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DARCY'S LAW

The basic law describes the flow of water or other liquids in permeable materials (e.g., soil, porous rock, concrete, timber, or other porous material). Darcy's law tells that the water flux q (m s^{-1}) at any point is proportional to the gradient of the water potential at that point and the coefficient of proportionality is the water conductivity coefficient:

$$\vec{q} = K(\psi) \cdot \text{grad}\psi$$

where: q is the water flux [m s^{-1}], $K(\psi)$ is the water conductivity coefficient [m s^{-1}] and ψ is the soil water potential [m].

Cross-references

[Soil Water Flow](#)
[Water Budget in Soil](#)

DATABASES ON PHYSICAL PROPERTIES OF PLANTS AND AGRICULTURAL PRODUCTS

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Definition

Physical properties of plants and agricultural products can be defined as the characteristics of described materials that are independent of the observer, measurable, can be quantified, and define the state of the material but not how it attained that state.

Introduction

Physical properties describe the unique, characteristic way a plant or agricultural product responds to physical treatments, for example, thermal, mechanical, or electrical processes. Knowledge of physical properties of described materials is essential for the design of equipment for their handling, storage, and processing. Data on physical properties of plants and agricultural products are needed as input to models predicting the quality and behavior of produce in preharvest, harvest, and postharvest situations. The properties of discussed materials are affected by many factors such as moisture content, growing location, growing year, and cultivar. Many properties also depend on other properties. Physical properties can change during processing operations.

Physical characteristics

The *size* of spherical particles like peas is easily defined by a single characteristic (its diameter). Complete specification of the form of the objects irregular in shape theoretically requires an infinite number of measurements. However, three mutually perpendicular axes account for some 93% of variation in volume (Mohsenin, 1986). *Length*, *width*, and *thickness* (m) are commonly used that correspond to major, intermediate, and minor axes, respectively. The dimensions increase linearly with increasing moisture content. The dimensions range approximately: (1) length: 0.8×10^{-3} – 18.5×10^{-3} m for seeds and grains, 8.6×10^{-3} – 26.3×10^{-3} m for fresh blueberries, cherries, cranberries, grapes and pistachio nuts, 43.2×10^{-3} – 94×10^{-3} m for fresh apples, peaches, pears, plums, potatoes, and tomatoes, (2) width: 0.6×10^{-3} – 11×10^{-3} m for seeds and grains, 11.4×10^{-3} – 17.8×10^{-3} m for fresh blueberries and cherries, 40.6×10^{-3} – 83.8×10^{-3} m for fresh apples, peaches, pears,

plums, potatoes, and tomatoes, (3) thickness: 0.4×10^{-3} – 10.0×10^{-3} m for seeds and grains, 6.35×10^{-3} – 17.8×10^{-3} m for fresh blueberries, cherries, and cranberries, 38.1×10^{-3} – 76.2×10^{-3} m for fresh apples, peaches, pears, plums, potatoes, and tomatoes. The size of irregularly shaped non-isometric object is a statistical parameter that depends on the direction of measurement. To reduce the resultant scatter in measured diameters, the size of object is expressed in a standardized form. An *equivalent diameter* is one of these forms. The volume diameter (diameter of the sphere having the same volume as object) is the most frequently used definition. For grains, the volume occupied by 1,000 kernels is commonly measured. The *geometric mean diameter* ($d_{eg} = (abc)^{1/3}$), where a is the longest intercept, b is the longest intercept normal to a , c is the longest intercept normal to a and b is used sometimes. Both diameters increase slightly with the increase of moisture content (linear function). The equivalent diameter for seeds and grains ranges approximately from 0.99×10^{-3} to 9.81×10^{-3} m. The geometric mean diameter ranges approximately: for seeds and grains: 2.93×10^{-3} – 8.33×10^{-3} m, for fresh blueberries and cherries: 10.4×10^{-3} – 17×10^{-3} m, for fresh apples, peaches, plums, pears, potatoes, and tomatoes: 43.4×10^{-3} – 73.7×10^{-3} m. A monodisperse material is characterized uniquely by the size of individual particles. A polydisperse material is characterized by a *particle size distribution* and by a *mean particle size*. Particle size distribution represents the relative amount of material defined either by the number of particles, their surface area, volume, or mass as a function of the particle size. The mean particle size represents the average value for the whole population of particles. *Roundness (angularity)* of an object is most commonly defined as the ratio of: (1) the largest projected area of object in natural rest position to the area of the smallest circumscribing circle, or (2) an average radius of corners or edges to the radius of the largest inscribed sphere. Roundness values differ for both of the above methods. *Sphericity* is most commonly defined as the ratio of: (1) the volume of an object to the volume of the smallest circumscribing sphere, or (2) the equivalent diameter (or the geometric mean diameter) of the object to the diameter of the smallest circumscribing sphere. Sphericity values differ for each of the above methods. Higher values of sphericity and roundness indicate that the object's shape is closer being spherical. Sphericity increases linearly with increasing moisture content. Sphericity ranges approximately: for seeds and grains: 0.58–0.93, for fresh apples, apricots, blueberries, cherries, peaches, and pears: 0.90–0.99. *Surface area* is the area of the outer surface of an object (m^2). *Specific surface area* is defined as the ratio of the surface area of an object to the volume of an object (m^{-1}). Both characteristics depend on linear dimensions of solids and on their moisture content. Surface area of fruits increases linearly with their increasing mass. For seeds and grains, surface area ranges approximately from 3×10^{-6} to $240 \times 10^{-6} m^2$ and specific surface area ranges approximately from

500 to $6,060 m^{-1}$. *Volume* is defined as the amount of three-dimensional space occupied by an object (m^3). Volume of the solid depends on its linear dimensions, surface area, moisture content, and temperature. Volume ranges approximately: for seeds and grains: 0.5×10^{-9} – $369 \times 10^{-9} m^3$, for fresh blueberries, coffee beans, cherries, and pistachio nuts: 0.3×10^{-6} – $4.5 \times 10^{-6} m^3$, for fresh apples, peaches, pears, plums, potatoes, and tomatoes: 44.2×10^{-6} – $349 \times 10^{-6} m^3$. For grains, the *mass* of 1,000 kernels is commonly measured (kg). Its value is an indicator of the grain size, which can vary relative to growing conditions and maturity, even for the same variety of a given crop. The 1,000-grain mass increases linearly with increasing moisture content and it ranges approximately from 3×10^{-3} to 440×10^{-3} kg. The mass ranges approximately: for fresh blueberries, cherries, cranberries, grapes, pistachio nuts, coffee beans, and walnuts: 0.15×10^{-3} – 7.5×10^{-3} kg, for fresh apples, apricots, peaches, pears, plums, potatoes, and tomatoes: 18.1×10^{-3} – 286×10^{-3} kg. The *solid (true) density* is the mass of solid divided by the volume occupied by the solid excluding the intergranular spaces ($kg m^{-3}$). True density of grains decreases linearly with increasing moisture content (the changes are not significant). True density can be treated as a measure of, among others, maturity (blueberries, peas, peaches, tomatoes), starch content (potatoes), and peel thickness (grapefruits). True densities range approximately: for seeds and grains: 700 – $2,000 kg m^{-3}$, for fruits and vegetables: 700 – $1,200 kg m^{-3}$, for wood: 400 – $1,300 kg m^{-3}$. *Bulk density* is the mass of a group of individual particles divided by the space occupied by the entire mass, including the air space ($kg m^{-3}$). The bulk density gives an idea of the storage space required for a known quantity of a particular, for example, grain. The bulk density can be affected by the following factors: mass of particles, their shape and dimensions, particle size distribution, the method used for filling the container, moisture content of particles, the amount and size distribution of foreign materials (chaff, fines, broken grains, and weed seeds). For example, a container filled using a spreader gives a higher bulk density than a container filled using a spout, the presence of foreign materials that are finer and heavier than grain kernels increases bulk density. The bulk density of some grains increase with an increasing moisture content whereas it decreases for some other grains. The bulk densities range approximately: for clean seeds and grains: 240 – $910 kg m^{-3}$, for fruits and vegetables: 220 – $830 kg m^{-3}$. The *porosity* (decimal) is defined as the ratio of the intergranular volume to the total volume occupied by the particles (i.e., the volume of particles plus the intergranular volume). Porosity depends on true and bulk density of material. Porosity allows fluids to flow through a mass of particles referred to as a packed bed. Beds with low porosity are more resistant to fluid flow and thus are more difficult to dry, heat, or cool. The porosity for clean seeds and grains ranges approximately from 0.26 to 0.80. *Shrinkage* is the decrease in volume of the material during processing such as drying. When moisture

is removed from material, there is a pressure imbalance between inside and outside of the material. This causes contracting stresses leading to material shrinkage or collapse. Shrinkage is defined as the ratio of the volume at a given moisture content to the initial volume of material before processing. Shrinkage depends mainly on moisture reduction (in the empirical formulas linear dependence is mostly assumed) and composition and structure of the material. Data on physical characteristics of plants and agricultural products have been compiled and further details can be taken from Mohsenin (1986), Cenkowski and Zhang (1995), Kaleta (1996), Kudra (1998), Pabis et al. (1998), Sablani and Ramaswamy (2003), Wilhelm et al. (2004), and Jayas and Cenkowski (2006).

Aerodynamic properties

The drag force, F_r ($F_r = C \rho_f A_p v^2$, where ρ_f is the fluid density, A_p is the projected area normal to direction of motion, v is the relative velocity between main body of fluid and object), exerted on an object held in a free stream depends on dimensionless *drag coefficient* C . Drag coefficient depends on the shape of the particle and the state of its surface, and on the Reynolds number Re . The drag coefficients for particles with regular geometric shapes are usually shown on log-log plot, as a function of Re . For turbulent flow and for the values of Re characteristic for the processes of cleaning, separating, and pneumatic transporting, the dependence of drag coefficient on Re can be neglected. The drag coefficients for agricultural products range approximately from 0.16 to 0.44 (Mohsenin, 1986; Kaleta, 1996; Jayas and Cenkowski, 2006). A free-falling body ceases to accelerate after some time and the body reaches a constant *terminal velocity*, at which the net gravitational accelerating force equals the resisting upward drag force. This velocity can be calculated theoretically for particles with regular geometric shapes. For irregularly shaped particles, the terminal velocity is determined experimentally. The terminal velocities range approximately (Mohsenin, 1986; Kaleta, 1996; Jayas and Cenkowski, 2006): for seeds and grains: 4.0–18.3 m s^{-1} , for fresh blueberries, cherries, cranberries, grapes, and pistachio nuts: 9.7–22.6 m s^{-1} , for fresh apples, apricots, peaches, plums, and potatoes: 22.9–41.5 m s^{-1} .

Thermal properties

Specific heat (heat capacity) is the heat required to increase the temperature of one unit of mass by 1° ($\text{J kg}^{-1} \text{K}^{-1}$). The specific heat depends on: composition of the material, moisture content, and temperature (in heat transfer problems of biological materials usually constant pressure prevails). Specific heat can be computed from the following equations: (1) for temperature above freezing: $c = 837 + 33.5M_w$ (Siebel, 1892), $c = 1424X_c + 1549X_p + 1675X_f + 837X_a + 4187X_w$ (Heldman and Singh, 1981), $c = c_s + 4186M_d$, (2) for temperature below freezing $c = 837 + 12.56M_w$ (Siebel, 1892),

