with growing weight, lifting surface and length of tested grain according to power or exponential relationship. On the other hand, the coefficient of aerodynamic resistance did not depend on any property of tested grain and therefore its average value was assumed as a characteristic property for a considered variety (Table 1).

Additionally, the investigation of horse bean and buckwheat was carried out for grain without seed cover due to technological requirements (Table 2).

In the case of maize, the grains for investigation were collected from three different zones of the cob. The first part of the cob (ca. one third of cob length from its rachis) called later A zone has the grains in the shape resembling a cone; the middle part, called B zone, has the grains in shape of disks with extended lifting surface; and the shape of grains from C zone (upper part of the cob) resembles spheres. The obtained results confirmed the influence of the shape of tested grains on their aerodynamic characteristics (Table 2).

To determine the effect of humidity on the aerodynamic characteristics, individual grains should be artificially moisturized. From dry grains with a defined humidity, one grain with a weight \( m \) is selected. When the weight \( m \) and humidity \( W \) of the grain are known, its dry matter \( m_s \) can be evaluated.

After immersing the grain in distilled water (for the time following from previously considered moisturizing dynamics), its weight rises to \( m_1 \) and humidity to \( W_1 \), which can be easily estimated from the following equations:

\[
W = \frac{m - m_s}{m} \cdot 100\%,
\]

\[
m_s = m \frac{100 - W}{100},
\]

\[
W_1 = \frac{m_1 - m_s}{m_1} \cdot 100\% \quad [\%]
\]

where:

\( W \), moisture of grain [%],
\( m \), mass of grain [mg],
\( m_1 \), mass of moisturizing grain [mg],
\( m_s \), dry substance [mg],
\( W_1 \), moisture of moisturizing grain [%].

After the first moisturizing, the lifting surface is evaluated and the grain is placed in the vertical air stream. When the grain is in an equilibrium state, the dynamic pressure is measured. The procedure is repeated several times for an individual grain.

After numerical elaboration of the experiment it has been stated that the humidity affects critical velocity in a

Grains, Aerodynamic and Geometric Features, Table 1 Basic geometry and aerodynamic properties of seeds (Szpryngiel and Kram, 1994; Kram and Szot, 1999; Kram et al., 2007a, b)

<table>
<thead>
<tr>
<th>Plant species</th>
<th>Mass, ( m ) [mg]</th>
<th>Length, ( l ) [mm]</th>
<th>Lifting surface, ( S ) [mm²]</th>
<th>Critical velocity, ( v_k ) [m/s]</th>
<th>Coefficient of fineness, ( k_s ) [m⁻¹]</th>
<th>Coefficient of aerodynamic resistance, ( k_a ) [-]</th>
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<tr>
<td>Westerwolds Ryegrass seeds without glume</td>
<td>1.35–6.35</td>
<td>4.24–7.74</td>
<td>3.85–10.88</td>
<td>3.22–10.88</td>
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<td>Meadow Fescue seeds without glume</td>
<td>1.0–3.85</td>
<td>4.88–9.76</td>
<td>3.31–7.75</td>
<td>2.68–5.34</td>
<td>1.366–0.344</td>
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<td>Smooth Brome-grass seeds without glume</td>
<td>1.55–6.35</td>
<td>3.54–7.58</td>
<td>2.64–7.65</td>
<td>2.83–5.29</td>
<td>1.225–0.351</td>
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<td>3.17–5.61</td>
<td>0.976–0.312</td>
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<td>Timothy Grass seeds without glume</td>
<td>0.20–1.05</td>
<td>1.10–2.00</td>
<td>0.50–1.34</td>
<td>4.44–6.17</td>
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<td>1.60–2.35</td>
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<td>3.60–5.73</td>
<td>6.35–14.67</td>
<td>5.66–9.64</td>
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<td>12.26–15.61</td>
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<td>9.0–12.1</td>
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Grains, Aerodynamic and Geometric Features, Table 2 Basic aerodynamic properties of grains

<table>
<thead>
<tr>
<th>Plant species</th>
<th>Mass, m [mg]</th>
<th>Lifting surface, S [mm²]</th>
<th>Critical velocity, vₜ [m s⁻¹]</th>
<th>Coefficient of fineness, k₀ [m⁻¹]</th>
<th>Coefficient of aerodynamic resistance, kₛ [⁻]</th>
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<td>Wheat Gama</td>
<td>31.9–67.8</td>
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<td>9.30–10.47</td>
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<td>9.48–10.94</td>
<td>0.109–0.082</td>
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<td>Wheat Jawa</td>
<td>21.8–61.7</td>
<td>12.00–23.94</td>
<td>8.44–10.12</td>
<td>0.138–0.096</td>
<td>0.416</td>
</tr>
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<td>Rye Motto</td>
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<td>9.77–29.57</td>
<td>8.19–9.90</td>
<td>0.146–0.100</td>
<td>0.431</td>
</tr>
<tr>
<td>Rye Dańkowskie Złote</td>
<td>26.3–54.9</td>
<td>12.79–22.20</td>
<td>8.78–10.32</td>
<td>0.127–0.092</td>
<td>0.405</td>
</tr>
<tr>
<td>Triticale Presto</td>
<td>23.5–62.0</td>
<td>13.29–24.94</td>
<td>7.22–9.85</td>
<td>0.188–0.101</td>
<td>0.464</td>
</tr>
<tr>
<td>Triticale Ugo</td>
<td>24.7–66.3</td>
<td>13.23–26.44</td>
<td>7.50–9.97</td>
<td>0.174–0.099</td>
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<td>barley Rastik</td>
<td>18.0–61.0</td>
<td>13.10–25.42</td>
<td>7.33–10.22</td>
<td>0.183–0.094</td>
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</tr>
<tr>
<td>barley Rataj</td>
<td>10.3–60.4</td>
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<td>4.94–9.20</td>
<td>0.402–0.116</td>
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<td>A</td>
<td>286</td>
<td>63.51</td>
<td>17.51</td>
<td>0.032</td>
<td>0.235</td>
</tr>
<tr>
<td>B</td>
<td>286</td>
<td>74.12</td>
<td>16.79</td>
<td>0.035</td>
<td>0.219</td>
</tr>
<tr>
<td>C</td>
<td>286</td>
<td>66.45</td>
<td>17.59</td>
<td>0.032</td>
<td>0.223</td>
</tr>
<tr>
<td>Maize BEKO210</td>
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<td></td>
<td></td>
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<tr>
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<td>18.01</td>
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Grains, Aerodynamic and Geometric Features, Table 3 Basic aerodynamic properties of moisturized grains

<table>
<thead>
<tr>
<th>Plant species</th>
<th>Mass, m [mg]</th>
<th>Moisture, W [%]</th>
<th>Lifting surface, S [mm²]</th>
<th>Critical velocity, vₜ [m s⁻¹]</th>
<th>Coefficient of fineness, k₀ [m⁻¹]</th>
<th>Coefficient of aerodynamic resistance, kₛ [⁻]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat Gama</td>
<td>30</td>
<td>8.6–34.3</td>
<td>13.25–20.06</td>
<td>9.30–10.47</td>
<td>0.113–0.099</td>
<td>0.460–0.340</td>
</tr>
<tr>
<td>Wheat Henika</td>
<td>30</td>
<td>9.3–32.7</td>
<td>13.69–19.50</td>
<td>9.82–10.99</td>
<td>0.102–0.081</td>
<td>0.377–0.306</td>
</tr>
<tr>
<td>Wheat Almari</td>
<td>30</td>
<td>9.3–31.6</td>
<td>20.14–27.66</td>
<td>9.75–11.10</td>
<td>0.103–0.080</td>
<td>0.448–0.367</td>
</tr>
<tr>
<td>Wheat Jawa</td>
<td>30</td>
<td>11.1–40.9</td>
<td>13.29–19.27</td>
<td>8.99–10.12</td>
<td>0.121–0.096</td>
<td>0.439–0.387</td>
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<tr>
<td>Rye Motto</td>
<td>30</td>
<td>12.5–32.8</td>
<td>12.34–17.78</td>
<td>8.49–9.33</td>
<td>0.136–0.113</td>
<td>0.465–0.389</td>
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<tr>
<td>Rye Dańkowskie Złote</td>
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<td>12.5–36.9</td>
<td>23.08–34.47</td>
<td>8.91–10.21</td>
<td>0.124–0.094</td>
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<td>Triticale Presto</td>
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<td>11.2–42.4</td>
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<td>11.2–44.9</td>
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<td>Maize KB270</td>
<td>286</td>
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<td>66.45–85.17</td>
<td>17.60–19.77</td>
<td>0.032–0.025</td>
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<td>Maize BEKO210</td>
<td>282</td>
<td>8.5–41.8</td>
<td>53.20–75.40</td>
<td>18.28–19.59</td>
<td>0.030–0.026</td>
<td>0.254–0.245</td>
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<tr>
<td>Lupine Bar</td>
<td>97</td>
<td>7.3–65.2</td>
<td>21.24–53.72</td>
<td>11.58–14.92</td>
<td>0.073–0.044</td>
<td>0.390–0.293</td>
</tr>
<tr>
<td>Lupine Radames</td>
<td>146</td>
<td>9.5–57.4</td>
<td>35.36–81.08</td>
<td>11.45–14.25</td>
<td>0.075–0.048</td>
<td>0.444–0.321</td>
</tr>
<tr>
<td>Soya bean Polan</td>
<td>122</td>
<td>9.9–63.3</td>
<td>32.32–78.52</td>
<td>11.95–13.52</td>
<td>0.069–0.054</td>
<td>0.412–0.329</td>
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<tr>
<td>Horse bean Tom</td>
<td>400</td>
<td>12.6–60.9</td>
<td>66.84–145.40</td>
<td>13.08–15.88</td>
<td>0.057–0.039</td>
<td>0.684–0.401</td>
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<tr>
<td>Horse bean Tom</td>
<td>620</td>
<td>12.6–55.3</td>
<td>93.04–173.96</td>
<td>13.33–16.07</td>
<td>0.055–0.038</td>
<td>0.569–0.406</td>
</tr>
</tbody>
</table>

high degree (Table 3). Generally, with an increase in grain humidity, its weight and lifting surface as well as critical velocity increase. Consequently, with the increase in critical velocity, both the coefficient of fineness and coefficient of aerodynamic resistance decrease (in case of moisturized grain, its coefficient of aerodynamic resistance also depends on humidity). There is however one exception. It is the soya bean (Table 3). With an increase in the grain humidity the critical velocity decreases and in consequence the other coefficients rise. It follows probably from the fact...
that a dry soya bean is almost a regular sphere which changes its shape after moisturizing into the shape of a flat bean with an extended lifting surface. However, all considered aerodynamic characteristics versus humidity can be described by the simple power or exponential equations.