where M_w is the moisture content, % w.b., M_d is the moisture content, d.b., X is the mass fraction of each constituent: carbohydrate (c); protein (p); fat (f); ash (a); water (w), c_s is the specific heat of the dry solid. The specific heat is most commonly calculated from regression equations obtained from empirical data (linearly increasing trend with increasing moisture content and increasing temperature is generally reported). Its value ranges approximately: for wood: 1,880–2,970 $\text{J kg}^{-1} \text{K}^{-1}$, for dry mass of plants, seeds, and grains: 990–2,050 $\text{J kg}^{-1} \text{K}^{-1}$, for fresh fruits and vegetables: above freezing: 3,140–4,100 $\text{J kg}^{-1} \text{K}^{-1}$, below freezing: 1,670–2,390 $\text{J kg}^{-1} \text{K}^{-1}$. The *thermal conductivity* ($\text{W m}^{-1} \text{K}^{-1}$) of a material is a measure of its ability to conduct heat. It defines the amount of thermal energy that is transmitted within a unit time and through a unit cross-sectional area when the temperature gradient across a body is a unit degree ($q = -k \nabla T$, where q is the heat flux, k is the thermal conductivity, ∇T is the temperature gradient). The thermal conductivity depends on the composition of the material, moisture content, temperature, and structure of the material including any factor that affects the heat flow path through the material (percent void spaces, shape, size, and arrangement of void spaces, heterogeneity, impurities, particle to particle contact, and fiber orientation). Theoretical models for the prediction of thermal conductivity of plants and agricultural products are based on the composition of material or on the arrangement and geometry of phases present in the material, but they lack accuracy (Sweat, 1992; Kudra, 1998; Saravacos and Maroulis, 2001; Sahin and Sumnu, 2006). Therefore, the thermal conductivity is most commonly calculated from regression equation (linearly increasing trend with increasing moisture content, increasing temperature, and increasing bulk density is generally observed). For high moisture materials below freezing, thermal conductivity increases with a decrease in temperature and a sudden jump in its value can be observed at freezing point. The thermal conductivity ranges approximately from 0.110 to 0.720 $\text{W m}^{-1} \text{K}^{-1}$ for wood and from 0.280 to 0.640 $\text{W m}^{-1} \text{K}^{-1}$ for fresh fruits and vegetables (above freezing). The *thermal diffusivity* ($\text{m}^2 \text{s}^{-1}$) is defined as the ratio of thermal conductivity to the product of density and specific heat. It relates the ability of material to conduct the heat to its ability to store the heat. Thermal diffusivity may be considered as the rate at which heat propagates (diffuses) through a material. The relationship between the moisture content and the thermal diffusivity is rather not a linear function (in the narrow range of moisture content, however, most commonly linear regression is applied). The thermal diffusivity ranges approximately: for wood: 0.94×10^{-7} – $2.2 \times 10^{-7} \text{m}^2 \text{s}^{-1}$, for seeds and grains: 0.81×10^{-7} – $1.64 \times 10^{-7} \text{m}^2 \text{s}^{-1}$, for fresh fruits and vegetables: 0.78×10^{-7} – $2.69 \times 10^{-7} \text{m}^2 \text{s}^{-1}$. Data for specific heat, thermal conductivity, and thermal diffusivity of plants and agricultural products have been compiled from Mohsenin (1980), Sweat (1992), Pabis et al. (1998), Kaleta (1999), Sablani and Ramaswamy (2003), and Jayas

and Cenkowski (2006). Regression equations for the prediction of these thermal properties can be found in the same bibliography. If the temperature of an object changes due to the heat transfer, then the heat transfer involves a transfer of sensible heat. The exchange of energy that occurs during a change in phase (without a temperature change) is called the latent heat. The *heat of fusion (solidification)* is the heat exchange during the phase change from liquid to solid. *Latent heat of vaporization* is the energy to change a liquid to vapor. The heat of vaporization is about seven times more than the heat of fusion, which is five times more than raising the temperature (sensible heating) by 100 K (Wilhelm et al., 2004). For materials of moisture content below approximately 0.14 d.b., to overcome the attractive forces between the adsorbed water molecules and the internal surfaces of material extra energy is needed in addition to the heat required to change the water from liquid to vapor (Pabis et al., 1998). Plants and agricultural products freeze at lower temperatures than pure water (approximately 269.5–272.8 K) due to the presence of solutes and solids in the water (*freezing point depression*) (Kaleta, 1999). Plants and agricultural products are living organisms and they must consume energy to maintain their life processes. They do this by a process of combustion that burns sugar to produce CO_2 and *heat of respiration*. Heat of respiration depends on product, its maturity, storage time (either an increase or a decrease) and increases exponentially with temperature. High respiration rate causes rapid deterioration in product quality (Mohsenin, 1980; Wilhelm et al., 2004).

Hygroscopic properties

The relation between material moisture content and air humidity is described by the drying equilibrium, which results from the fact that liquid moisture trapped in fine capillaries exerts a vapor pressure lower than that of liquid with a free surface. Drying equilibrium is determined experimentally by allowing sufficiently long contact of the bone dry material with air at a given humidity. Points obtained for various air humidities at the same temperature form the isotherm called the *equilibrium moisture content* (EMC) – equilibrium relative humidity (ERH) relationship (EMC represents the moisture content that the material will attain if dried for an infinite time at a particular relative humidity and temperature). The thermodynamic equilibrium can be obtained by moisture desorption (drying) or adsorption, therefore, the respective isotherm is strictly called either a desorption, or adsorption (Kudra and Strumillo, 1998). Desorption isotherms usually give higher moisture content than adsorption isotherms, which results in a hysteresis loop. The composition of the product, its temperature, storage time, drying temperature, and the number of successive adsorption and desorption affects hysteresis. Typical plants and agricultural products desorption/adsorption isotherms are S-shaped and they may be described by a number (~80) of mathematical relations (most of them are semiempirical or empirical equations with two or three fitting parameters).

The commonly used equations are: the Langmuir, Brunauer–Emmett–Teller (BET), Iglesias–Chirife, the modified Henderson, Chen, Chung–Pfoest, Halsey, Oswin, and Guggenheim–Anderson–de Boer (GAB) (Rizvi, 1992). Constants of selected equations for the isotherm of various grains and seeds are given by Kaleta (1996), Pabis et al. (1998), and Jayas and Cenkowski (2006). The mechanism of moisture movement during the falling rate period of plants and agricultural products drying is mainly by diffusion. This can be described by Fick's law. Water can move in a solid in the form of liquid and/or vapor. The overall (total) *coefficient of water diffusion* is the sum of the liquid and vapor diffusion coefficients. Water diffusivity in solids depends on their temperature, moisture content, and structure. The overall coefficient of water diffusion ($\text{m}^2 \text{s}^{-1}$) is described by a number of semiempirical or empirical equations (Cenkowski and Zhang, 1995; Pabis et al., 1998; Saravacos and Maroulis, 2001). The Arrhenius-type equation to describe the relationship between diffusion coefficient and temperature and exponential relationship between coefficient and moisture content is mostly used. Shrinkage influences the water diffusion coefficient.

Mechanical properties

The coefficient of friction of the plants and agricultural products is necessary in designing of conveying, transporting, and storing structures. The *friction coefficient* is defined as the ratio between the friction force (force due to the resistance of movement) and the normal force on surface of contact (e.g., wall of the silo). Two types of friction coefficients are considered, the *static coefficient* determined by the force capable to initiate the movement and the *dynamic coefficient* determined by the force needed to maintain the movement of products in contact with the surface, which depends on the type and nature of the material in contact. An increase in coefficients of static and dynamic friction for various grains with increase in moisture content (mostly linear) is mostly observed. Both coefficients depend on the product and surface material. The friction coefficient ranges approximately (Mohsenin, 1986; Sablani and Ramaswamy, 2003; Jayas and Cenkowski, 2006): for seeds and grains: 0.11–0.76, for fresh apples and tomatoes: 0.24–0.88, for wood shavings and chopped grass, straw, and hay: 0.20–0.80. The *angle of natural repose* is the angle formed between the element of a cone and the base of piled cone (the angle with the horizontal at which the product will stand when piled). The properties of the particles forming medium (dimensions, shape, surface frictional properties, deformation ability) influence the value of this angle. The angle of repose increases with an increase in moisture content. Its value for grains ranges approximately from 17° to 45° (Mohsenin, 1986; Sablani and Ramaswamy, 2003). The other mechanical properties of plants and agricultural products can be measured by uniaxial compression, uniaxial tension, shear, and bending. The type of loading, preparation of the specimen,

loading rate, strain (deformation) rate, and other factors are dependent upon the product and desired use of the data (details are given by Mohsenin (1986), Cenkowski and Zhang (1995), and Wilhelm et al. (2004)).

Electromagnetic properties

Electromagnetic radiation is transmitted in the form of waves and it can be classified according to wavelength and frequency. The electromagnetic spectrum is very broad (from the shortest cosmic rays to the longest electric waves). Only a few specialized, narrow regions are utilized in plants and agricultural products applications. These include visible light, infrared, and microwave frequencies. When radiation of a specific wavelength strikes an object, it may be reflected, transmitted, or absorbed. The interaction of visible light and matter is referred to as a *color*. Most of the plants and agricultural products are opaque, they do not allow any transmission of light but absorb and/or reflect all the light striking. If all the visible light is absorbed, the object appears black. If all the visible light is reflected, the object appears white. The selective absorption of different amounts of the wavelength in the visible region determines the color of the object because reflected wavelengths are visible to the observer (e.g., green object reflects the green light spectrum but absorbs violet, blue, yellow, orange, and red). The color of a product is affected by the surrounding lighting intensity and wavelength. Thus, the color an observer perceives of an object can be influenced by changing the ambient light. For this reason, optical properties of product are considered as they interact with light. The human perception of color is highly subjective. Therefore, instrumental methods for color measurement have been developed (Munsell, CIE, CIE $L^*a^*b^*$ (CIELAB), Hunter Lab, and Lovibond). The color of an object is measured and represented by spectrophotometric curves, which are plots of fractions of incident light (reflected or transmitted) as a function of wavelength throughout the visible spectrum. Further details about color are given by Wilhelm et al. (2004) and Sahin and Sumnu (2006). In microwave heating, the dielectric properties of interest are the dielectric constant and the dielectric loss factor. *Dielectric constant* is the ability of a material to store microwave energy. *Dielectric loss factor* is the ability of a material to dissipate microwave energy into heat and this parameter is a measure of microwave absorptivity. As microwaves move through the object, the rate of heat generated per unit volume decreases. For materials having a high loss factor, the rate of heat generated decreases rapidly and the penetration depth of energy decreases. *Power penetration depth* (m) is the depth at which power decreases to e^{-1} of its original value. It depends on both dielectric constant and dielectric loss factor. Dielectric properties of plants and agricultural products depend on moisture content, temperature, composition and physical structure of the material, and the frequency of the oven. At low moisture content, variation of dielectric constant

and dielectric loss factor with moisture content is small. The increase in moisture content increases dipolar rotation and therefore both dielectric properties increase. The temperature dependence of dielectric properties depends on the ratio of bound to free moisture content. If the water is in bound form, the dielectric properties increase with increasing temperature. For the free water, the dependence on the temperature is opposite. At frequencies of home type microwave oven and at ambient temperature, the dielectric constant ranges approximately from 45 to 75 and the dielectric loss factor ranges approximately from 15 to 20 for seeds, grains, and fresh fruits and vegetables (Sahin and Sumnu, 2006).

Conclusions

Physical properties describe the unique, characteristic way a plant or agricultural product responds to physical treatments. Knowledge of these properties constitutes important engineering data in design of machines, processes, and controls and it is necessary for determining the efficiency of a machine and an operation and for evaluating the quality of the final product. Much of the data in the literature is of limited value because not enough supporting data are included, such as detailed product description, temperature, and error in measurement. The product description should include the cultivar, moisture content, maturity, and any pretreatment. Details of the experiment should include sample size, surface conditions, porosity, fiber orientation, sampling procedure, and process variables. The description should provide sufficient detail so that the reader can duplicate exactly the entire experiment. Insufficient description of product and process variables causes very often that data taken from several published sources differ a lot.

Data on physical properties of plants and agricultural products are scattered in an enormous number of scientific papers. Therefore, there is an urgent need to set all the data in order. This may enable some kind of systematization and generalization. Up to now, such extensive, well elaborated databases on all physical properties of plants and agricultural products do not exist and therefore the most important data available in the literature have been summarized in this contribution to give a good start point for such a database for future.

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Cross-references

Dielectric Properties of Agricultural Products
 Electrical Properties of Agricultural Products
 Fruits, Mechanical Properties and Bruise Susceptibility
 Grains, Aerodynamic and Geometric Features
 Modeling the Thermal Conductivity of Frozen Foods
 Physical Properties as Indicators of Food Quality
 Physical Properties of Raw Materials and Agricultural Products
 Rheology in Agricultural Products and Foods
 Shrinkage and Swelling Phenomena in Agricultural Products
 Water Effects on Physical Properties of Raw Materials and Foods

DATABASES OF SOIL PHYSICAL AND HYDRAULIC PROPERTIES

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Definition

In this chapter, we review databases of international interest that contain significant quality and quantity of soil physical and hydraulic information – with a special emphasis given to soil hydraulic properties.

Introduction

Soil–plant–atmosphere modeling, weather and climate prediction, erosion modeling, and nutrient management advisory are examples for studies that require knowledge of soil physical and hydraulic properties. However, many such properties are costly and tedious to measure both in the field and in the laboratory. For this reason, the number of samples for which soil physical properties are determined in a particular laboratory or institute is usually limited. It has been recognized that collecting such fragmented data into larger databases can benefit all contributors and beyond. By establishing larger, national, or international scale databases, access to larger quantity and variety of data is facilitated; a wider range of methods can be examined and compared, and the user can derive conclusions that may be more widely applicable. In this chapter, the history, structure, contents, and availability of international databases of soil physical and hydraulic properties are summarized; certain data standardization issues are discussed; and a few challenges and database limitations are highlighted.

History of soil physical and hydraulic databases

Storage and retrieval of soil physical data developed with the advances made in (computerized) storage of information; first ASCII files replaced laboratory notebooks, but spreadsheets soon followed. Searchable relational database programs are the platform of choice today for modern databases.

For some countries, data collections at the national or regional scales have existed for decades. Examples for data collections of soil physical properties in particular countries, of which extensive research has been reported, include the databases of Australia (McKenzie et al., 2008), Belgium (Vereecken et al., 1989; Cornelis et al., 2001), Brazil (e.g., Tomasella et al., 2000, 2003), France (Bruand et al., 2004), Germany (Horn et al., 1991; Krahmer et al., 1995), Hungary (Rajkai et al., 1981; Nemes, 2002), the Netherlands (Wösten et al., 2001), Poland (Gliński et al., 1991), and the USA (Rawls et al., 1982; Soil Survey Staff, 1997). Some of these data collections, however, represent only certain region(s) of the listed countries.

Upon recognition of the strengths of and need for combining available data, some data collections were formed by individual scientists following an extensive literature search for the desired data (e.g., Rawls et al., 1982, 1998). Other data collections were formed by an open call and volunteered data by scientists from various parts of the World. The resulting Unsaturated Soil Hydraulic Database (UNSODA) (Leij et al., 1996) and Grenoble Catalogue of Soils (GRIZZLY) (Haverkamp et al., 1998) were the first two truly international soil hydraulic databases. Different funding agencies also recognized the need for joint efforts and provided funds to support collection and analyses of data of different contributors (e.g., Hydraulic Properties of European Soils (HYPRES), Wösten et al., 1999). The International Soil Reference and Information Centre

(ISRIC) has assembled two databases that contain soil hydraulic properties and that are of international use. At the request of the Global Soil Data Task (GSDT) of the Data and Information System of the International Geosphere Biosphere Programme (IGBP-DIS), ISRIC prepared a uniform soil data set for the development of pedotransfer functions, which we will call the IGBP-DIS database (Tempel et al., 1996). Staff at ISRIC has also made available different versions of a global soil profile database that was developed in the framework of a project entitled “World Inventory of Soil Emission Potentials” (WISE, Batjes, 2002a, b, 2008). The WISE and IGBP-DIS databases contain, among many other attributes, soil physical and hydraulic data that originate from other independent international data sources like the Food and Agriculture Organization (FAO) (Food and Agriculture Organization, 1989) and the ISRIC Soil Information System. However, the majority of the IGBP-DIS database, and a lesser part of the WISE database originate from the National Soil Survey Characterization database (NSSC) of the U.S. Department of Agriculture Natural Resources Conservation Service (USDA-NRCS) (Soil Survey Staff, 1997) that holds data primarily of U.S. soils. While the NRCS-NSSC database is mostly a national scale database for the USA, it is discussed together with the above international databases due to its sheer size (>100,000 samples), the wide variety of soil types it covers, and the variety of measured and derived data that are available. Despite being a U.S. national database, the NRCS-NSSC database still includes a limited amount of data from other countries.

It is commonly seen that tropical countries, emerging market countries, and newly industrialized countries are underrepresented either in such international databases or only limited amount of detailed soil physical and hydraulic data are available for them – with only a few countries as exceptions. This has been recognized by several authors (e.g., Nemes et al., 2001; Batjes, 2002a) and some of the implications have been discussed by Tomasella et al. (2003) or De Condappa et al. (2008). Differences in environmental factors that influence soil development are such between the tropical and temperate climate zones that conclusions resulting from soils research may not always be applicable across climate zones. However, projects are increasingly being initiated to expand knowledge on soil hydraulic characteristics of soils in tropical and subtropical countries. The Soil Physics Research Unit of the University of Ghent, for example, is in collaboration with several local scientists to assemble data collections for Chile, Congo, Kenya, Syria, and Tanzania and aims to extend such collaboration to additional countries (Dr. W. Cornelis, 2009, personal communication). Similar projects are in progress – or data collections exist – in Burundi (Bagarello et al., 2009), Cuba (Dr. M.E. Ruiz Perez, 2009, personal communication) or Iran (B. Ghanbarian, 2009, personal communication).

The WISE and IGBP-DIS databases also contain data for tropical and subtropical countries. The amount and detail of physical and hydraulic properties for these soils

vary greatly, but WISE (version 1.1) has such data for ~1,000 soil horizons from 17 countries and IGBP-DIS contains such data for ~900 horizons from 24 countries. India, Israel, China, Brazil, Peru, Botswana, Indonesia, Thailand, Turkey, Columbia, Cuba, and Kenya are best represented in one or both of these two databases. Upgraded versions of WISE (versions 2.1 and 3.1) tend to contain soil hydraulic data for more samples from tropical and subtropical countries; however, information on the water retention curve is limited to fewer points.

In many cases, however, data collected by different scientists or institutions remain fragmented. For example, large amounts of soil physical data have already been collected in Iran, but the data appear to remain stored and utilized by individual research groups locally (B. Ghanbarian, 2009, personal communication). The situation appears to be similar in Indonesia as well (Suprayogo et al., 2003); but this phenomenon is not unique for these countries.

Database structure, contents, and limitations

International databases of soil physical and hydraulic properties typically comprise of multiple interconnected tables, linked by identifiers that are either a unique number or a unique combination of information on the sampled location, and the soil horizon/layer. The complexity of the cited databases differs greatly. Some database properties, advantages, and disadvantages are listed in Table 1.

The range of properties that they cover varies; some of the databases are rich in information about the environment of the sampled location, the methodology used at sampling and measurements, while others contain less information. Some of the databases contain measurements of the same property or characteristic measured under different conditions. Examples are the NRCS-NSSC database with some properties determined under different conditions (e.g., bulk density of oven dried soil vs. wet soil at – 33 kPa pressure) or calculated for different fractions of the soil; or the UNSODA database in which hydraulic characteristics are determined for many samples under both wetting and drying conditions and/or in situ (field) or in the laboratory. The location of the reported soils may or may not be spatially referenced, it varies from database to database. The UNSODA database, for example, is not spatially referenced, while the HYPRES database contains the originally available spatial coordinates for most samples. It is also of concern what areas and types of soil the databases actually represent. Users of databases often equate the represented area or soil types with the named source area (e.g., HYPRES – European, Rawls et al. (1982) – U.S.). However, inhomogeneity is often seen in databases in terms of geographical distribution or the representation of soil types, which both can have potentially significant consequences (cf. Nemes et al., 2009). Local experimental preferences can also bring, for example, textural or geographical imbalances to databases. One such example is cited by Nemes et al. (2009): fine-textured salt-affected soils are typically

Databases of Soil Physical and Hydraulic Properties, Table 1 Selected characteristics of international soil physical and hydraulic databases

	UNSODA	GRIZZLY	NRCS-NSSC	HYPRES	IGBP-DIS	WISE (version 3.1)
Reference	Leij et al., 1996, Nemes et al., 2001	Haverkamp et al., 1998	Soil Survey Staff, 1997	Wösten et al., 1999	Tempel et al., 1996	Batjes, 2008
Approx. database size	790	660	>100,000	5,521	>100,000	>48,000
Number of tables	36	4	23 (varies with issuance)	6	1	7
Resource area	Worldwide	Mostly Europe, USA	Mostly USA	Europe (West)	Worldwide	Worldwide
Tropical soils	Very few	Very few	Few	No	Yes	Yes
Methodology	Mixed	Mixed	Uniform	Mixed	Mixed	Mixed
Water retention $\theta(h)$	Yes	Yes	Yes (limited points)	Yes	Yes	Yes
Saturated conductivity $[K(s)]$	Yes	Some	No	Yes	No	No (some in version 1.1)
Unsaturated conductivity $[K(\theta)]$	Yes	Some	No	Yes	No	No
Field soil hydraulic data	Yes	No	No	No	No	No
Availability of database	Free	Free	Free	Limited	Free	Free
Strength	Field hydraulic data available	Detailed $\theta(h)$ data	Database size, uniform methodology	Most $K(s)$ and $K(\theta)$	Tropical data	Tropical data
Weakness	Database size	Database size, ease of availability	Limited $q(h)$ points, no $K(s)$, $K(\theta)$	Limited access/availability	Limited $\theta(h)$ points, no $K(s)$, $K(\theta)$	Limited $\theta(h)$ points, no $K(s)$, $K(\theta)$
Notes	Built-in reporting with graphics	Three countries and one U.S. state dominate	Different measurement conditions exist	Sample geographic distribution varies	Includes much of NRCS-NSSC	Earlier versions stored $\theta(h)$ at more pressures

overrepresented in Hungarian data collections due to special interest by generations of scientists, despite the fact that such soils represent only a fraction of the area of Hungary.

In terms of hydraulic properties, the range and detail of data that each international database covers varies. The NRCS-NSSC database is the largest original data collection that contains soil hydraulic data. Those are, however, typically limited to two or three water retention points (-10 , -33 , and $-1,500$ kPa) and no hydraulic conductivity data is available. For some of the samples more water retention points exist. On the contrary, the UNSODA and HYPRES databases contain, for most soils, water retention measured at least at 4–8 pressures. More than half the samples in HYPRES and UNSODA also have information on saturated hydraulic conductivity – and fewer on unsaturated hydraulic conductivity. Since most of the soils in IGBP-DIS and some in WISE originate from the NRCS-NSSC database, the availability of water retention data resembles that of NRCS-NSSC. However, a significant portion of the non-U.S. soils in these two databases has four to eight points of the water retention curve measured and available. WISE (version 3.1) contains water retention data at only 3 pressures; which are standard pressures, however. The HYPRES database appears to be the largest international collection of detailed soil water retention and hydraulic conductivity measurements on undisturbed samples. The availability of field measurements of soil hydraulic properties is typically very limited; the UNSODA database holds probably the only substantial collection of field measured soil hydraulic data. Users of the original measured data need to be aware that replicate measurements are often stored for the soil samples.

Data compatibility and standardization

All the listed international databases of soil physical properties are being frequently used in transnational research. Due to the history of international data collections and the existence of various measurement methods and standards worldwide, compatibility of data between databases has always been a concern. Often, even within a database it is of concern. In the simplest cases, conversion is simply a matter of unit conversions (e.g., K(s) expressed in cm/day or in mm/h); in other cases, it requires the use of an empirically developed conversion factor to achieve compatibility (e.g., organic carbon vs. organic matter content). A more difficult task is to convert information that is based on, for example, a complex set of criteria (e.g., national soil classification into World Reference Base for Soil Resources (WRB) or Soil Taxonomy classifications). The availability of multiple methods that seemingly determine the same property warrants that the measurement results are often difficult to compare. Often such methods (1) apply different sampling techniques (e.g., disturbed or undisturbed sample; soil core or soil clod); (2) are used under different environmental conditions (field or

laboratory measurements; different states of wetness at measurement); or (3) are based on entirely different theoretical backgrounds (e.g., soil particle-size measurements by pipette/hydrometer methods vs. the laser diffraction method). Even if the same measurement technique is used, the use of different standards in different countries or laboratories can make data conversion a daunting task, as witnessed by, for example, the rich literature on converting and/or standardizing particle-size distribution (e.g., Nemes and Rawls, 2004 and therein).

Standardization of data has been handled differently in the different international databases. In the NSSC database, standardization took place at the measurement level, since measurements were typically taken according to one set of standards (Soil Survey Staff, 2004). In other cases, data have been assembled from various sources and have either been standardized by the managers of the database (HYPRES, Wösten et al., 1999; Nemes et al., 1999) or such standardization has not taken place (UNSODA, WISE, IGBP-DIS). However, in HYPRES, the original data format and description has also been conserved to allow any future reassessment or reclassification of the data. Documentation of the original data source(s) and of the actual database should be consulted carefully for a better understanding of applied data standards.

Water retention and hydraulic conductivity data that originate from different countries/institutions were typically not measured at standard pressure values. Some projects require that such data are standardized (e.g., Wösten et al., 1999). Their standardization usually takes place by applying one of the continuous water retention and hydraulic conductivity models, most frequently the coupled Mualem–van Genuchten model (Mualem, 1976; van Genuchten, 1980). When any such standardized data are used, it needs to be considered that even such advanced equations do not always fit perfectly to the measured data.