Summary

The investigations on aerodynamic properties are very time consuming and laborious, thus they require numerous repetitions. For the estimation of the coefficient of aerodynamic resistance the value of lifting surface is necessary. The last can be assessed in several ways. The measurements of critical velocity are carried out in various measuring stands but since the main idea consisting in keeping the grain in a vertical air stream is maintained, their results are comparable. The values of critical velocity for various seeds, obtained over several years by different authors are collected in Table 4.

Bibliography


Bezruczkin, I. P., 1936. Farm Machine, No. 3.


Cross-references

Agrophysical Properties and Processes

Grain Physics

Grains, Aerodynamic and Geometric Features, Table 4 The values of critical velocity for various plant species

<table>
<thead>
<tr>
<th>Plant species</th>
<th>Critical velocity, ( v_c ) [m/s]</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat</td>
<td>8.90–11.50</td>
<td>Bezruczkin (1936)</td>
</tr>
<tr>
<td>Rye</td>
<td>8.36–9.89</td>
<td>Bezruczkin (1936)</td>
</tr>
<tr>
<td>Oats</td>
<td>8.08–9.11</td>
<td>Bezruczkin (1936)</td>
</tr>
<tr>
<td>Barley</td>
<td>8.41–10.77</td>
<td>Bezruczkin (1936)</td>
</tr>
<tr>
<td>Flax</td>
<td>8.69–10.85</td>
<td>Bezruczkin (1936)</td>
</tr>
<tr>
<td>Alfalfa</td>
<td>5.46</td>
<td>Bilanski et al. (1962)*</td>
</tr>
<tr>
<td>Soybeans</td>
<td>13.50</td>
<td>Bilanski et al. (1962)*</td>
</tr>
<tr>
<td>Millet</td>
<td>9.83–11.80</td>
<td>Bezruczkin (1936)</td>
</tr>
<tr>
<td>Flax</td>
<td>4.66</td>
<td>Bilanski et al. (1962)*</td>
</tr>
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<td>Soybeans</td>
<td>13.50</td>
<td>Bilanski et al. (1962)*</td>
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<tr>
<td>Jojoba seed</td>
<td>13.90</td>
<td>Coates and Yazici (1990)</td>
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<td>African breadfruit</td>
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<tr>
<td>Seeds</td>
<td>8.02</td>
<td>Omobuwojo et al. (1999)</td>
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<tr>
<td>Hull</td>
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<td>Hull</td>
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<tr>
<td>Pine nuts</td>
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</tr>
<tr>
<td>Nut</td>
<td>7.01–8.86</td>
<td>Faruk Ozguven and Kubiay Vursavus (2005)</td>
</tr>
<tr>
<td>Kernel</td>
<td>6.21–8.10</td>
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<tr>
<td>Hull</td>
<td>3.18–4.40</td>
<td></td>
</tr>
<tr>
<td>Sunflower seed</td>
<td>2.54–3.53</td>
<td>Gupta et al. (2007)</td>
</tr>
<tr>
<td>Conilon coffee cherries (moisture content 8.7–56.1%)</td>
<td>11.03–15.47</td>
<td>Alfonso Junior et al. (2007)</td>
</tr>
<tr>
<td>Conilon coffee beans (moisture content 10.5–41.5%)</td>
<td>9.00–11.44</td>
<td></td>
</tr>
</tbody>
</table>

*In the original textbook by the author, the critical velocity is presented in feet per second \((v[fps])\), to simplify the considerations it has been recalculated in meters per second \((v[m/s])\), assuming 1 ft = 0.3048 m.
GRASS FIBERS, PHYSICAL PROPERTIES

Majda Sfiligoj Smole, Silvo Hribernik
Department of Textile Materials and Design, University of Maribor, Maribor, Slovenia

Definition
Grass fibers are sclerenchyma elongated cells which occur in different parts of plants, mainly in the stems and leaves. They can be found in ground and vascular tissues for mechanical support, but sometimes they occur in dermal tissues as well (Langer et al., 1991; Pazourek et al., 1997). This type of cell is of particular importance for the production of bast textile fibers as flax, hemp, etc.

Origin
Grasses (Poaceae) form one of the largest plant families consisting of some 650–785 genera and about 10,000 species (Petersen, 1981; Holmes, 1989; Leslie et al., 1992; Moser et al., 1996). Members of this family occur abundantly in every climatic region and certain possibilities for their nontraditional application are evident, e.g., production of pulp and paper (e.g., Pahkala, 2001). Perennial Ryegrass (Lolium perenne), Italian Ryegrass (L. multiflorum), Hybrid Ryegrasses (L. perenne × multiflorum), Timothy (Phleum pratense), Fescues (Meadow fescue – Festuca pratensis, Tall Fescue – F. arundinacea) are some of the most important representatives in this group of grasses, while legumes are presented by white clover (Trifolium repens), red clover (Trifolium pratense), and lucerne (Medicago sativa).

Isolation: The biological and chemical procedures for leaves and stems retting (i.e., separation of the fibers from the rest of the plant), respectively can be used to obtain technical grass fibers in the form of fiber bundles. However, mechanical separation of the fiber bundles is additionally needed (Sfiligoj Smole et al., 2004). The fiber bundles are mainly inhomogeneous and sclerenchyma cells are often accompanied by tracheary elements. Fiber content in stems is higher when compared to that in leaves (e.g., fiber content in hybrid ryegrass stems is 39.5% and in leaves it is 7.9%).

Fibers morphology
Scanning electron microscope images of the longitudinal views of the fibers isolated from hybrid ryegrasses by alkaline procedure are given in Figures 1 and 2.

Properties
The length of the elementary cells in grasses and legumes is between 0.5 and 3 mm; slightly shorter fiber cells are present in leaves when compared to the cells from stems. The diameter of the isolated cells is approximately 10–18 μm. Due to the history of the grasses (deformation and damage caused by the treatment of grasses, maturity grade, and conditions during grass growth), the plant structures vary considerably in their properties. Nevertheless, the mechanical properties of fiber bundles of the grass leaves in the axial direction are lower in comparison to the mechanical properties of fiber bundles of the stems, although the differences are insignificant. The stress–strain behavior of fiber structures indicates a rigid character. Elongations of samples at break are rather low, but higher than in the case of whole stems or leaves. The elongations vary between 1.5% and 5.5% and tenacities from 7.5 to 21 cN tex⁻¹. The obtained values are comparable with the mechanical properties of some textile bast fibers, e.g., jute, hemp, or coir.

Bibliography
GRAVIMETRIC WATER CONTENT

The ratio of water mass to dry matter mass.

GRAVITATIONAL POTENTIAL

The gravitational potential at a point is equal to the work by the exterior force as a particle of unit mass is brought from infinity to its position in the gravitational field.

GRAVITY HEAD (GRAVITY POTENTIAL)

The amount of work required to raise a body a specified height in a gravity field. Gravity head is expressed as energy per weight and is equal to the distance $Z$, of a measurement point in the soil above an arbitrary reference height ($z$). Gravity potential is expressed as energy per volume and is equal to the product of the distance raised, $Z$, the water density, $\rho$ and the gravitation constant, $g (\rho gZ)$.

GRAZING-INDUCED CHANGES OF SOIL MECHANICAL AND HYDRAULIC PROPERTIES

Julia Krümmelbein
Soil Protection and Recultivation, Brandenburg University of Technology, Cottbus, Germany

Synonyms
The influence of grazing on soil physical properties

Definition
Grazing. The activity of wild or domestic herbivores (e.g., deer, sheep, cattle) walking around and feeding on plants (mainly grasses and herbs).

Introduction
Soils that are grazed by animals undergo mechanical stresses, partly normal forces (load) and partly shearing forces (slip). The amount of loads and shearing forces depends on the kind of grazing animals and is sometimes comparable to agricultural machinery (Greenwood and McKenzie, 2001). Grazing and treading animals affect the (top) soil due to mechanical damage of the sod and the uppermost soil layers and due to soil deformation (Greenwood and McKenzie, 2001; Krümmelbein et al., 2006). Trampling by grazing animals results in the deformation and compaction of particularly the top soil (Zhang and Horn, 1996; Villamil et al., 2001; Greenwood and McKenzie, 2001; Martinez and Zinck, 2004; Krümmelbein et al., 2006; Tian et al., 2007). Grazing also influences the amount and composition of soil organic matter by the export of biomass and its return as excrements. This in turn influences biological activity and thus natural regeneration of soil structure by root activity (Angers and Caron, 1998; Greenwood and McKenzie, 2001).

Compressive and shearing soil deformation by grazing animals

The intensity and amount of deformation depends on the soil water content and the amount of pressure exerted on the soil; it becomes more distinct and more visible the higher the water content, and the stress exerted on the soil is, in comparison to the internal soil strength (Horn and Rostek, 2000; Arvidsson et al., 2003). The trampling effect of grazing animals is depending on their weight, hoof size, and kinetic energy. The pressure exerted on the soil becomes higher when the grazing animal is moving. While an animal is moving, only three or two and in extreme situations (e.g., while escaping) only one hoof touches the ground, meaning that the whole body mass is transferred by a reduced hoof area. Scholefield et al. (1985) measured that the pressure of a walking cow is twice as high as the pressure of a standing cow. Shearing forces due to grazing have widely been ignored although they are transmitted on the soil surface by all moving and scrabbling animals. We have to consider that such dynamic shearing movements modify soil structure and thus decrease soil stability (Peth, 2004; Krümmelbein et al., 2006). With increasing soil water content this effect becomes more pronounced, shearing occurs more frequently and it particularly occurs in the upper soil layer. Grazing leads to increasing values of precompression stress. This indicates a grazing-induced compaction of the soil, along with increasing soil strength against compressive forces and an increasing bulk density (Peth, 2004; Krümmelbein et al., 2006). Cyclic loading experiments have shown that with increasing grazing intensity the soil becomes less sensitive to repeated loading (Krümmelbein, 2007). The soil structure deterioration due to grazing is not only pointed out by increasing strength against compressive forces but also by decreasing
angles of internal friction with increasing grazing intensity (Krümmelbein et al., 2006; Krümmelbein, 2007). The angle of internal friction is one component of shear strength and a measure for the structural development of a soil; the greater the angle of internal friction, the further advanced is the structural formation of the soil (Silva et al., 2004).

**Effects of soil deformation**

**Pore system**

Soil compaction is characterized by a volume decrease, particularly of the coarse pore volume, accompanied by an increase of the fraction of smaller pores. The structural change due to grazing is also reflected by decreasing values of vertically oriented saturated hydraulic conductivity with increasing grazing intensity and particularly by the anisotropy of the saturated hydraulic conductivity (Krümmelbein et al., 2006). The total pore volume decreases, the pore size distribution shifts showing a decrease of coarse pores and an increase of medium and fine pores (Greenwood and McKenzie, 2001; Peth, 2004; Krümmelbein, 2007). Due to grazing, there is not only a modification in the total pore volume and the pore size distribution, but also a decrease in the pore continuity. The decrease of pore volume and pore continuity and the changed pore size distribution affect soil functions, e.g., air and water conductivity, which are decreased in deformed soils (Vogeler et al., 2006; Krümmelbein et al., 2006), water retention (Kutílek et al., 2006; Krümmelbein, 2007), and soil biological processes (Whalley et al., 1995).

**Infiltration and saturated hydraulic conductivity and its anisotropy**

Even more sensitive to compaction than the pore volume is the pore continuity (Ball and Robertson, 1994). Pore continuity in turn determines saturated hydraulic conductivity and air permeability. In general, the saturated hydraulic conductivity is not only decreased due to a grazing-induced formation of a platy structure, but also becomes higher in the horizontal compared to the vertical direction and results in anisotropic flow conditions (Dömer Fernández, 2005; Krümmelbein et al., 2006).

The alterations in flow direction and pore continuity by grazing also reduce the water infiltration into the soil because of the loss of macropores open to the surface. Removal of vegetation also decreases the number of root channels that are important for water infiltration into the soil (Pietola et al., 2005; Kennedy and Schillinger, 2006).

**Water repellency**

Infiltration can also be decreased by changes in water repellency. Soils of higher grazing intensities mostly show decreased water repellency at comparable soil water contents because less soil organic matter accumulates which enhances the potential water repellency (Krümmelbein, 2007). Because of the high amounts of living and dead biomass on ungrazed sites, the soil water content of those sites mostly is higher than on grazed sites (Zhao et al., 2007). In turn, water repellency increases with decreasing water contents, accordingly the actual water repellency is often higher on grazed than on ungrazed sites (Zhao et al., 2007). The higher the water repellency, the lower is the amount of water infiltrating into the soil (Lamparter et al., 2006). Water repellency also affects capillary rise negatively (Bachmann et al., 2001). The combination of effects of soil compaction, shearing, water repellency, etc. leads to higher runoff rates on grazed compared to ungrazed sites (Greenwood and McKenzie, 2001).

**Interrelation between mechanical and hydraulic properties**

The mechanical and hydraulic changes described above are interlinked with each other. They commonly have negative effects for the productivity of grassland soils and their ecological functioning (Greenwood and McKenzie, 2001). Poor physical quality of soils due to soil compaction can, apart from the negative economical impact due to productivity losses, sometimes lead to drastic environmental consequences, such as flood disasters as, e.g., encountered lately in areas of Central Europe (Akkermann, 2004) and landslides in hilly or mountainous areas. Soil compaction deteriorates the pore system and induces increasing intra-aggregate bulk density and a reduced interaggregate macropore system, followed by an even more intense shear-induced deterioration of soil structure. Thus, as the final stage even a complete aggregate homogenization due to shear forces can occur on grazed soils, which results in lower infiltration rates, higher run off and greater probability for water erosion events (Pietola et al., 2005; Peth and Horn, 2006). Thus, structure degradation and sparse vegetation enhance not only water but also wind erosion (Hesse and Simpson, 2006; Zhao et al., 2007). In many semi-arid areas, compaction and structural degradation of the top soil resulting from intense grazing has led to widespread degradation processes (Krümmelbein et al., 2006; Krümmelbein, 2007), such as wind erosion resulting in heavy dust emissions (Li et al., 2003). It is well known that on intensely grazed grassland soils also water erosion is a common phenomenon during strong rainfall events, partly accompanied by severe gully development (Arnaez et al., 2007; Wei et al., 2007).

**Soil recovery from structure degradation**

Soils have a limited ability to structurally recover from former mechanical deterioration such as compaction (Drewry, 2006; Krümmelbein, 2007). In general it is known that due to wetting and drying cycles and, consequently, swelling and shrinkage, soil structure is able to recover from a compacted or even homogenized state by forming new aggregates. Because these aggregates are surrounded by the interaggregate pore space, wetting and drying may also be able to improve the aeration and water...
infiltration as well as the thermal properties of the soil in dependence of the number and intensity of these swell-shrink processes (Horn, 1994). Especially, soils with a clay content of more than 12% show intense swelling and shrinkage processes (Horn, 2002). Structure homogenizing processes, e.g., mechanical disturbance of the soil, lead to normal shrinkage accompanied by crack formation and separation of the soil into smaller parts (Janssen et al., 2006). Wetting and drying of homogenized soils create planes of weakness, along which the soil breaks into aggregates (Utomo and Drexler, 1982). A formerly disturbed soil can partly regain its strength over a period of time. When the original strength is regained, it is called thixotropy (Utomo and Drexler, 1982; Markgraf et al., 2006).

Wiermann and Horn (2000) showed that a less-derived Luvisol exhibited distinct signs of regeneration after a single compaction event, e.g., in terms of increasing macroporosity and gas permeability at 10 cm depth. North Ethiopian soils degraded by grazing show distinct signs of regeneration after 5 years (Mekuria et al., 2007). Biological activity of soil fauna and flora can further enhance structure formation and remediation due to various mechanisms (Horn and Drexler, 1989). Soil fauna influences structure due to its grubbing and digging actions in the soil, leaving loosened zones (channels) surrounded by compacted areas (channel walls) (Schrader et al., 2007). Bossuyt et al. (2006) and Pulleman et al. (2005) describe the important contribution of earthworms to microaggregate formation and incorporation and protection of organic matter in these aggregates. The saprophagous macrofauna can furthermore enhance microbial respiration and biomass and increase the water retention of the soil due to litter fragmentation and soil mixing, thus increasing organic matter accumulation and relocation (Frouz et al., 2007).

Plant roots can also influence the recovery of soil structure in various ways. They form continuous vertical pores and therefore disrupt and reaggregate homogenous soils into smaller units. This is due not only to the shearing and compressive forces roots exert on the soil, but also to the water uptake of the roots, followed by more intense and frequent wetting and drying cycles close to the roots, creating more negative pore water pressure, which induces crack formation and age hardening of existing soil aggregates as mentioned above. Roots furthermore increase the structural soil stability with fine roots and root hairs growing around soil aggregates; fungal hyphae can be associated to plant roots and further enhance the binding of soil aggregates as well as plant residues (Greenwood and McKenzie, 2001). Former studies revealed a positive correlation between root mass and porosity in pastures and an increased infiltration due to macropores created by living roots (Greenwood and McKenzie, 2001). Even when the roots are dead, the continuity of the old root channels and the cracks induced by shrinkage due to root water uptake persisted and kept the infiltration rate at a high level (Priebskat et al., 1994). Czarnes et al. (2005) showed that the exudates of plant roots and microbes in the rhizosphere together with intense wetting and drying cycles improve soil structure. Recently advanced x-ray microtomographies of soil aggregates allow to show the complexity of intra-aggregate pore systems (Schrader et al., 2007; Peth et al., 2008) and prove that soil microorganisms significantly contribute to the processes of aggregate formation by improving their habitat (Feeney et al., 2006), inducing crack formation in the soil (Preston et al., 2001) and by rearranging clay particles adjacent to them (Chenu, 1993, 2001). Micro organisms can also influence the amount and distribution of water repellency; carbon in turn influences soil wettability (Hallett et al., 2004) and mechanical stability (Horn, 1994; Chenu et al., 2000; Mataix-Solera and Doerr, 2003). Herrick and Lal (1995) pointed out the importance of excretal return to tropical pastures to keep soil organisms active and maintain good physical pasture properties. Recapitulating it can be stated that soil flora and fauna, including micro organisms and, accordingly, carbon content and composition and mechanical as well as hydraulic processes are closely interlinked with each other and with external factors such as climate and management.