Database availability

While their documentation is publicly available, availability of data of some of the listed databases is limited by license agreements or the need for an agreement with the author(s) or owners (e.g., Rawls et al., 1982 data; HYPRES). Others are free to obtain from the authors or are readily available online for running queries or downloading data (e.g., GRIZZLY; NRCS-NSSC, <http://ssldata.nrcs.usda.gov/>; UNSODA, <http://www.ars.usda.gov/Services/docs.htm?docid=8967>; WISE, <http://www.isric.org/>; IGBP-DIS, <http://www.isric.org/>). Regardless of which data source is being used, source organizations require the user to cite the source of data in their works.

Additional challenges, future needs

Existing databases provide invaluable information to many environment-related studies, but future data collections should address particular needs in order to advance further. One of the concerns is of course the completeness

of data sets. While additional properties of historic data are unlikely to be recovered, new data collections should put emphasis on completeness in terms of frequently used information. This does not only cover laboratory measurements but also information collected in the field upon profile description and sampling.

With the emergence of global positioning devices, spatial referencing should present only a small challenge in the future. Knowing the spatial location of sampled profiles will help in improving the accuracy of new maps. Improving the distribution of samples in sparsely sampled areas could also help in drawing more reliable conclusions for many areas. Hence, related studies that visit and explore previously un-surveyed areas are strongly encouraged. Along with the spatial expansion, a temporal expansion should also be explored. It is known that some soil properties change temporally on a human timescale; sometimes even within days or weeks (e.g., by tillage practices). Often there is an annual cycle involved. Such changes are typically seen in cultivated areas and in areas with cyclic freeze–thaw conditions. A one-time measurement will not represent local conditions well throughout the year. So far, only a limited number of studies explored such variable soil hydraulic conditions via periodic sampling of the same soils. Many modeling-based studies rely on information from large databases, and such temporally variable properties are not currently represented in such databases. Measurement and documentation of temporally variable soil physical and hydraulic properties is encouraged.

Structural development influences the physical behavior of the soil through influencing the characteristics of the void space. Therefore, information on soil structure should be logged for the benefit of future users. Characterization of the void space in soils using modern imaging techniques is also gaining popularity. Once these techniques will become more affordable and more widely applicable, such information could be stored along with other soil physical data. Knowing the architecture of void space in the soil is essential in advancing our knowledge about solute transport; but such knowledge has long been only inferred indirectly from the characteristics of the solid phase of soils.

It has been recognized in the past that while laboratory measurements give us an understanding of characteristics and processes in the soil, they do not always provide full and unbiased information about soil conditions in the field. Hence, studies that involve in situ measurements are of special interest, since they may provide more insight into true field conditions and our understanding about the differences in field and laboratory conditions. It has also been recognized that the use of different techniques to determine a particular property or characteristic can pose a challenge while forming conclusions from such data. However, it also provides a great opportunity to examine differences among such techniques and to explore pathways and interpretations between them.

Hence, documentation on how data were collected should always be passed along with the data itself.

Summary and conclusions

We attempted to give a summary of significant – primarily international – sources of soil physical and hydraulic data. Historic soil physical and hydraulic data are being used in a variety of ways worldwide. Their advanced, well-documented, and searchable storage and management is therefore essential for the success of future applications. Though soil hydraulic properties are time consuming to measure, decades of research yielded a wealth of such information that are stored in national/provincial and international databases. The presented databases differ in their source area, extent, structure, applied methodology, level of detail, and in many additional factors. Completeness of data records is also a great challenge; and so is an equal representation of different areas and soil types. Regardless, whether used alone or combined with other data sources such data collections present great opportunities and an invaluable resource for many researchers, educators, practitioners, and policy makers worldwide. Use of these and other databases however, requires caution; interpretations and conclusions have to be drawn with care.

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Cross-references

[Aeration of Soils and Plants](#)
[Bulk Density of Soils and Impact on Their Hydraulic Properties](#)
[Coupled Heat and Water Transfer in Soil](#)
[Field Water Capacity](#)
[Hydraulic Properties of Unsaturated Soils](#)
[Hydropedological Processes in Soils](#)
[Hysteresis in Soil](#)
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[Water Budget in Soil](#)
[Water Use Efficiency in Agriculture: Opportunities for Improvement](#)

DEFLATION

A process of wind erosion, by which the loose top layer of the soil is blown away, generally following the denudation and pulverization of the soil in arid regions.

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Wind Erosion

DEFLOCCULATION

The inverse of flocculation. At low ionic strength of soil solution and domination of alkali metal cations, especially at higher pH values, soil colloidal particles can be dispersed.

Cross-references

Conditioners, Effect on Soil Physical Properties
Flocculation and Dispersion Phenomena in Soils

DEGRADATION OF SOIL

The deterioration of soil productivity by such processes as erosion, organic matter depletion, leaching of nutrients, compaction, breakdown of aggregates, waterlogging, and/or salination.

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Cross-references

Physical Degradation of Soils, Risks and Threats
Soil Physical Degradation: Assessment with the Use of Remote Sensing and GIS

DENITRIFICATION

Reduction of nitrogen oxides (usually nitrate and nitrite) to molecular nitrogen or nitrogen oxides with a lower oxidation state of nitrogen by bacteria activity (denitrification) or by chemical reaction involving nitrite (chemodenitrification). Nitrogen oxides are used by

bacteria as terminal electron acceptors in place of oxygen in anaerobic or microaerobic respiratory metabolism.

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Cross-references

Greenhouse Gas Fluxes: Effects of Physical Conditions
Greenhouse Gases Sink in Soils
Oxidation-Reduction Reactions in the Environment

DENSITY

See *Bulk Density of Soils and Impact on their Hydraulic Properties*

DESERTIFICATION: INDICATORS AND THRESHOLDS

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Synonyms

Land degradation; Soil degradation

Definition

Desertification is a process by which susceptible areas lose their productive capacity. Desertification means land degradation in arid, semiarid and dry subhumid areas resulting from various factors, including climatic variations and human activities. While land degradation occurs everywhere, it is only defined as “desertification” when it occurs in dry lands.

Introduction

Land degradation and desertification is a paramount international problem, and indicators have been developed to follow it (Doran and Parkin, 1996; Middleton et al., 1997; Dregne, 1986). Many are based on plant communities, or soil loss or salinity.

However, indicators they tend to monitor the status quo over large time periods and are more suitable for crisis assessment than for risk prevention. They are also poorly suited for the sensitive monitoring of the success of remediation efforts.

Therefore, the UN Convention to Combat Desertification (UNCCD) and other organizations have emphasized the continuing need for indicator development based on the mechanisms of land degradation, which are known and have been the object of many studies. In view of

global change, such indicators are especially needed. Changes will often be slow and subtle. An early warning system is required to indicate the need for countermeasures, while they are still economical.

In response to this need, INDEX (acronym for Indicators and Thresholds for Desertification, Soil Quality, and Remediation), a specific targeted research project (STREP) dealing with “Research on mechanisms of desertification and soil quality” was initiated and carried out within the Sixth Framework of the European Commission.

Indicator development: a methodological outline

Indicators for desertification can be applied at different spatial and temporal scales (Figure 1). The goal within INDEX was to investigate the possibility of developing indicators, which reflect ecological quality at the soil level rather than at the more traditional field and catchment levels.

The indicator development was attained in five steps, which narrowed down an initial list of 100 soil parameters to finally three indices, using the following procedure:

1. Analysis of a broad range of parameters on various degraded soils
2. Testing the parameters on a variation of pressure levels
3. Temporal and spatial verification
4. Practical aspects of parameter application as an indicator
5. Combining the remaining parameters into indices using factorial analysis.

Step 1: Tested soil parameters included

- Soil microbiological parameters (bulk functions such as microbial biomass carbon and soil respiration, as well as enzymatic activities and molecular biological parameters)
- Humus parameters (bulk humus, humo-enzymes, and available humus)
- Physical parameters (such as particle size stability, hydraulic parameters, and pore size distribution)

A complete list of all performed analysis is given in [Appendix A](#).

Step 2: The testing was performed on soils from sites across Europe (listed in [Appendix B](#)), where a variation of influencing factors (“pressures” according to the European Environmental Agency’s DPSIR concept – see [Figure 2](#)) related to soil deterioration and desertification could be observed either because of a natural variation along a catena or because of different experimental treatments. The following types of pressures were taken into consideration:

Type I: lack of vegetation as the result of desertification processes

Type II: soil erosion

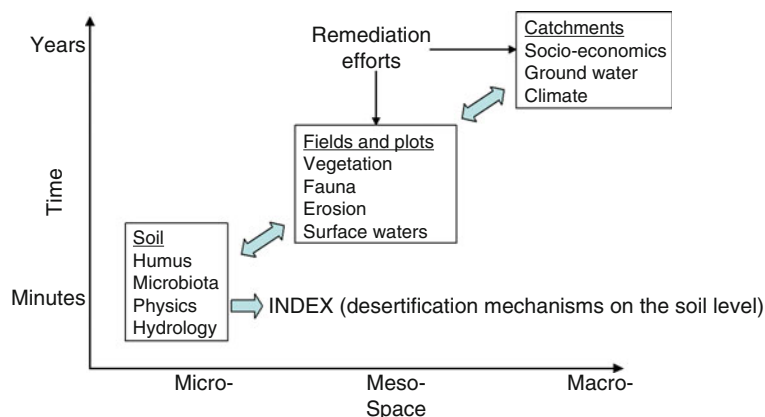
Type III: agricultural management

Only those soil parameters were selected as potential indicators, which reacted logically according to a change of the pressure level.

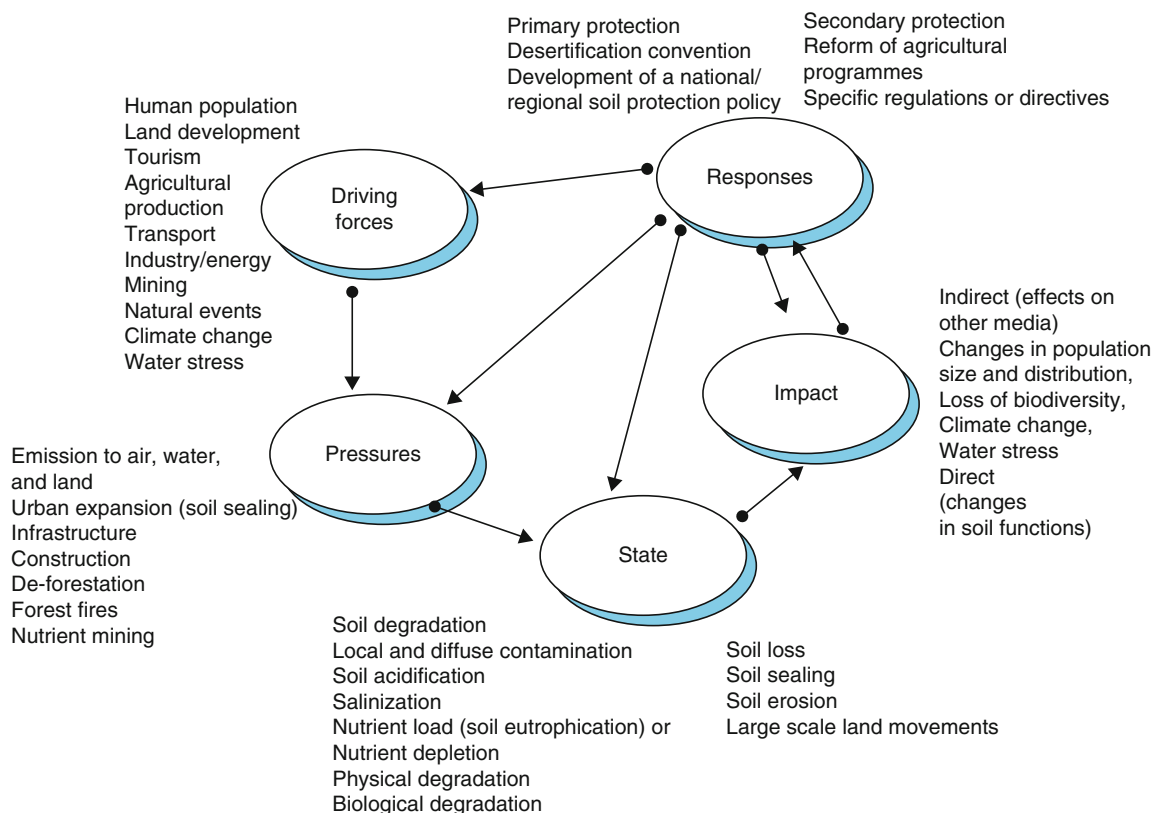
Step 3: Only those parameters, which gave reproducible results from subsequently taken soil samples over the period of 1½ years and on verification sites, which have not been used for *step 2* were considered sufficiently robust and were retained.