Summary and conclusions
Grazing affects the physical conditions of soils. The effects which can be attributed to grazing are limited to the upper 10–15 cm below surface. Most of the changes are unfavorable in terms of productivity and ecosystem services of grassland ecosystems. Grazing induced changes of soil mechanical and hydraulic properties are strongly interrelated with each other and lead to an increased sensitivity to wind and water erosion. The susceptibility of soils to structural deterioration increases with increasing water content. Repeated mechanical loading combined with shearing forces as applied by grazing animals adversely affect soil structure along with diminishing angles of internal friction and a decrease of the total and coarse pore volume. This in turn affects the pore water pressure and the occurrence and orientation of water menisci, which in dry states are concave, thus stabilizing. If due to the compression of coarse pores the hydraulic conductivity of the soil becomes too low to remove excess soil water from the pore system during loading, soil compaction leads to less negative and sometimes even positive pore water pressure during loading, resulting in convex, thus mechanically destabilizing menisci according to the effective stress equation (Nuth and Lalou, 2008). With incomplete drainage of excess soil water, soil strength can be severely decreased. Soil mechanical changes are interconnected with changes in the pore system; accordingly, soil functions such as hydraulic conductivity and air conductivity are influenced by grazing. Water infiltration and saturated hydraulic conductivity, which are highly depending on the pore diameter and pore continuity, are also highly sensitive to deformations induced by mechanical stresses exerted by grazing animals.
Natural soil recovery due to wetting and drying cycles, soil fauna, root growth, and decay occurs but takes several years to decades. It is also not proofed that recovery will ever lead back to the state before being influenced by grazing.

Bibliography


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Cross-references

Anisotropy of Soil Physical Properties
Bulk Density of Soils and Impact on Their Hydraulic Properties
Compaction of Soil
Desertification: Indicators and Thresholds
Field Water Capacity
Hydraulic Properties of Unsaturated Soils
Hydrophobicity of Soil
Infiltration in Soils
Mechanical Resilience of Degraded Soils
Physical Degradation of Soils, Risks and Threats
Plant Roots and Soil Structure
Pre-Compression Stress
Pre-Compression Test
Shrinkage and Swelling Phenomena in Soils
Soil Compactibility and Compressibility
Soil Functions
Spatial Variability of Soil Physical Properties
Stress–Strain Relations
Subsoil Compaction
Wind Erosion

GREENHOUSE, CLIMATE CONTROL

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Synonyms
Optimization of greenhouse parameters

Definition

Climate control refers to the desired value of the greenhouse inside parameters as temperature, light, humidity, and CO2 concentration in order to provide optimal conditions for the plants.

With respect to the energy cost, the temperature in greenhouse should keep around a desired level. Lower accuracy requires higher set point in temperature, which results in more energy consumption (Tantau, 1997). The temperature can be increased by heating of the air and, at the same time, the use of thermal screens may decrease the energy consumption during nighttime periods.

The light control is mainly based on the requirement of the plant growing age.
The control of humidity provides to avoid the extremely high or low air humidity values. Concerning to energy saving avoiding the high humidity is more important. The control of humidity can be achieved by heating and/or by ventilation.

CO₂ concentration can be controlled by opening the top window in the greenhouse.

In order to assess appropriate control strategies, the productivity and quality of the plant should be provided duration of growing. The set-points are based on the practical experiments, but it is aimed to modify them according to the plant responses, which can be reached via leaf conductivity, CO₂ consumption, or nutrient uptake. The set-point for control variables has a strong influence on the energy consumption of greenhouses. The climate control computer has got a feeding control extension, which provides nutrients in solution to plants (van Henten, 1994).

**Bibliography**


**Cross-references**

Agrophysical Objects (Soils, Plants, Agricultural Products, and Foods)
Coupled Heat and Water Transfer in Soil
Drought Stress, Effect on Soil Mechanical Impedance and Root (Crop) Growth
Evapotranspiration
Greenhouse Gas Fluxes: Effects of Physical Conditions
Plant Drought Stress: Detection by Image Analysis
Plant Wellness

**GREENHOUSE EFFECT**

Inhibition of the atmospheric transmission of outgoing thermal radiation from the earth, due to the presence of certain gases in the atmosphere. The principal “greenhouse gas” is water vapor. Another important one is carbon dioxide, the concentration of which has been increasing due to forest clearing, cultivation of formerly virgin soils, and – especially – the burning of fossil fuels (coal, petroleum, natural gas).

**Bibliography**


**Cross-references**

Greenhouse Gas Fluxes: Effects of Physical Conditions
Greenhouse Gases Sink in Soils
Greenhouse, Climate Control

**GREENHOUSE GAS FLUXES: EFFECTS OF PHYSICAL CONDITIONS**

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**Definition**

**Physical conditions:** Soil moisture, soil temperature, air pressure, rainfall, snowfall, flooding, drainage, aeration, freezing, and thawing affecting plant roots, soil fauna, and soil microbial activities, producing and consuming greenhouse gases in soil.

**Greenhouse gases:** Including carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) produced and consumed in soil and absorbing and emitting radiation within the thermal infrared range in the atmosphere.

**Carbon dioxide (CO₂):** Colorless and odorless gas (mol weight 44.010 g mol⁻¹; density 1.977 g L⁻¹ at 1 atm and 0°C; solubility in water 0.47 g CO₂·C L⁻¹ at 1 atm and 20°C), consumed by plants during photosynthesis to make organic matter, and produced by respiration of animals, plants, and microorganisms to obtain energy through decomposition of organic matter.

**Methane (CH₄):** Colorless and odorless gas (mol weight 16.042 g mol⁻¹; density 0.717 g L⁻¹ at 1 atm and 0°C; solubility in water 0.018 g CH₄·C L⁻¹ at 1 atm and 20°C), oxidized by photochemical reaction in the atmosphere and consumed by methanotrophic bacteria in dry soil, and produced by methanogenic bacteria in wet soil.

**Nitrous oxide (N₂O):** Colorless and odorless gas (mol weight 44.013 g mol⁻¹; density 1.977 g L⁻¹ at 1 atm and 0°C; solubility in water 0.79 g N₂O·N L⁻¹ at 1 atm and 20°C), consumed by denitrifying bacteria and produced by nitrifying and denitrifying bacteria.

**Gas flux:** Amount of gas flowing through a unit area per unit time.

**Introduction**

An increase in the concentrations of greenhouse gases (GHG; carbon dioxide [CO₂], methane [CH₄] and nitrous oxide [N₂O]) in the troposphere causes global warming (Prather et al., 2001). The global atmospheric concentrations of CO₂, CH₄, and N₂O have increased from a pre-industrial value of about 280 ppm, 715 ppb, and 270 ppb, respectively, to 379 ppm, 1,774 ppb, and 319 ppb in 2005 (Forster et al., 2007). Increase of GHG emissions increases radiative forcing warming the earth. Contribution of CO₂, CH₄, and N₂O to total radiative forcing in 2005 is 63%, 18%, and 6%, respectively, and chlorofluorocarbons (CFCs) and others account for the rest of 13% (Forster et al., 2007). Global warming potential (GWP), which is the index in order to compare the relative radiative forcing of different GHGs and GWP in 100-year
time horizon is 1 for CO₂, 25 for CH₄, and 298 for N₂O (Forster et al., 2007). N₂O is a long-lived gas and contributes to stratospheric ozone destruction (Cicerone, 1987).

Soil is the major source of GHG emissions into the atmosphere. Land use change contributes 20% of total CO₂ emission into the atmosphere (7.9 Gt C year⁻¹ in the 1990s); rice paddy, and wetland soils contribute 34% of total CH₄ emission (515 Mt CH₄ year⁻¹); and agricultural soils contribute 24% of total N₂O emission (16.2 Mt N year⁻¹) (Prather et al., 2001).

CO₂, CH₄, and N₂O are produced and consumed in soil by mainly microbial activities, which changes the concentrations of these gases in soil. Soil microbial activities are influenced by soil environment factors, which are soil temperature; soil moisture; available carbon; nutrients; acidity; redox potential, which are affected by the factors of climate, topography, soil texture, soil structure, vegetation, and land use. Change in soil gas concentration varies concentration gradients between the soil and the atmosphere, regulating gas diffusion fluxes through the soil. Slower flux provides the opportunity for further microbial reaction in the soil. Also, the gas flux is influenced by the pressure gradient. Some of the gases dissolved in soil water leach into groundwater and secondarily emitted after drainage water is discharged to the ground surface. The rates of production and consumption of GHGs, diffusion, mass flow, and dissolved gas leaching in soil are the main factors controlling GHG exchange between the soil and the atmosphere. This paper provides the information about the effect of soil physical conditions on the controlling factors for soil CO₂, CH₄, and N₂O fluxes.

CO₂

CO₂ is produced in soil through heterotrophic respiration (organic matter decomposition by heterotrophic organisms) and plant root respiration. The emission of CO₂ is called soil respiration (Raich and Schelesinger, 1992). Increase of heterotrophic respiration in soil decreases soil organic carbon. Supplying oxygen molecule from the atmosphere into soil through aeration proceeds soil heterotrophic respiration. Tillage stimulates the heterotrophic respiration and reduces soil organic carbon (Jarecki and Lal, 2003). Increase of soil temperature increases soil microbial activity. There is a relationship between soil temperature (T) and CO₂ emission (F_c) from soil as follows:

\[ F_c = a \exp(b T) \]  

where \( a \) and \( b \) are fitted constants.

Figure 1 shows an example of the relationship between soil temperature at a depth of 5 cm and CO₂ fluxes measured by chamber method at the root-included plot and root-excluded plot in a Japanese grassland (Shimizu et al., 2009). The CO₂ fluxes were higher in spring (beginning of March to end of June) than in other seasons (beginning of July to end of February) at the same temperature due to the decomposition of litter supplied into soil during the winter, resulting in being divided into two groups at each plot. The relationship between the CO₂ flux and the soil temperature in each plot was well explained by Equation 1 for each season. There was a significant difference in the regression between the seasons (\( P < .001 \)) in root-included plot, while there was no significant difference between the season in the regressions for the root-excluded plot (Table 1).

The \( Q_{10} \) value is the rate of increase in CO₂ emission with 10°C of increase in soil temperature along with the exponential relationship between them. It was calculated by applying the fitted constant (b) obtained from Equation 1 to Equation 2.

\[ Q_{10} = \exp(10 \times b) \]  

The \( Q_{10} \) value of CO₂ fluxes of the Japanese grassland was higher in root-included plot (4.50) than in root-excluded plot (3.61) (Table 1). The \( Q_{10} \) values of CO₂ fluxes derived from plant root respiration and soil organic

Greenhouse Gas Fluxes: Effects of Physical Conditions, Figure 1 Relationship between CO₂ flux and soil temperature in root-included plot (a) and root-excluded plot (b) (From Shimizu et al., 2009). Data represent mean ± SD (\( n = 6 \)). The lines indicate the exponential regression models for each season (solid line, from the beginning of March to the end of June; dashed line, from the beginning of July to the end of February), and the models are described in Table 1.
matter decomposition in mixed-hardwood forest soil of temperate zone were 4.6 and 2.5, respectively (Boone et al., 1998). Also, the $Q_{10}$ value of CO$_2$ fluxes at an intact site of Siberian larch forest was 4.35, while it decreased to 1.69 and 2.09 at the burnt and cutover sites, respectively (Takakai et al., 2008a). These findings suggest that $Q_{10}$ value of CO$_2$ flux is higher in root respiration than in soil organic matter decomposition.

There is an optimal water filled pore space (WFPS) for soil CO$_2$ production, which is around 60% (Linn and Doran, 1984). However, in actual field there is an interaction between soil moisture and soil temperature, and there is a tendency that temperature increases with decreases of soil moisture. Therefore, sometimes CO$_2$ fluxes correlated with not only soil temperature positively but also soil moisture negatively. Soil temperature is a better predictor for CO$_2$ fluxes, and a $Q_{10}$ function can predict reasonably annual CO$_2$ fluxes. However, rapid decline in CO$_2$ fluxes caused by significant drought was found in the Harvard Forest in central Massachusetts. Figure 2 shows that the rate of the decline in CO$_2$ fluxes correlated exponentially with decreasing soil matric potential (the rate of the decline in CO$_2$ fluxes = 1.21 × $a$ × $b$ × (matric potential)) $R^2$ = 0.83, $P < .01$). Combining this function of the decline in CO$_2$ fluxes to the soil matric potential and $Q_{10}$ function can provide better prediction of CO$_2$ fluxes (Davidson et al., 1998). However, CO$_2$ fluxes in crop fields in tropical dryland correlated better with soil moisture content than with soil temperature (Singh et al., 2009).

Figure 3 shows the CO$_2$ fluxes derived from soil organic matter decomposition measured at the root-excluded plots established in the 11 upland crop fields with different types of soil (Brown Forest soils, Brown Lowland soils, Gray Lowland soils, Psedogleys) with various texture (18.4–51.6% of sand content) in Mikasa city, central Hokkaido, Japan, over the no snow cover months (mid-April to early November) from 2003 to 2005 (Mu et al., 2008). The seasonal pattern of soil CO$_2$ fluxes mainly followed the seasonal changes in soil temperature but was occasionally interrupted by soil moisture fluctuation. Soil CO$_2$ fluxes increased with increasing soil temperature prior to June. Large fluctuation in soil CO$_2$ fluxes was observed from June to August, which was coincided with drying/rewetting events occurring during this period. After August, soil CO$_2$ fluxes declined with decreasing soil temperature. The instantaneous CO$_2$ fluxes ranged from 0.1 to 234 mg C m$^{-2}$ h$^{-1}$ for 2003 and from 2.6 to 231 mg C m$^{-2}$ h$^{-1}$ for 2005. Several significantly high emission episodes (300–500 mg C m$^{-2}$ h$^{-1}$) were recorded at the sites investigated following heavy rainfall within the previous week (amounting to 33–82 mm) in 2004.

Multiple regression analysis for correlation of logarithmic value of the CO$_2$ flux to soil temperature and WFPS showed that soil temperature alone or together with WFPS, clay content, and CN ratio could explain 27–76% of the temporal variation in the instantaneous soil CO$_2$ fluxes at the sites. Furthermore, there was a significant quadratic relationship between mean CO$_2$ flux or cumulative CO$_2$ emission and clay plus silt content (Figure 4). In contrast, mean CO$_2$ flux and cumulative CO$_2$ emission had no significant relationship with the mean values of soil temperature and moisture ($P > .2$). This suggests that soil texture is important for explaining spatial variability in soil CO$_2$ flux between sites within the same climate region. According to the quadratic function in Figure 4, soil mean or cumulative CO$_2$ flux will increase with increasing clay plus silt content at a clay plus silt content to 63%, but a further increase in clay plus silt content will lead to a decrease in soil CO$_2$ flux. Soil clay and silt facilitate soil aggregation and increase the stability of soil aggregates, which can reduce fluctuation in temperature and water content and can protect microorganisms from predation by soil fauna (Hassink et al., 1993). As a result, soil microbial biomass and microbial activity appeared to increase with increasing clay and silt content.
This might be a reason for the increase in soil CO\textsubscript{2} flux at the lower contents of clay and silt. In contrast, it is well known that soil clay and silt can absorb organic matter and stop it from being decomposed by microorganisms (Hassink et al., 1993). When the content of clay and silt exceeds a certain level (in this case 63%), the organic matter available for the decomposition might become limited and leads to a decrease in soil CO\textsubscript{2} flux. As a consequence of the negative relationship between soil CO\textsubscript{2} flux and higher fine particle content in soils, soil carbon content might be expected to increase with increasing fine particle content.

Indirect CO\textsubscript{2} emission through the subsurface drainage in an onion field of Gray Lowland soil in central Hokkaido, Japan, increased with increase of discharge rate during snowmelt season and rainfall events, and annual

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**Greenhouse Gas Fluxes: Effects of Physical Conditions, Figure 3**

Seasonal patterns in (a) local weather conditions, (b) soil temperature, (c) moisture, and (d) soil CO\textsubscript{2} fluxes derived from soil organic matter decomposition in the 11 upland crop fields with different types of soil in Mikasa city, central Hokkaido, Japan. WFPS, water-filled pore space. Error bars indicate the standard error (\(n = 3\)). A is grassland soil, others are cropland bare soils (Mu et al., 2008).
indirect CO₂ emission was 13.2 g C m⁻² year⁻¹, which corresponds to 2.5% of the direct CO₂ emission from soil to the atmosphere (Sawamoto et al., 2003). Indirect CO₂ emissions observed at different land uses of a well-permeable loamy soil varied with the land use. It was higher in a paddy rice field (33.4 and 36.7 g C m⁻² year⁻¹) than in upland fields (7.62 and 8.01 g C m⁻² year⁻¹) in a soybean field and 11.7 and 10.5 g C m⁻² year⁻¹ in a upland rice field (Minamikawa et al., 2009). Flooding was the most influential factor determining the indirect emission in the paddy rice plots, because flooding substantially increased the drainage volume and thus increased the indirect emission.

CH₄

CH₄ is produced by methanogenic bacteria and consumed by methanotrophic bacteria (Mer and Roger, 2001). When the soil redox potential (Eh) is below −200 mV after flooding, methanogenic bacteria produce CH₄ using acetate and CO₂ and H₂, which are produced by fermenting and syntrophic bacteria under anaerobic condition (Yamane and Sato, 1964; Conrad, 1999). In general, contribution of acetate and CO₂ and H₂ to CH₄ production is 67% and 33%, respectively. However, excess CO₂ production occurs when some of the soil organic acids act as electron acceptor (Yao and Conrad, 2000). Most methanogenic bacteria have their optimum pH at 7 (Goodwin and Zeikus, 1987). CH₄ production in soil is influenced by soil temperature. CH₄ production in various wetlands increases with increasing temperature from 2°C to 39°C (Bergman et al., 1998). CH₄ production is also influenced by the substrate. Significantly low CH₄ production was found in ombrotrophic bogs composed of acid and fibric peat in temperate region (Moore and Knowles, 1990).

Methanotrophic bacteria oxidized CH₄ in aerobic spot in soil (Hanson and Hanson, 1996). Measurements in flooded rice fields indicated that 80% of the methane produced was oxidized at the soil surface (Conrad and Rothfus, 1991). CH₄ uptake by aerobic soil decreases with an increase of water-filled pore space (WFPS) (Nesbit and Breitenbeck, 1992; Sitaula et al., 1995). Also, CH₄ uptake rate is decreased by the addition of NH₄ (Steudler et al., 1989) due to both a competitive inhibition of the CH₄ mono-oxygenase (MMO) enzyme as well as a noncompetitive (toxic) inhibition by hydroxylamine (NH₂OH) or nitrite (NO₂⁻) produced by NH₄⁺ oxidation (King and Schnell, 1994). Less temperature dependence of CH₄ consumption was found compared to that of CH₄ production in peat soil (Dunfield et al., 1993).

CH₄ fluxes between the soil and the atmosphere are determined by the balance of CH₄ production and CH₄ consumption in soil (Conrad, 1995) and strongly influenced by water table position (Moore and Knowles, 1990). Measurements in three ecosystems of forest, oil plum and sago plum in tropical peatland, Sarawak, Malaysia, showed that CH₄ was emitted at forest and sago plum with high groundwater table and it was taken up at oil plum with low groundwater table (Melling et al., 2005). CH₄ emission from the grassland of permafrost in Yakutsk was observed when the grassland was flooded with snow melting and permafrost thawing (Takakai et al., 2008b).