Step 4: This was used to eliminate such parameters, which caused experimental difficulties or required very complicated analytical procedures. [Table 1](#) shows the remaining parameters after *step 4*.

Step 5: This step combined these parameters ([Table 1](#)) to three indices (one for each pressure type), applying a factor analysis for *type I* and *type III* sites in order to reduce dimensionality. For pressure *type II*, a single parameter remained from *step 4*, so no factor analysis was required. At sites of *type I* the first factor accounted for 65–92% of the variation according to the sampling site and date. In most cases, however, only one factor was extracted, and this was used as the appropriate index. At sites of *type III* only one factor was extracted, which explained 57–99% of the variation according to the site and the sampling date.



Desertification: Indicators and Thresholds, Figure 1 The various temporal and spatial scales of possible indicators of soil quality.



Desertification: Indicators and Thresholds, Figure 2 The European Environmental Agency's (EEA's) DPSIR concept as applied to soil degradation processes. Indicators as investigated in the Indicators and Thresholds for Desertification, Soil Quality, and Remediation (INDEX) project reflect the soil state and pressure state relationships.

Desertification: Indicators and Thresholds, Table 1 Selected soil parameters according to pressure type

I: Lack of vegetation as the result of desertification processes	II: Soil erosion	III: Agricultural management
Basal respiration	% particles <0.01 mm in pyrophosphate	β -Glucosidase activity
Microbial biomass carbon		Urease activity
ATP		
Basic phosphatase activity		
Proteins		
β -Glucosidase activity		
Fluorescence efficiency		

A brief explanation on selected parameters

Microbial biomass carbon. This indicates the amount of living microorganisms in soil and reacts to soil degradation processes (Smith et al., 1993; Garcia et al., 2002). It is determined by a fumigation-extraction procedure (Sims and Haby, 1971).

Basal respiration in soil. This parameter indicates the activity of heterotrophic microorganisms and was frequently used to indicate the biological state of soils

(Nannipieri et al., 1990; Pascual et al., 2000). The basal respiration was determined for incubated samples by measuring CO_2 release with a CO_2 IR detector.

ATP. Adenosine triphosphate (ATP) is used by living organisms as a transmitter of energy. It therefore indicates microbial activity on a general level. ATP was extracted by a method described by Webster et al. (1984).

Proteins. Water-soluble proteins (albumin was measured as a representative) are an important labile N-source for living organisms. They were determined according to Lerch et al. (1992).

Urease activity. Under the umbrella term "urease," we include all those hydrolases capable of acting on the C–N (non-peptide) bonds of lineal amides. They are exocellular enzymes of a basically microbial origin, as has been demonstrated by several researchers (Ceccanti and Garcia, 1994).

Phosphatase activity. The agronomic and biotechnological importance of phosphatase is that it activates the transformation of organic into inorganic phosphorous, thus making it available to plants. The phosphatase detected in acid soils is normally acidic, while in basic soils it is usually alkaline (Dick and Tabatabai, 1993).

Glucosidase activity. Glucosidase is an enzyme acting the hydrolysis of the glucosidase bonds of the long

carbohydrate chains. The hydrolysis of these substrates play an important role in the microorganisms' attainment of energy from the soil and has shown to perform as a biomarker for degradation processes (Pascual et al., 2000).

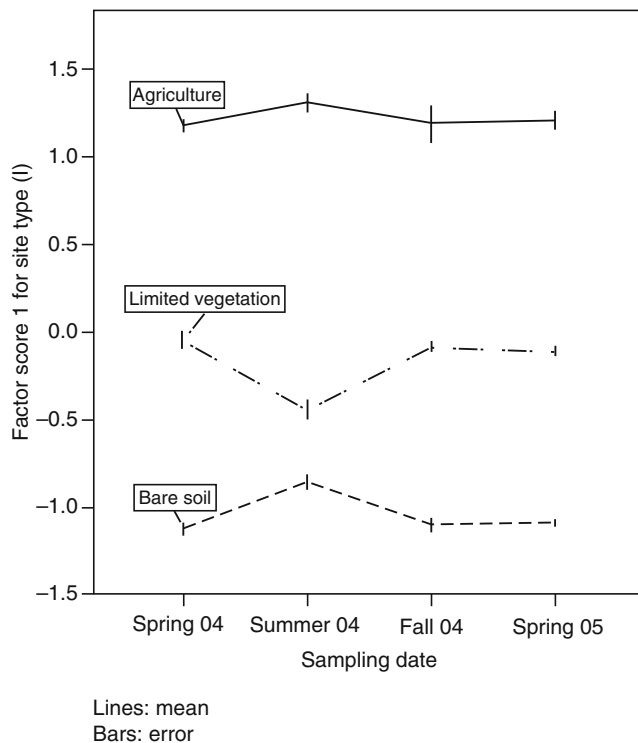
Fluorescence efficiency. Mobile humus in the humus fraction will react more sensitively than other components such as the humic acids. It is also known as dissolved organic matter (DOM) and is a poorly defined pool of compounds, which are available for biogeochemical processes (Zsolnay, 2003). One simple way to obtain it is by aqueous extractions. Its organic carbon content can be quantified, and qualitatively characterized with its UV absorption and fluorescence emission spectra. An interesting parameter is the fluorescence efficiency, which is proportional to the quantum yield (Ewald et al., 1988).

Applications of the indices

Sites with a lack of vegetation as the result of desertification processes (site *type I*)

Figure 3 gives an example from the Puch experimental site (Germany), where the highest values were found at the agricultural plot, the lowest values at the bare soil and the plot with limited vegetation in between. Although the variation of vegetation has been induced artificially at this site, the index developed gives a clear pattern showing how the soil quality reflects the differences in plant cover.

Very similar results were obtained at various catenae in Spain. Figure 4 gives an example of the application of the



Desertification: Indicators and Thresholds,
Figure 3 Differentiation of treatments at Puch by the first factor.

first factor to the Santomera catena: highest values were found at the forest site, lowest at the bare site, while the site with shrub had values in between them.

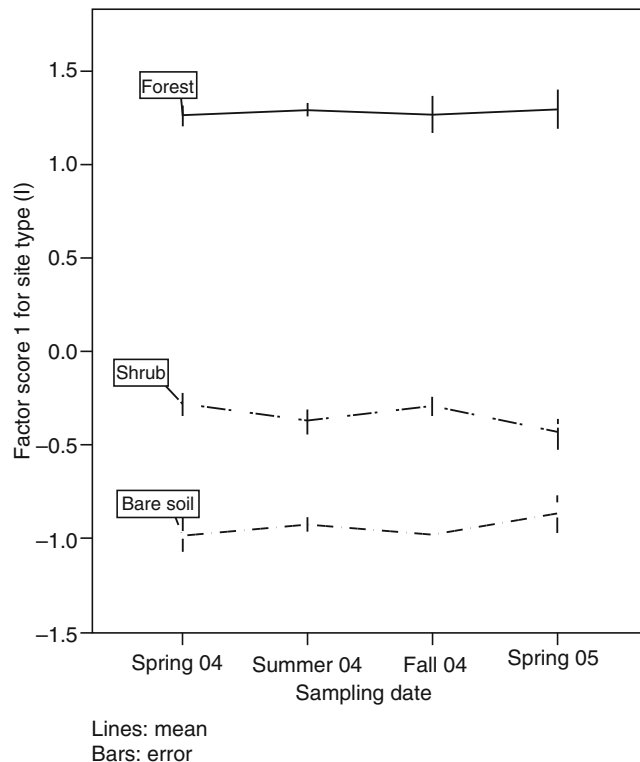
At the Carcavo catena (Spain) the index differentiated between (1) a revegetated site, (2) an abandoned site with natural vegetation, and (3) a degraded soil located in a very barren part of that landscape. Furthermore, the effect of exposition could clearly be seen. The indicator showed that the soil from a north slope had distinctly higher values than that from a south slope. Figure 5 displays the first factor scores for this site.

Sites with soil erosion (*type II*)

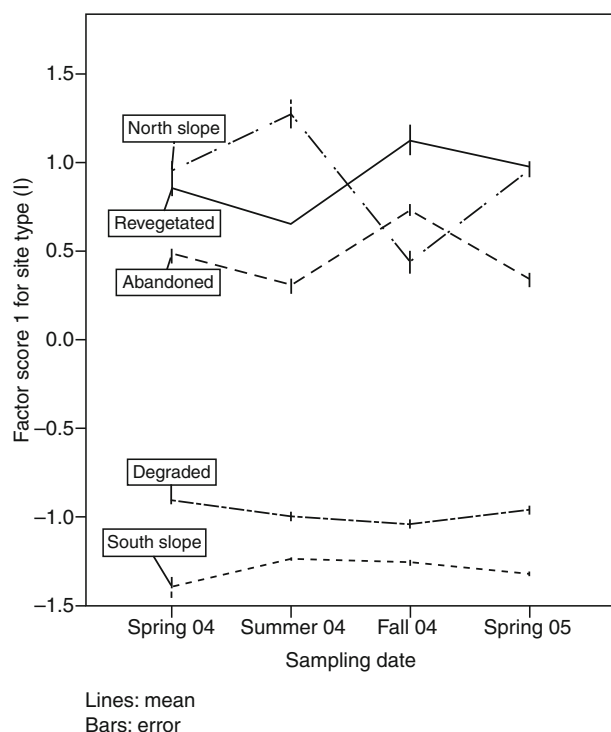
Figure 6 illustrates the application of the indicator to a catena near Gödöllő (Hungary). At sites of *type II*, soil erosion is not linked to a major variation of plant cover. At the Gödöllő catena, all three locations have been used for agriculture. As the indicator was only measured once in 2004 and in 2005, time series were not possible, but Figure 6 displays box plots of the values obtained during the 2 years.

Sites with different types of agriculture (*type III*)

The type of agriculture (organic vs. conventional) was clearly distinguished at the soil level by the applied indicator. Figure 7 shows the results for the sites in Tuscany (Italy) as an example.

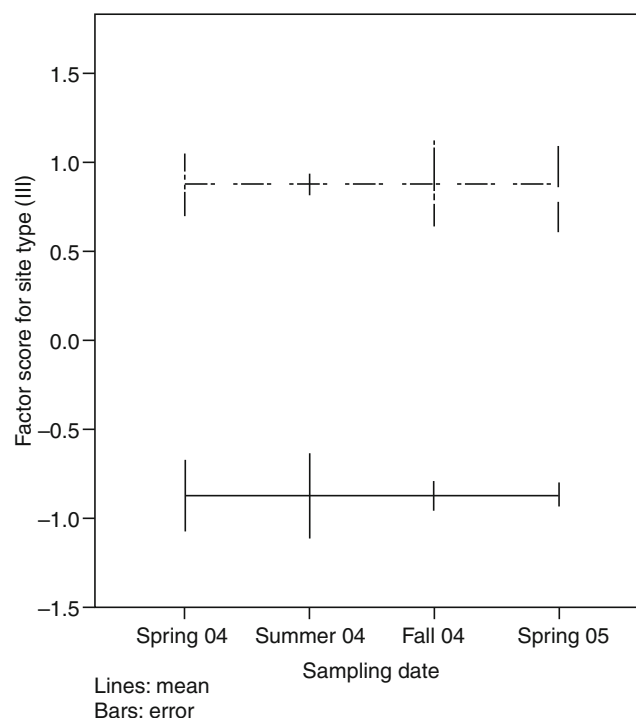


Desertification: Indicators and Thresholds,
Figure 4 Differentiation of different vegetation types along the Santomera catena by the first factor.



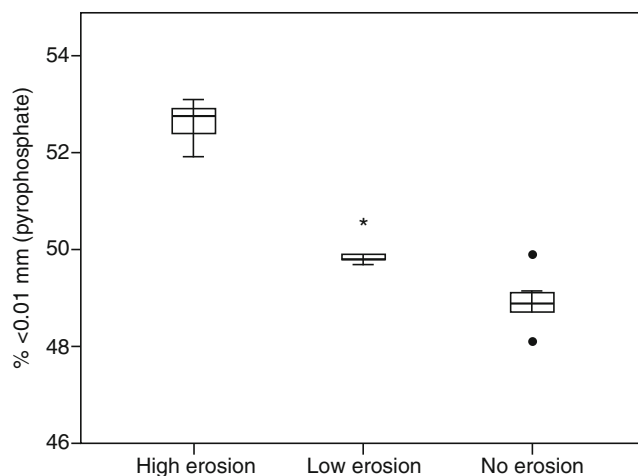
Desertification: Indicators and Thresholds,

Figure 5 Differentiation of sites along the Carcavo catena by the first factor.



Desertification: Indicators and Thresholds,

Figure 7 Differentiation of organic farming and conventional agriculture at sites in Tuscany.