Figure 5 shows the processes involving CH₄ emission from rice paddy field. CH₄ is emitted mostly through rice aerenchyma and, at a lower level, through diffusion and ebullition after CH₄ was produced by methanogenic bacteria in anaerobic soil through organic matter decomposition, and CH₄ was consumed by methanotrophs in oxidized zones (rhizosphere, lower part of culms, soil–water interface, and submergence water) (Schütz et al., 1989). Once soil is flooded and water logged, anoxic and anaerobic conditions quickly develop in rice paddy soils due to decreasing aeration, resulting in the sequential utilization of a series of electron acceptors such as oxygen, NO₃⁻, Mn(IV), Fe(III), and SO₄²⁻. CH₄ production starts under highly reductive conditions after alternative electron acceptors have been depleted (Takai, 1970). CH₄ produced in rice paddy soils is emitted to the atmosphere by three pathways: molecular diffusion, ebullition as gas bubbles, and rice aerenchyma transport. Contributions from individual pathways vary over time and space, and rice aerenchyma is the major pathway accounting for more than 90% of the total CH₄ emitted from soils over the
growing season due to inhibition of upward gas diffusion by flooding. A fraction of CH$_4$ produced in soils is oxidized in the rhizosphere, either aerobically by oxygen released from plant roots or anaerobically by other electron acceptors such as Fe(III) and SO$_4^{2-}$/CO$_3^{2-}$.

Figure 6 shows an example of CH$_4$ flux from the continuous flooded rice paddy field in Japan (Yagi et al., 1996). The CH$_4$ flux gradually increased until the beginning of August and decreased thereafter until the final drainage, with minimum flux occurring in the early morning and the maximum flux in the early afternoon. The mean CH$_4$ flux ranged from 2 to 16 mg CH$_4$ m$^{-2}$ h$^{-1}$ during the period of flooding, but the CH$_4$ flush of 140 mg CH$_4$ m$^{-2}$ h$^{-1}$ in maximum was observed at 8 h after water table dropped below the soil surface associated with final drainage for harvest. The CH$_4$ emission decreased below 1 mg CH$_4$ m$^{-2}$ h$^{-1}$ at 3 days after the final drainage. Soil Eh at 2 and 5 cm depths were between $-288$ and $-165$ mV during the flooding period, indicating that the redox potential in the surface layer of the paddy soil was low enough for active methanogenesis. However, after final drainage, the soil Eh increased significantly. The large CH$_4$ flush after final drainage was possibly caused by a direct diffusion of CH$_4$ entrapped in soil through macropores and cracks in soil after the removal of the water seal by final drainage, followed by a rapid decrease in the CH$_4$ emission. Total CH$_4$ emission during the cultivation period was 14.8 g CH$_4$ m$^{-2}$, and the CH$_4$ flush after final drainage accounted for 7% of the total CH$_4$ emission.

CH$_4$ emissions from paddy fields are also influenced by agricultural management practices, mainly drainage practices and residue incorporation into soil. Total CH$_4$ emission during a rice cultivation period was reduced from 42% to 45% by two 3-day and 6-day short-term draining practices in the midseason of rice cultivation compared to the CH$_4$ emissions in a continuous flooded field (Yagi et al., 1996). In a Texas rice paddy field, a 6-day draining practice and three 2- to 3-day draining practices reduced total CH$_4$ emission by 48% and 88%, respectively (Sass et al., 1992). There was a significant correlation between rice straw carbon application rate (0–219 g C m$^{-2}$) and total CH$_4$ emission during cultivation period (4.04–40.8 g C m$^{-2}$ per cultivation period) in continuously flooded paddy fields in central Hokkaido, Japan (Naser et al., 2007). Similar trends have also been observed in rice paddy fields in Italy (Schütz et al., 1989), Texas, USA (Sass et al., 1990), Japan (Yagi and Minami, 1990), the Philippines (Wassmann et al., 1996),
and Louisiana, USA (Kongchum et al., 2006). However, CH$_4$ emission per unit dry matter of rice straw applied during the rice growing period season was significantly higher in the snowy temperate region than in other regions because of deep snow cover, low temperature, and unplowed conditions which might have retarded the decomposition of rice straw over the winter fallow (Naser et al., 2007).

Contribution of ebullition with falling atmospheric pressure has been less than 10% of total annual CH$_4$ emission (Schütz et al., 1989), but abrupt CH$_4$ flux from a Japanese wetland, which can change by two orders of magnitude within several tens of minutes was recently found due to the release of free-phase CH$_4$ triggered by a drop in air pressure (Tokida et al., 2007).

Indirect CH$_4$ emission through subsurface drainage in an onion field of Gray Lowland soil in central Hokkaido, Japan, increased with increase of drainage rate during snowmelt season and rainfall events (Sawamoto et al., 2003). Annual indirect CH$_4$ emission was 11.5 mg C m$^{-2}$ year$^{-1}$, which corresponds to 58% of the direct CH$_4$ emission from soil to the atmosphere. This high contribution suggests subsoil CH$_4$ production. On the other hand, in a well-permeable loamy soil, indirect CH$_4$ emissions were considerably low even in paddy field (Minamikawa et al., 2009). The values were 2.20 and 0.964 mg C m$^{-2}$ year$^{-1}$ in a paddy rice field, 0.145 and 0.159 mg C m$^{-2}$ year$^{-1}$ in a soybean field, 0.238 and 1.28 mg C m$^{-2}$ year$^{-1}$ in an upland rice field, and the proportion of the indirect CH$_4$ emission to the direct CH$_4$ emission from the soil to the atmosphere was only 0.05% and 0.03%, 0.30–0.22% and 0.46–2.64%, respectively.

N$_2$O

N$_2$O is mainly formed as a by-product of nitrification and as an intermediary of denitrification (Bremner, 1997). In aerobic condition, autotrophic nitrification is the main source of N$_2$O, but heterotrophic nitrification is generally regarded as a minor source of N$_2$O (Inubushi et al., 1996; Wrage et al., 2001). However, at low pH, N$_2$O is formed by chemodenitrification, which is the chemical decomposition of HNO$_2$, following reaction with organic (e.g., amines) or inorganic (e.g., Fe$^{2+}$) compounds (van Cleemput, 1998). At low O$_2$ concentration around 1 kPa dissolved O$_2$, N$_2$O is produced through nitrifier-denitrification process, which is a biological process proceeding NH$_4^+$ oxidation using NO$_3^-$ reduction simultaneously (Muller et al., 1995). Under anaerobic condition, N$_2$O is produced as an intermediary mainly through denitrification and anaerobic ammonium oxidation (Anammox). Heterotrophic denitrification, in which NO$_3^-$ is converted to N$_2$ with organic matter decomposition, is the significant process for N$_2$O production. Autotrophic denitrification in which NO$_3^-$ is converted to N$_2$ with the oxidation of sulfide (Cardoso et al., 2006) or ion oxidation (Tilt et al., 1998). Anammox is also a biological process in which NH$_4^+$ is converted to N$_2$ with NO$_2^-$ reduction as the electron acceptor (Strous et al., 1997; Kampschreur et al., 2008).

During nitrification and denitrification which are the major processes producing N$_2$O in soil, NO is also produced. Figure 7 shows a conceptual “hole-in-the-pipe” model, using the analogy of a leaky pipe, which suggests three levels regulating N$_2$O and NO emission from the soil to the atmosphere (Firestone and Davidson, 1989; Davidson and Verchot, 2000). At first level, there are
factors controlling the rates of nitrification and denitrification (the “flow through the pipe”), which are the amounts of raw material (soil mineral N), soil temperature, and soil moisture; at second level, there are factors regulating the proportions of N$_2$O and NO productions in nitrification and denitrification (the “size of the holes in the pipe”), which are acidity, concentrations of NO$_3^-$, and available carbon in soil; and at third level, there are factors controlling the consumption of N$_2$O and NO within the soil matrix, which are diffusion and mass flow in soil depending on soil texture, soil structure, air-filled pore space, temperature, and air pressure. Increase of soil moisture decreases air-filled pore space, which decreases gas diffusivity in soil, increasing the opportunities for further microbial reaction in soil.

Optimal moisture condition for organic matter decomposition (mineralization) and nitrification is around 60% of water-filled pore space (WFPS), while the optimal condition for denitrification is at saturation of the WFPS, with sufficient presence of nitrate and available organic carbon (Linn and Doran, 1984). The ratio of N$_2$O–N/NO–N ranges from 0.2 to 1 during nitrification and is approximately 100 during denitrification (Lipschultz et al., 1981).

Figure 8 shows examples of the seasonal and yearly variation in N$_2$O fluxes (a) and N$_2$O–N/NO–N ratio (b) measured in an Onion field of Gray Lowland soil in central Hokkaido, Japan (Toma et al., 2007). The measurements were conducted in four treatments; chemical N fertilization and organic matter application, with plants (FOP); chemical N fertilization only, without plants (F); organic matter application only, with plants (OP); and control, no fertilization, or organic matter application, without plants (C). In chemical N fertilizer–applied treatments (FOP and F), there were two peaks in the periods from May to June and from late August to October (Figure 8a), and the N$_2$O–N/NO–N ratio decreased to less than 1 from May to June and increased to approximately 100 from September to October (Figure 8b). These indicate nitrification after spring N fertilization and denitrification with increase of rainfall. On the other hand, in no chemical N fertilizer–applied treatments (OP and C), only one peak was found in the period from August to October (Figure 8a), and the N$_2$O–N/NO–N remained above 1 from May to June (Figure 8b). There was a significant correlation between 2-month N$_2$O emission from May to June and mean temperature during these months ($n = 8$, $r^2 = 0.53$, $P < .05$; Figure 9a). The N$_2$O production after spring fertilization resulting from the nitrification process may be affected by temperature. The 2-month N$_2$O emissions from September to October in the FOP and OP treatments, however, were positively correlated with the precipitation during these months ($n = 8$, $r^2 = 0.39$, $P < .1$; Figure 9b).

Figure 10 shows the relationship between total N application rate and N$_2$O emission from Japanese upland fields, with measurement period more than 90 days. N$_2$O emission increased with increase of N application rate and was generally higher in poorly drained soil than that in well-drained soil (Akiyama et al., 2006).

Huge amount of annual N$_2$O emission of 259 kg N ha$^{-1}$ year$^{-1}$ in maximum was found at the croplands of tropical peatland in Palangka Raya, central Kalimantan, Indonesia. During the rainy season, N$_2$O fluxes from the soil surface of the croplands increased with increase of NO$_3^-$ content in the soil when water-filled pore space in the top soil exceeded 60–70% (Takahai et al., 2006). Acid-tolerant Janthinobacterium sp. as an N$_2$O emitter isolated from the cropland peat soil showed high ability of denitrification (NO$_3^-$ reduction) but low activity of N$_2$O reductase (Hashidoko et al., 2008).

In temperate and boreal climates with periodic soil freezing and thawing, high N$_2$O emission from soil in the winter and early spring is usually observed (Christensen and Tiedje, 1990; Flessa et al., 1995).
Seasonal variation in \( \text{N}_2\text{O} \) flux (a) and \( \text{N}_2\text{O}\text{–N}/\text{NO}\text{–N} \) ratio (b) at the onion fields of Gray Lowland soil (GL) in central Hokkaido, Japan (From Toma et al., 2007). The arrows indicate the time of chemical fertilizer application (CF), root cutting (RC), and harvest and residue application (H). The four treatments were: chemical nitrogen fertilization and organic matter application, with plants (FOP); chemical nitrogen fertilization only, without plants (F); organic matter application, with plants (OP); no fertilization or organic matter, and no plants (C). Error bars indicate standard deviation.
Biological denitrification is the main process in N\textsubscript{2}O production when soil is undergoing the process of freezing and thawing (Müller et al., 2002; Öquist et al., 2004). This might be caused by an imbalance of N\textsubscript{2}O-producing and N\textsubscript{2}O-reducing activities of denitrifying communities enhanced by the freeze–thaw cycles (Yanai et al., 2007).

Indirect N\textsubscript{2}O emission through subsurface drainage in an Onion field of Gray Lowland soil in central Hokkaido, Japan, increased with increase of drainage rate during snowmelt season and rainfall events (Sawamoto et al., 2003). Direct N\textsubscript{2}O emission from the field increased significantly with increase in precipitation in the growing seasons (Kusa et al., 2002), and NO\textsubscript{3}/NO\textsubscript{2} leaching increased with increase of precipitation in the same field (Hayashi and Hatano, 1999). Annual indirect N\textsubscript{2}O emission was 74.7 mg N m\textsuperscript{-2} year\textsuperscript{-1} which corresponds to 4.6% of the direct N\textsubscript{2}O emission from the soil to the atmosphere. The NO\textsubscript{3} concentration in the drainage ranged from 8.5 to 25.5 mg N L\textsuperscript{-1} and the dissolved N\textsubscript{2}O concentration ranged from 19.3 to 189 μg NL\textsuperscript{-1}.

But, there was no significant relationship between N\textsubscript{2}O–N and NO\textsubscript{3}–N concentration. The ratio of N\textsubscript{2}O–N/NO\textsubscript{3}–N (kg kg\textsuperscript{-1}) ranged from 0.00076 to 0.0105 (Sawamoto et al., 2003). The ratio has been estimated to be 0.0024 using 15 data sets of N\textsubscript{2}O and NO\textsubscript{3} concentrations in drainage water (Sawamoto et al., 2005). In a well-permeable loamy soil in Tsukuba, Japan, considerably different tendency in indirect N\textsubscript{2}O emission was found.

**Summary**

Soil is the major source of CO\textsubscript{2}, CH\textsubscript{4}, and N\textsubscript{2}O emissions into the atmosphere. Those gases are produced and consumed in soil by mainly microbial activities which are strongly influenced by soil environmental factors. This paper reviewed the relationship between the fluxes of those gases and soil environmental factors.

Soil temperature is the most important soil environmental factor for CO\textsubscript{2} flux from soil. However, significant drought declined soil CO\textsubscript{2} flux rapidly and heavy rain event induced episodic CO\textsubscript{2} flux from soil. Different soils within a watershed have different relationships between CO\textsubscript{2} flux and soil temperature and soil moisture. However, soil texture significantly influenced CO\textsubscript{2} emission from the soil during a growing season, and there was a critical clay and silt content for the CO\textsubscript{2} emission.
Soil moisture is the most important soil environmental factor for CH4 flux from soil, because CH4 is produced by methanogenic bacteria in anaerobic soil and consumed by methanotrophic bacteria in aerobic soil. In paddy field, rice aerenchyma is the major pathway during the growing season due to inhibition of upward gas diffusion by flooding. Final drainage at the end of growing season in paddy field often induced large CH4 flush due to a direct diffusion of CH4 entrapped in soil after the removal of the water seal by drainage. Short-term drainage practice during the growing season in paddy field reduced the CH4 emission, but the increase of rice straw incorporation significantly increased CH4 emissions.

Soil temperature and soil moisture are significant soil environmental factors for N2O flux from soil, because N2O is mainly formed as a by-product of nitrification and as an intermediary of denitrification. Long-term observation in an upland field indicated that N2O emission induced by nitrification increases by the increase of soil temperature, and N2O emission induced by denitrification increases by the increase of precipitation. Very high N2O flux was found at the croplands of tropical peatland in Indonesia when water-filled pore space in the top soil exceeded 60–70%. This was ascribed to acid-tolerant bacteria with low activity of N2O reductase. On the other hand, soil freezing and thawing in temperate and boreal climates enhances high N2O flux from soil in the winter and early spring.

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Carbon dioxide sequestration (or carbon sequestration) is the term given for locking up CO$_2$ somewhere other than the atmosphere. In biological sequestration, carbon is naturally sequestered in plants, soils, and in ocean life. Soils represent a short to long-term carbon storage medium, and contain more carbon than all terrestrial vegetation and the atmosphere combined and are a major reservoir of carbon and an important sink. Because of the relatively long period of time that carbon spends within the soil and is thereby withheld from the atmosphere, it is often referred to as being sequestered (Swift, 2001). Plant litter and other biomass are accumulated as organic matter in soils especially in litter and soils of colder regions such as the boreal forests. The carbon sequestration potential of soils (by increasing soil organic matter) is substantial. Improving the humus levels of these soils would both improve soil quality and increase the amount of carbon sequestered in these soils. Decomposition rates can be slowed by reducing tillage and by growing crops with low residue quality that is more difficult for microbes to decompose. No tillage implants seeds without turning the soils reduce the loss of soil organic matter. Natural soils retain carbon in stable microaggregates for up to hundreds of years unless environmental conditions are changed and the stable soil structure is damaged (Luo and Zhou, 2006). The C sequestration potential of a soil depends on the vegetation it supports, its mineralogical composition, the depth of the soil, soil drainage, the availability of water and air, the temperature of the soil environment, and the chemical characteristics of the soil organic matter and its ability to resist microbial decomposition (Swift, 2001). Conversion of the soil to pastureland, particularly with good management of grazing, can sequester more carbon. Thus, soil restoration and woodland regeneration, no-till farming, cover crops, nutrient management, manuring and sludge application, improved grazing, water conservation and harvesting, efficient irrigation, agroforestry practices, growing energy crops on spare lands, and pyrolyzing the biomass to biochar are recommended management practices to increase the soil carbon sequestration (Lal, 2004). The chemosynthetic autotrophs (chemolithotrophs) take carbon dioxide as their carbon source for growth and derive their energy from oxidation of inorganic materials like iron, sulfur, ammonia, and nitrite. Grasslands contribute
huge quantities of soil organic matter over time, mostly in the form of roots, and much of this organic matter can remain unoxidized for long periods. They also deposit carbon directly to the soil in the form of char that does not significantly degrade back to carbon dioxide. No-till pastures, particularly with good management of grazing, can sequester even more carbon in the soil. The wetlands cover only 3% of land area but store nearly 37% of global terrestrial carbon. As a consequence of anoxic conditions, the rate of organic matter decomposition is slow and carbon tends to accumulate in wetland soils. Wetland soil carbon storage is sensitive to climatic changes, water table fluctuations, and human disturbances. Peat lands cover about 75% of the wetlands by area and are particularly important for storage of soil carbon (Luo and Zhou, 2006). Organic matter in peat bogs undergoes slow anaerobic decomposition below the surface and fixes more carbon from the atmosphere than is released. Peat bogs absorb approximately one-quarter of the carbon stored in land plants and soils. Forests are carbon stores, and they are carbon dioxide sinks when they are increasing in density or area. As part of photosynthesis, trees absorb carbon dioxide from the atmosphere and store it as carbon. Rapidly growing trees absorb a larger amount of carbon dioxide. The sink effect exists only when they grow in size. Mature trees grow less rapidly and thus have a lower intake of carbon dioxide. One ton of dry wood is equivalent to 1.8 tons of carbon dioxide. Upon harvesting, wood can be incorporated into construction or a range of other durable products, thus sequestering its carbon over years or even centuries. Management measures to improve carbon storage in forest include prolonging rotation, changing tree species, continuous cover forestry, fire control, combined water storage with peat swamp afforestation, fertilization, and reducing the rate of deforestation. (Luo and Zhou, 2006).

CH₄ sink
The atmospheric concentration of CH₄ has increased and is more than doubled during the past 200 years (Mancinelli, 1995). Aerobic consumption of CH₄ is common in soils and aquatic environments. There are only two important sinks for atmospheric CH₄. The major sink is reaction of CH₄ with hydroxyl radical. Additionally, CH₄ is consumed by aerobic microbial activity in soils. The soil CH₄ sink is sensitive to nitrogen fertilization. Methanotrophs play a major role in the reduction of the release of methane into the atmosphere from environments such as rice paddies, landfills, bogs, and swamps where methane production is relatively high and from aquatic systems, soils, forest, tundra, and agricultural soils.