Desertification: Indicators and Thresholds,

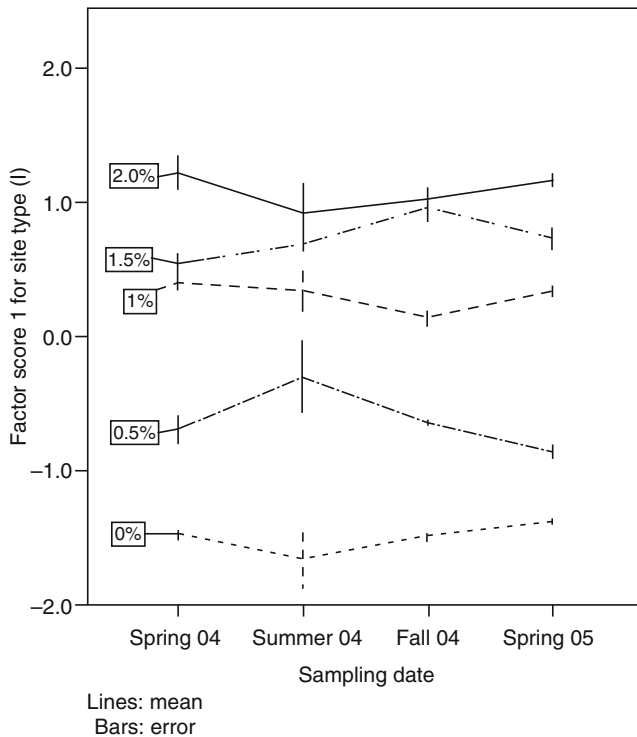
Figure 6 Differentiation of soils with different degrees of soil erosion along a Catena near Gödöllő.

Effects of soil remediation

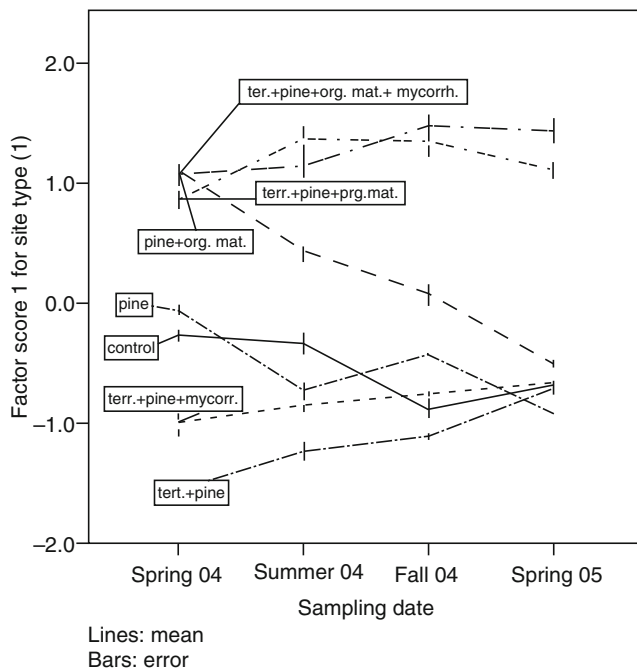
The index developed for sites where desertification was linked to the density of vegetation (sites of *type I*), proved to be very suitable for monitoring the effects of soil remediation. In the case of the Abanilla experimental site,

different amounts of organic matter (municipal solid waste) were added 18 years ago (percentages in [Figure 8](#) give the quantities incorporated into the upper 15 cm of the soil). No further remediation action has taken place since. The application of the index leads to the conclusion that an addition of up to 1.5% of organic matter had a strong lasting effect. However, a further increase of organic matter addition did not cause additional major soil improvements over a long time period and could therefore be avoided for economical reasons.

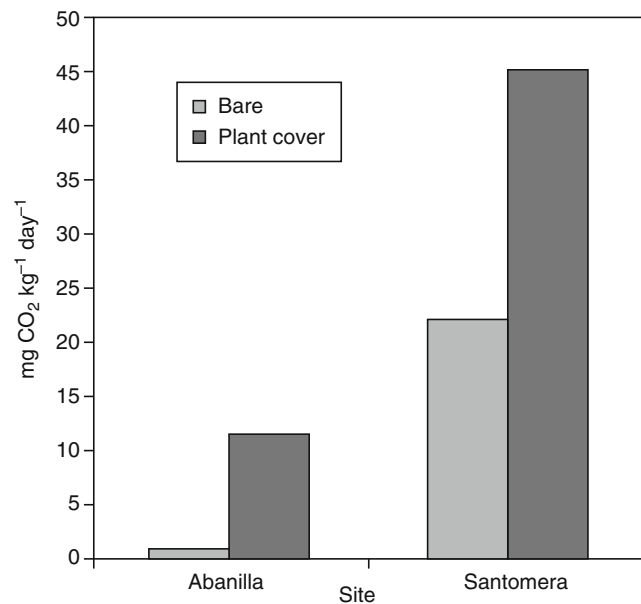
At the Aguilucho experimental site, the effects of reforestation, terracing, application of mycorrhiza, and the addition of organic matter have been tested in various combinations. The index shows ([Figure 9](#)), that only the combination of reforestation (pine), organic matter addition, and terracing had a lasting effect. Terracing and reforestation alone or together did not yield better results than the control, indicating the need for organic matter addition. However, without terracing, organic matter addition and reforestation did not have a positive effect. This inference may be attributed to erosion effects on the steep terrain, which are prevented by the terraces, which also improve water retention. Addition of mycorrhiza had no major effect as compared to treatments with no mycorrhiza. Again, this example demonstrates that the index is a sensitive tool to monitor if and how soil quality is improved by remediation measures in a region with a threat of desertification.



Desertification: Indicators and Thresholds, Figure 8 Effect of different levels of organic matter addition on the soil index at Abanilla experimental site.



Desertification: Indicators and Thresholds, Figure 9 Effect of reforestation, organic matter addition, mycorrhiza application, and terracing on the soil index at Aguilucho experimental site.



Desertification: Indicators and Thresholds, Figure 10 Soil respiration increases with plant cover density. Bare soils at one site, however, may have higher values than locations with plant cover at another.

Limitations

A universal approach comparing soil degradation across all sites was not tenable. Figure 10 gives an example: soil respiration values increased with plant density at each site, but for example, the bare location at Santomera had higher respiration values than the location with high plant coverage at Abanilla, which is only a few kilometers away.

For this same reason, no universal thresholds for the indices here can be established, but measurements have to be made relative to those local reference plots. In case of a soil remediation, this would imply for instance that the success of any remediation has to be proven against control plots. If the degree of soil degradation or desertification needs to be monitored, the index may be used for indicating different degrees of degradation along a catena or within a landscape. It can also be used to follow temporal changes at a given location.

Summary

The developed indices are well suited to indicate differences of soil degradation as related to desertification processes and the effects of remediation. They are sensitive and react quickly to changes in soil management. Although they are relatively robust to seasonal influences, repeated measurements in time are recommended. Fortunately, the indices are relatively inexpensive and can be done without great effort. Threshold values, however, need to be deduced from local reference sites, as the indices only work on a relative scale.

Acknowledgment

The following institutions participated in the described research: GSF (Helmholtz Zentrum München), CSIC – Consejo Superior de Investigaciones Científicas, I.S.E. – Consiglio Nazionale delle Ricerche, University of Szeged, Szent Istvan University, University of Warwick, wpa Beratende Ingenieure GmbH.

Appendix A: List of tested parameters

Microbial parameters

Total organic carbon, humic substances, carbon, water-soluble carbohydrates, proteins, biomass carbon, accumulative respiration, basal respiration, $q\text{CO}_2$, ATP, dehydrogenase activity, urease activity, BAA protease activity, β -glucosidase activity, basic phosphatase activity, Shannon–Weaver index of diversity.

Humus parameters

Bulk: Total organic carbon, total inorganic carbon, total pyrophosphate extractable carbon, total pyrophosphate extractable carbon > 10,000 Da, total nitrogen

Enzyme activities in pyrophosphate soil extracts: β -glucosidase, phosphatase, urease, protease BAA

Pyrolytic indices of soil: Mineralization index: furfural/pyrrole, humification index: benzene/toluene, mineralization index: pyrrole/phenol, energetic index: aliphatic/aromatic

Pyrolytic Indices of pyrophosphate extracts: Mineralization index: furfural/pyrrole, humification index: benzene/toluene, mineralization index: pyrrole/phenol, energetic index: aliphatic/aromatic, β -glucosidase activity in the stable humic complex after IEF (isoelectric focusing), carbon percentage of the stable humic complex (bands 3 and 4) after IEF, with respect to the total IEF located carbon, relative content of β -glucosidase activity of the stable humic complex (bands 3 and 4) with respect to the total carbon content in the soil extract (fraction > 104 Dalton)*1,000, β -glucosidase: specific enzyme activity in dialyzed soil extracts (fraction > 104 Dalton)*1,000

Aqueous (0.1 N CaCl_2) extracts: WEOC (water extractable organic carbon) in extraction solution, WEOC per gram dry soil, UV absorption of solution ($\lambda = 254$ nm), summed emission fluorescence ($\lambda_{\text{ex}} = 254$ nm; $\lambda_{\text{em}} = 300\text{--}480$ nm), lower emission fluorescence ($\lambda_{\text{ex}} = 254$ nm; $\lambda_{\text{em}} = 300\text{--}345$ nm), higher emission fluorescence ($\lambda_{\text{ex}} = 254$ nm; $\lambda_{\text{em}} = 435\text{--}480$ nm), absorptivity (UV/DOC), relative summed emission fluorescence (SF/DOC), relative lower emission fluorescence (L/DOC), relative higher emission fluorescence (H/DOC), humification Index (H/L), and fluorescence efficiency (SF/UV)

Physical soil parameters

Pore volume, total cumulative volume, specific surface area, pore radius average, moisture retained by disturbed samples, particle size (0.01 mm) in water (A), particle size (0.01 mm) in pyrophosphate (B), dispersion factor short = A/B, aggregate stability (Sekera optical method).

Rheological parameters

Water content of soil suspension, maximum of shear stress vs. time function, initial shear stress, area of thixotropic loop in low shear region from 0.1 to 10 s^{-1} , extrapolated yield value from shear stress vs. shear rate function, slope of the linear part of down flow curve (shear stress vs. shear rate function).

Appendix B: List of testing and verification sites

Sites for parameter testing (step 2)

Country	Location	Variation of treatments (pressures)	Type of site
Germany	Puch	Agricultural mismanagement and absence of vegetation	Agricultural field
Hungary	near Gödöllő	Soil erosion	Agricultural catena
Italy	Basilicata	Different agricultural practices under arid climate	Agricultural field
	Tuscany	Different agricultural practices under moderate climate	Agricultural field
Spain	Abanilla	Erosion and mismanagement	Catena
	Carcavo	Revegetation of a degraded forest	Degraded forest catena
	Santomera	Deforestation	Forest plots
	Santomera	Erosion and mismanagement	Catena

Sites for spatial verification (step 3)

Country	Location	Variation of treatments (pressures)	Type of site
Cyprus	Zygi	Different agricultural practices under arid climate	Agricultural field
Austria	Mistelbach	Soil erosion	Agricultural catena
Italy	Agri Basin	Erosion and mismanagement	Catena

Sites with specific soil remediation measures

Country	Location	Tested remediation measures
Spain	Abanilla	Addition of various amounts of organic matter Aguilucho
		Terracing, reforestation, organic matter addition, mycorrhiza

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Cross-references

Biochemical Responses to Soil Management Practices
 Climate Change: Environmental Effects
 Enzymes in Soils
 Management Effects on Soil Properties and Functions
 Microbes, Habitat Space, and Transport in Soil

DETACHMENT

Erosion process begins with detachment of a particle from surrounding material. This process sometimes requires breaking of bonds which hold particles together.

Cross-references

Water Erosion: Environmental and Economical Hazard

DETERMINISTIC MODEL

Model based upon the concept that a discrete value exist for the variable of interest at each point in space and given a set of input values, a unique output can be determined.

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Cross-references

Agrophysics: Physics Applied to Agriculture

DEW POINT

The temperature at which the vapor pressure of the atmosphere reaches a point of saturation and the vapor begins to condense into droplets of liquid water.

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DIELECTRIC LOSS TANGENT

See *Organic Dusts, Electrostatic Properties*

DIELECTRIC PROPERTIES OF AGRICULTURAL PRODUCTS

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Synonyms

Electric permittivity

Definition

Dielectric properties. Those characteristics of poorly conducting materials that determine their interaction with electric fields.