Aerobic methane oxidation
Methane-oxidizing microorganisms (methanotrophs) are found in variety of soil and aquatic environments and play an important role in regulating atmospheric methane content. Oxidation of methane to carbon dioxide in soils occurs primarily as part of aerobic metabolism in methanotrophic bacteria. Methanotrophs are able to metabolize methane as their only source of carbon and energy mostly in soils, where methane is produced. Methanotrophs are often concentrated in a narrow band where methane diffusing away from its source (an anaerobic zone) meets oxygen from the air. Although nearly all methane oxidizers are obligate aerobes, they are microaerophilic, preferring oxygen level lower than atmospheric levels. The net reaction of methane oxidation under aerobic conditions can be described as CH₄ + O₂ → CO₂ + H₂O (Mancinelli, 1995).

Methane is oxidized in soil by methanotrophs with the use of a chain of enzymes such as methanol, formaldehyde, formate, and nonspecific aldehyde dehydrogenases (Large, 1983). It was found that during incubation of a Mollic Gleysol with methane in the headspace dehydrogenase activity of the soil significantly increased, compared to the control value, after 2 days to its maximum and decreased slowly during the next days (Brzezińska et al., 1998).

Methanotrophic bacteria posses both dissimilatory and assimilatory pathways of methane oxidation. In dissimilatory pathways, methane is oxidized completely to carbon dioxide, thereby producing cellular energy, and none of the carbon becomes cellular material, or biomass. In assimilatory pathways, methane is oxidized and converted to cellular biomass. In both pathways, methane is first oxidized to methanol by methane monoxygenase (MMO) using molecular oxygen, which is then oxidized to formaldehyde. The formaldehyde can be used as reducing power in the electron transport chain, oxidized to formate, or assimilated by the cell via the ribulose monophosphate pathway and/or the serine pathway. The cell then either oxidized the formate to carbon dioxide or uses it as reducing power to drive the electron-transport chain. Several physicochemical factors influence rates of methane oxidation in soil, including soil diffusivity, water potential, and levels of oxygen, methane, ammonium, nitrate, nitrite, and cooper. Most of these factors exert influence through interactions with MMO (Mancinelli, 1995). In general, methanotrophic activity increased with increasing CH₄ addition in the different range of initial methane content. Soils are characterized by different requirements with respect to threshold methane concentration expressed as high- or low-affinity oxidation. The differences in methanotrophic activity mainly depend on differences in organic matter content and availability and methanotrophs existing in the soils (Włodarczyk et al., 2004).

Anaerobic oxidation of methane
Anaerobic oxidation of methane (AOM) is a microbial process occurring mainly in anoxic marine sediments and reducing the emission of methane from the ocean into the atmosphere. During AOM, methane is oxidized with sulfate as the terminal electron acceptor: CH₄ + SO₄²⁻ → HCO₃⁻ + HS⁻ + H₂O. AOM is mediated by
a syntrophic consortium of methanotrophic archaea and sulfate-reducing bacteria. Recent investigations have shown that some consortia of archaea and bacteria are also able to oxidize methane with nitrate instead of sulfate (Raghoebrasing et al., 2006). But recent findings suggest that this nitrate-reducing process coupled to methane oxidation can also be performed by a single bacterium without the need for an archaean partner.

**N₂O sink**

Natural production and emission to the atmosphere of nitrous oxide is from microbial activity in soils and in the aquatic systems. N₂O is greenhouse gas that increased by 16% over the last 200 years. N₂O uptake has been observed in soils, aquatic systems, and riparian zones. A complete denitrification, at which N₂O is reduced to N₂, is assumed to be the main elimination or sink process of N₂O in the soils, beside dissolution in water. However, other types of N₂O sink were observed, for example, N₂O fixation with following transforming to NH₃. Only 1% of the microbes in soils have the ability to produce the enzyme N₂O reductase that reduces N₂O to N₂. The production of the enzyme is controlled by environmental influences like oxygen concentration and the concentration of the denitrification intermediate products. The potential of this process depends highly on the N₂O and O₂ concentrations, and aggregate sizes in the soil (Vieten, 2008). Next factors affecting N₂O uptake by soils are nitrogen availability, soil wetness, temperature, soil drainage conditions, and soil pH. Maximum N₂O reduction was measured at pH 6 and 7 (Smith et al., 1983). Agricultural soils are usually fertilized and therefore not likely to be sinks for N₂O, some studies report on N₂O uptake in fertilized fields; several studies report on considerable N₂O uptake in forest soils, which may potentially be important sinks for atmospheric N₂O; riparian zones depending on local conditions may be potential sinks for N₂O; N₂O uptake may occur in the open ocean (Kroeze et al., 2007). Because the N₂O emission at the soil surface is the result of production and consumption processes, some research has concentrated on net N₂O production. However, there are some reports of net negative fluxes of N₂O (i.e., fluxes from the atmosphere to the soil). Low mineral N and large moisture contents have sometimes been found to favor N₂O consumption. Denitrification is the responsible process, reducing N₂O to N₂. However, it has also been reported that nitrifiers consume N₂O in nitrifier denitrification. The wide range of conditions found to allow N₂O consumption, ranging from low to high temperatures, wet to dry soils, and fertilized to unfertilized plots. Generally, conditions interfering with N₂O diffusion in the soil seem to enhance N₂O consumption. Soil sink could help account for the current imbalance in estimated global budgets of N₂O (Chapuis-Lardy et al., 2007). N₂O emission and consumption is regulated within a narrow redox potential range +120 to +250 mV (Yu et al., 2001) and +200 to 230 mV (Włodarczyk et al., 2005) due to the balance of N₂O production and its further reduction to N₂. The interval of redox potentials allowing the existence of gaseous nitrous oxide in the equilibrium or “quasi-equilibrium” with the soil is very narrow and does not exceed 50 mV (Figure 1). Soils texture and particle size distribution significantly differentiated soil ability to N₂O consumption. Nitrous oxide sink showed a significant positive correlation with the fraction 0.05–0.002 mm and a negative one with the fractions >0.05 mm (Włodarczyk et al., 2005).

**Summary**

Sink of the main greenhouse gases in the Earth’s atmosphere such as CO₂, CH₄ and N₂O were viewed. Mitigation of greenhouse gases emission leads to minimizing the effects of global warming. The main natural carbon sinks are absorption of carbon dioxide by the oceans and photosynthesis by plants and algae. The main manmade sinks are landfills and carbon capture and storage proposals. Methanotrophs play a major role in the reduction of the release of methane into the atmosphere from environments such as rice paddies, landfills, bogs, and swamps where methane production is relatively high. Anaerobic oxidation of methane is a microbial process reducing the emission of methane from the ocean into the atmosphere. A complete denitrification, at which N₂O is reduced to N₂, is assumed to be the main elimination or sink process of N₂O in the soils, besides dissolution in water. Forest soils and riparian zones may potentially be important sinks for atmospheric N₂O depending on local conditions.

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GROUND-PENETRATING RADAR, SOIL EXPLORATION

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Ground-penetrating radar (GPR) is a noninvasive, high-resolution geophysical method used in soil exploration. Ground-penetrating radars transmit short pulses of high- to ultra-high frequency (center frequencies from 12.5 MHz to 2.6 GHz) electromagnetic energy into the ground to detect subsurface interfaces. A time-scaled system, GPR measures the time that it takes pulses of electromagnetic energy to travel from an antenna to a subsurface interface and back. Interfaces often correspond to major soil, stratigraphic, and lithologic layers or features. Whenever a pulse contacts an interface separating layers with different relative dielectric permittivity ($\varepsilon_r$), a portion of the energy is reflected back to a receiving antenna. The more abrupt and contrasting the permittivity on opposing sides of an interface, the greater the amount of energy that is reflected back to the antenna and the greater the amplitude of the recorded signal. To convert the travel time into a depth scale, the velocity of pulse propagation or the depth to a reflector must be known.

A typical GPR system consists of a radar control unit with antenna (Figure 1). The control unit serves as a user interface and consists of a colored screen, microprocessor, and mass storage device. Choice of antenna is depth, target, and soil dependent. Higher frequency antennas provide greater resolution but do not penetrate as deeply as lower frequency antennas. Soils having high electrical...
conductivity rapidly attenuate radar energy, restrict penetration depths, and severely limit the effectiveness of GPR (Daniels, 2004; Jol, 2009). The electrical conductivity of soils increases with increasing water, soluble salt, and/or clay contents.

Ground-penetrating radar provides spatially continuous records of the subsurface. Figure 2 is a representative radar record from an area of Pomona soils, which form in sandy over loamy marine sediments in Florida (USA). In Figure 2, the continuity and depths to both the spodic and argillic horizons are highlighted with segmented lines.

In soil exploration, GPR is principally used to document the presence, depth, lateral extent, and continuity of subsurface soil horizons, stratigraphic layers, and lithologic units (Collins, 2008; Daniels, 2004; Jol, 2009). It has also been used to: identify preferential flow pathways, animal burrows, and buried drainage tiles; assess root biomass and hydrocarbons in soils; study soil moisture dynamics, water table depths, and the movements of agrochemicals; predict groundwater flow patterns; and characterize near-surface hydrologic conditions.

Cross-references
Electrical Properties of Soils
Hydopedological Processes in Soils
Mapping of Soil Physical Properties
Nondestructive Measurements in Soil

GROUNDWATER

The water in the saturated portion of the soil or the underlying porous materials.

GULLY (LINEAR) EROSION

The erosion process whereby water accumulates and often recurs in narrow channels and, over short periods, removes the soil from this narrow area to considerable depths, often defined for agricultural land in terms of channels too deep to easily ameliorate with ordinary farm tillage equipment, typically ranging from 0.5 m to as much as 25–30 m.

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