Introduction

Dielectrics are a class of materials that are poor conductors of electricity, in contrast to materials such as metals that are generally good electrical conductors. Many materials, including living organisms and most agricultural products, conduct electric currents to some degree, but are still classified as dielectrics. The electrical nature of these

materials can be described by their dielectric properties, which influence the distribution of electromagnetic fields and currents in the region occupied by the materials, and which determine the behavior of the materials in electric fields. Thus, the dielectric properties determine how rapidly a material will warm up in radio frequency or microwave dielectric heating applications. Their influence on electric fields also provides a means for sensing certain other properties of materials that may be correlated with the dielectric properties, by nondestructive electrical measurements. Therefore, dielectric properties of agricultural products may be important for applications in the agricultural industry that will benefit consumers in general.

Further definitions

A few simplified definitions of dielectric properties are necessary for meaningful discussion of their applications. A fundamental characteristic of all forms of electromagnetic energy is their propagation through free space at the velocity of light, c . The velocity of propagation v of electromagnetic energy in a material other than free space depends on the electromagnetic characteristics of that material and is given as

$$v = \frac{1}{\sqrt{\mu\epsilon}} \quad (1)$$

where μ is the magnetic permeability of the material and ϵ is the electric permittivity. For free space, this becomes

$$c = \frac{1}{\sqrt{\mu_0 \epsilon_0}} \quad (2)$$

where μ_0 and ϵ_0 are the permeability and permittivity of free space. Most agricultural products are nonmagnetic, so their magnetic permeability has the same value as μ_0 . These materials, however, have different permittivities than free space. The permittivity can be represented as a complex quantity

$$\epsilon = \epsilon' - j\epsilon'' \quad (3)$$

where $j = \sqrt{-1}$. The complex permittivity relative to free space is then given as

$$\epsilon_r = \frac{\epsilon}{\epsilon_0} = \epsilon'_r - j\epsilon''_r \quad (4)$$

where ϵ_0 is the permittivity of free space, the real part ϵ'_r is called the dielectric constant, and the imaginary part ϵ''_r is the dielectric loss factor. These latter two quantities are the dielectric properties of practical interest, and the subscript r will be dropped for simplification in the remainder of this article. The dielectric constant ϵ' is associated with the ability of a material to store energy in the electric field in the material, and the loss factor ϵ'' is associated with the ability of the material to absorb or dissipate energy, that is, to convert electric energy into heat energy. The dielectric loss factor, for example, is an index of

a material's tendency to warm up in a microwave oven. The dielectric constant is also important because of its influence on the distribution of electric fields. For example, the electric capacitance of two parallel conducting plates separated by free space or air will be multiplied by the value of the dielectric constant of a material if the space between the plates is filled with that material.

It should also be noted that $\epsilon = \epsilon' - j\epsilon'' = |\epsilon|e^{-j\delta}$ where δ is the loss angle of the dielectric. Often, the loss tangent, $\tan \delta = \epsilon''/\epsilon'$, or dissipation factor, is also used as a descriptive dielectric parameter, and sometimes the power factor, $\tan \delta / \sqrt{1 + \tan^2 \delta}$, is used. The ac conductivity of the dielectric σ in S/m is $\sigma = \omega\epsilon_0\epsilon''$, where $\omega = 2\pi f$ is the angular frequency, with frequency f in Hz. In this article, ϵ'' is interpreted to include the energy losses in the dielectric due to all operating dielectric relaxation mechanisms and ionic conduction.

Agricultural products

Dielectric properties of agricultural products have been of interest for many years (Nelson, 2006). One of the earliest applications of such electrical properties was the study of dc electrical resistance of grain for rapidly determining its moisture content. In later work with radio-frequency (RF) measurements, changes in the capacitance of sample-holding capacitors, when grain samples were introduced between the capacitor plates, were correlated with grain moisture content and used for grain moisture measurement. The subsequent development of electrical grain moisture meters has been described in earlier reviews (Nelson, 2006).

The use of the dielectric properties of grain for moisture measurement has been the most prominent agricultural application for such data. In the early work, no quantitative data on the dielectric properties of the grain were reported. Interest generally focused on the influence of a grain sample on the response of an electrical circuit, and the instrument readings were calibrated with values measured by standard procedures for moisture determination. The need for quantitative values of the dielectric properties arose from research on the application of RF dielectric heating to agricultural problems. The first quantitative data on the dielectric properties of grain were reported for barley along with a method for reliable measurement of those properties in the 1-MHz to 50-MHz frequency range (Nelson et al., 1953). Quantitative dielectric properties data, obtained for similar reasons, were soon reported in Russia for wheat and other grain and crop seeds (Knipper, 1959). Extensive measurements on grain and crop seed in the 1-MHz to 50-MHz range, taken over a decade of research on RF dielectric heating applications, were summarized and made available for use in electric moisture meter design and other applications (Nelson, 1965).

The other principle application for dielectric properties of agricultural materials has been for use in research on potential dielectric heating applications. One of these applications was the possible selective dielectric heating

for control of insects that infest stored grain (Nelson and Whitney, 1960; Nelson, 1996).

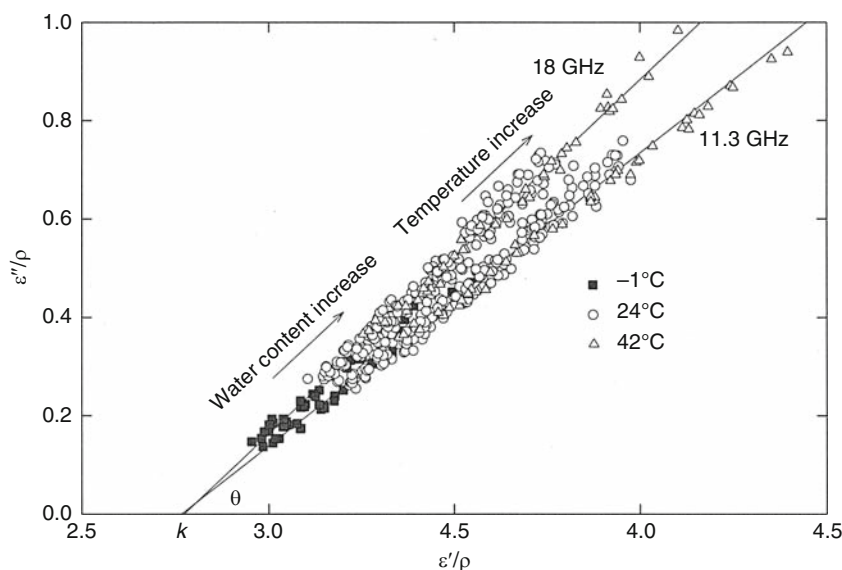
The principles governing the interaction between materials and RF and microwave electric fields, as influenced by the dielectric properties, have been detailed in a recent review article (Nelson, 2006). The same article included a review of principles and techniques for dielectric properties measurements at frequencies ranging from audio frequencies through radio frequencies well into the microwave region. Sources of dielectric properties data for a number of agricultural products will be identified in this article, and some typical data for such dielectric properties will be presented here.

Cereal grains and oilseeds

Dielectric properties of grain and seed over wide ranges of frequency and moisture content have been summarized previously, and graphical and tabular data are available for reference (ASAE, 2000). Models for calculating dielectric constants of many cereal grains and soybeans as functions of frequency, moisture content, and bulk density have been reported (Nelson, 1987; Kraszewski and Nelson, 1989; ASAE, 2000). Some recent dielectric spectroscopy measurements (Nelson and Trabelsi, 2006) on ground hard red winter wheat at frequencies from 10 MHz to 1,800 MHz over the temperature range from 25°C to 95°C were reported (Nelson and Trabelsi, 2006). The earlier reported data were useful to those developing improved grain and seed moisture meters. The recent measurements were part of a study to improve understanding of the temperature dependence of grain permittivity.

Although grain moisture meters, which sense the moisture content through correlations between the RF dielectric properties of the grain and its moisture content, have been in common use for more than 60 years, more recent advances have been reported in use of higher frequencies in the microwave range for grain and seed moisture sensing (Trabelsi et al., 1998). The basis for one such application is illustrated in Figure 1. Here, the dielectric constant and loss factor of hard red winter wheat, each divided by bulk density ρ of the grain, are plotted in an Argand diagram in the complex plane. Note that, at a given frequency, all of the points, regardless of moisture content and temperature, lie along a straight line. The slope of the line increases with frequency and pivots about a point on the $\epsilon''/\rho = 0$ axis that represents the ϵ'/ρ value for completely dry or very cold grain. The equation of the straight line provides a means for determining the bulk density of the grain independent of moisture content and temperature and also provides a basis for sensing moisture content independent of density from the measured permittivity at a single frequency (Trabelsi et al., 1998). This microwave-sensing technique should be useful for monitoring moisture content in moving grain and other particulate materials, since it offers a density-independent method for sensing moisture content in granular and particulate materials.

Another application for dielectric properties of grain was involved in the study of high-frequency dielectric heating for the selective heating of stored-grain insects (Nelson, 1996). In this instance, the dielectric properties of hard red winter wheat and a common stored-grain insect, the rice weevil, *Sitophilus oryzae* L., were measured over a broad range of frequencies and compared to



Dielectric Properties of Agricultural Products, Figure 1 Complex-plane plot of the dielectric constant and loss factor, divided by bulk density, for hard red winter wheat of various moisture contents and bulk densities at indicated temperatures for two frequencies, 11.3 GHz and 18.0 GHz (Trabelsi et al., 1998).

determine the frequencies for optimally heating the insects. Results of that study are summarized in Figure 2. Because the loss factor is the dominant characteristic determining the energy absorption and heating, the frequency range between about 10 MHz and 100 MHz provides the best opportunity for selective heating of the insects.

Fruits and vegetables

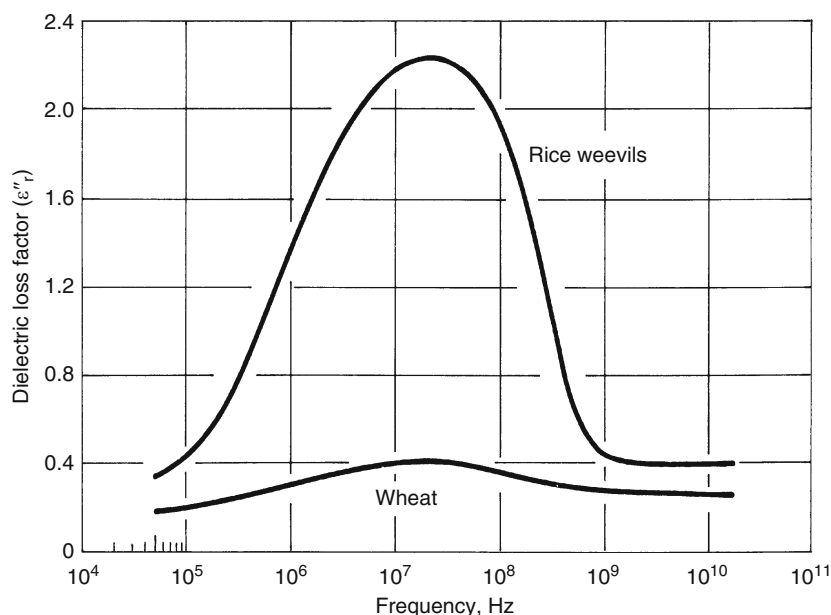
Because of the need for rapid nondestructive quality measurements for fresh fruits and vegetables, the dielectric properties of a few products were measured at microwave frequencies (Nelson, 1980; Nelson, 1983; Nelson, 1992). Although these studies provided background data on dielectric properties of several fruits and vegetables, the measurements did not show any promise for detecting peach maturity or hardcore condition in sweet potatoes by measurements at single frequencies (Nelson, 1980). Therefore, broadband permittivity measurements were initiated to study the dielectric properties of several fruits and vegetables over the frequency range from 200 MHz to 20 GHz (Nelson et al., 1994). Measurements over the same frequency range were obtained for tree-ripened peaches, *Prunus persica* (L.) Batsch., of different maturities (Nelson et al., 1995). Differences in the dielectric properties for different stages of maturity were noted at particular frequencies, and permittivity-based maturity indices, which combined the dielectric constant values at 200 MHz and the loss factor values at 10 GHz, were suggested, but it was noted that much more work was needed to establish their practicability.

Because the dielectric constants of peaches at different maturities diverged at the lower end of the frequency range, it appeared worthwhile to explore the dielectric

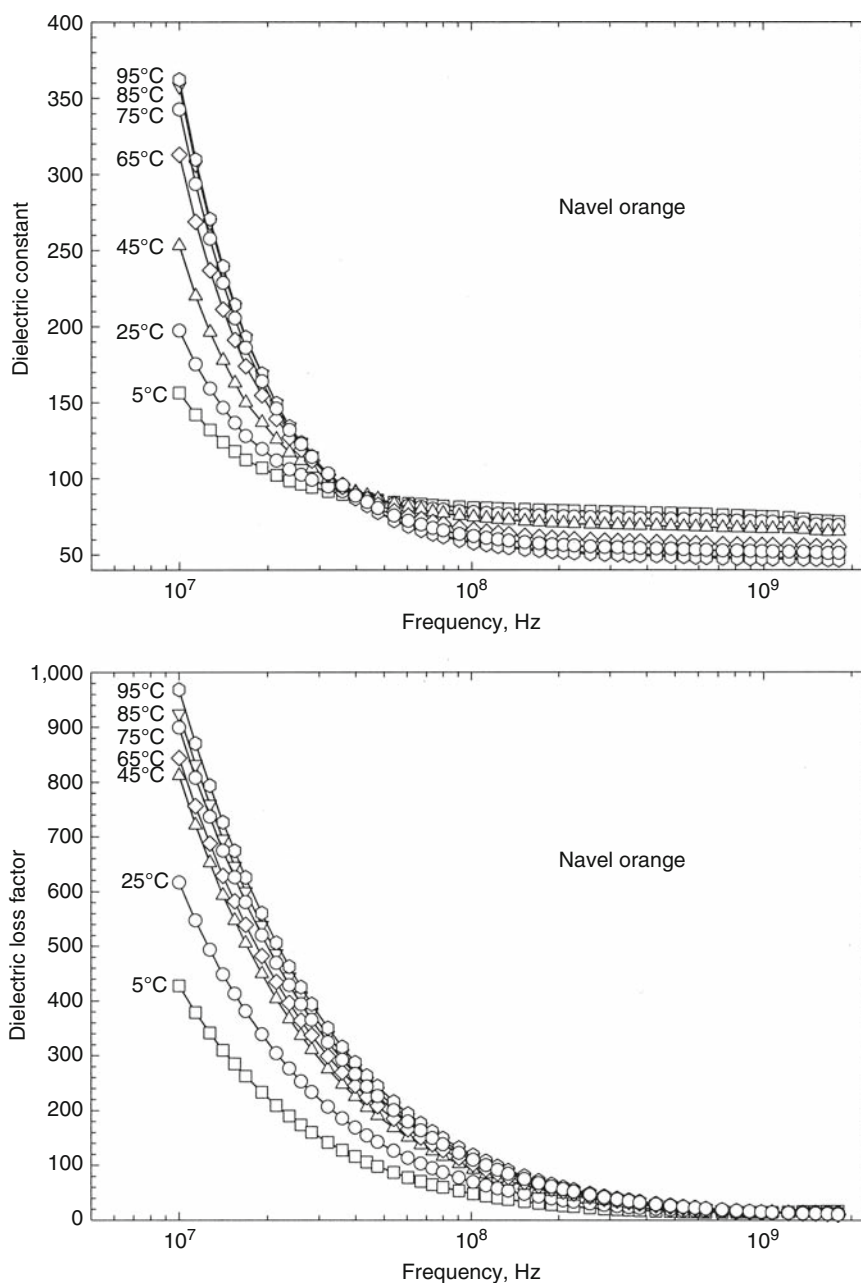
behavior of some fruits and vegetables at frequencies somewhat below this range (Nelson, 2003). Also, because changes in the dielectric properties of materials are important in RF and microwave heating, temperature-dependent data were obtained. An example of permittivity data obtained in the frequency range from 10 MHz to 1.8 GHz over the temperature range from 5°C to 95°C is shown in Figure 3 for navel orange, *Citrus aurantium* subsp. bergamia, tissue (Nelson, 2006). In Figure 3, the temperature dependence of the dielectric constant disappears at about 40 MHz. Above that frequency, the temperature coefficient for the dielectric constant is negative, but below that frequency the temperature coefficient is positive. This is most likely the frequency above which dipole relaxation accounts for most of the energy loss and below which ionic conduction is the dominant loss mechanism. That frequency varied for different fresh fruits and vegetables, but generally ranged between about 20 MHz and 120 MHz (Nelson, 2005).

Dielectric properties of freshly harvested melons have been studied to determine whether useful correlations exist between their dielectric properties and sweetness, as measured by soluble solids content (Nelson et al., 2006; Nelson et al., 2007). Although interesting correlations were obtained relating dielectric properties and soluble solids in complex-plane plots, correlations for predicting melon sweetness from the dielectric properties have so far not been successful (Nelson et al., 2007).

Dielectric properties of apples were recently measured and studied to determine whether they might be useful in sensing quality of stored apples (Guo et al., 2007a). Dielectric properties of the apples remained relatively constant during the 10-week refrigerated storage period.



Dielectric Properties of Agricultural Products, Figure 2 Variation with frequency of the dielectric loss factor of bulk samples of adult rice weevils and wheat at 24°C from 50 kHz to 12 GHz (Nelson, 1996).

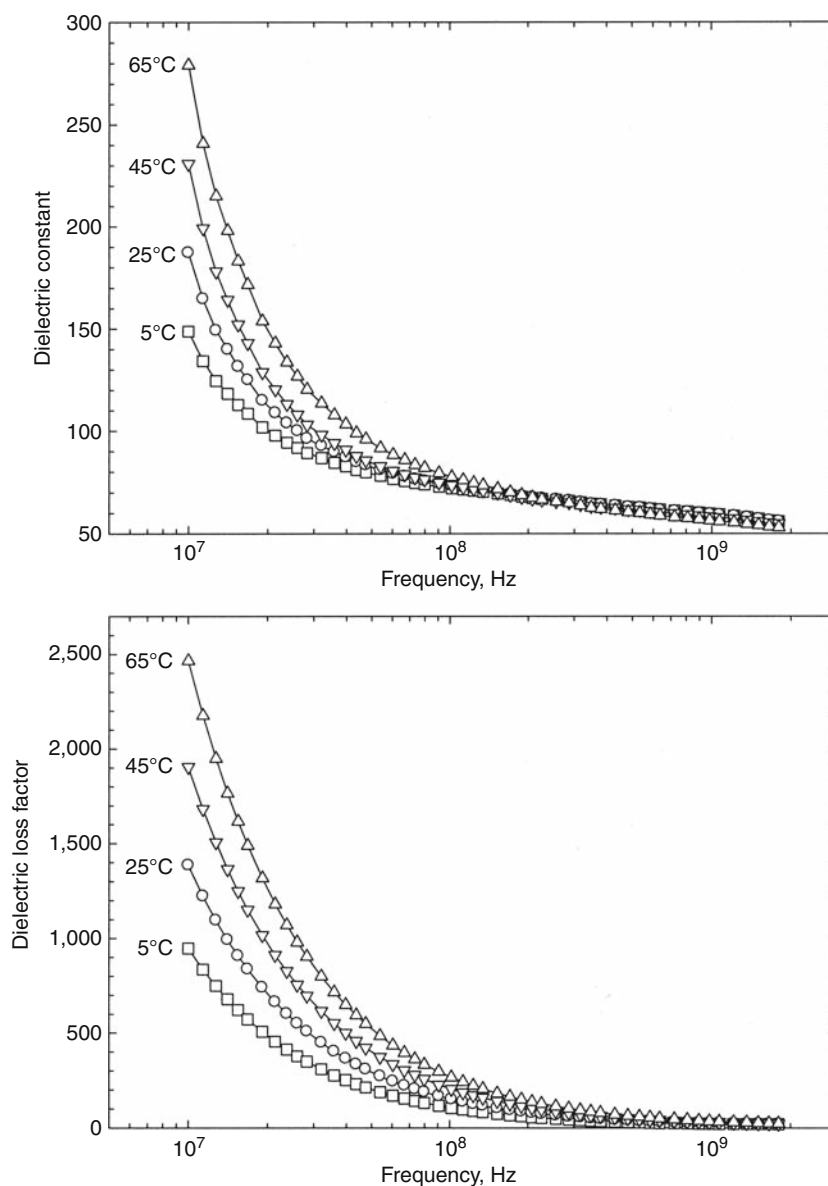


Dielectric Properties of Agricultural Products, Figure 3 Frequency and temperature dependence of the permittivity of navel orange, *Citrus aurantium* subsp. *bergamia*, at indicated temperatures (Nelson, 2003).

Dielectric properties of a commercial apple juice product were measured over the 200-MHz to 20-GHz frequency range (Nelson and Bartley, 2002). Because of the high water content of the apple juice, the dielectric relaxation of liquid water was clearly evident in resulting data. The temperature dependence of the dielectric properties of the apple juice is also very similar to that of pure liquid water, with the relaxation frequency for pure water shifting from below 20 GHz to higher frequencies as temperature increases (Hasted, 1973).

Poultry products

Some dielectric spectroscopy measurements have been taken recently on poultry products in exploratory work on quality sensing (Zhuang et al., 2007). Dielectric properties values for fresh chicken breast meat in the 10–1,800-MHz frequency range at temperatures from 5°C to 65°C are shown in Figure 4. These curves show frequency dependence of the dielectric properties similar to those for tissues of fruits and vegetables. Probable



Dielectric Properties of Agricultural Products, Figure 4 Frequency and temperature dependence of the dielectric properties of fresh chicken breast meat, Pectoris major, deboned at 2-h postmortem (Zhuang et al., 2007).

potential was indicated for using dielectric properties to assess meat quality characteristics.

Dielectric spectroscopy measurements were also taken on the albumen and yolk of fresh chicken eggs and at weekly intervals during 5 weeks of storage (Guo et al., 2007b). Dielectric properties changed during the storage period, but they did not correlate well with traditional quality factors for eggs.

Summary

Dielectric properties of materials are defined, and the importance and usefulness of the dielectric properties of agricultural products are discussed briefly, pointing out

their use in the rapid sensing and measurement of moisture content in grain and seed and in governing the behavior of materials subjected to RF and microwave electric fields for dielectric heating applications. Sources of information on the dielectric properties of such products are provided, and values of the dielectric constants and loss factors are presented graphically for a few products, including grain, fruit, and poultry products. These examples provide information not only on typical values of the dielectric properties, but also on their dependence on such variables as frequency of the alternating electric fields applied, moisture content, and temperature of the products.

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Cross-references

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DIFFUSE DOUBLE LAYER (DDL)

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Synonyms

Electrical double layer (EDL); Electrical triple layer (ETL)

Definition

Diffuse double layer (DDL) is an ionic structure that describes the variation of electric potential near a charged surface, such as clay, and behaves as a capacitor.

Formation: Clays are aluminosilicates in which some of the aluminum and silicon ions are replaced by elements with different charge. For example, aluminum (Al^{3+}) may be replaced by iron (Fe^{2+}) or magnesium (Mg^{2+}), leading to a net negative charge. When suspended in an electrolyte, clay particles are surrounded by a hydrosphere of adsorbed water that contains a thin layer of adsorbed cations. Outside this layer, ions of opposite polarities form an electrically neutral diffuse layer. The adsorbed cations are influenced by electrostatic attraction, but those in the diffuse layer are influenced by two equal but opposing forces: electrostatic attraction and diffusive forces. This ionic structure consisting of the negative surface charges, adsorbed cations, and diffuse layer is known as the diffuse double layer, DDL. The thickness of the DDL is $<10^{-6}$ cm (Pamukcu, 1997).

Models: The Helmholtz, Gouy–Chapman, and Gouy–Chapman–Stern models describe the structure of a DDL. The first model states that the surface charge is neutralized by cations placed rigidly at an increment of their radius from the surface. The surface charge potential is dissipated linearly from the surface to the cations. The hypothesis of the rigid layers of cations is, however, questionable. The loosely held cations diffuse into the

liquid phase until the counter potential restricts this process – is the assumption of the second model. This assumption, also questionable, treats ions as point charges and physically limitless approach of the ions to the surface. The third model postulates that ions have finite size and the first layer of ions is at a distance equal to the radius of the ion from the surface. Also, some of the ions are adsorbed by the surface in the plane, and this layer is called the Stern layer.

Main features: Clay particles are surface-active materials and many of their properties depend on the activity of surface phenomena. The cations in the Stern layer can be replaced by other cations; thus, they are exchangeable and become available to plants. The capacity of a soil for exchange of cations between the soil and the surrounding solution is its cation exchange capacity, CEC. The cations in the DDL move along the clay–water surface under the influence of an electrical field (Revil and Glover, 1997) resulting in the surface electrical conduction. Increasing electrolyte concentration or decreasing water content reduces the thickness of DDLs and hence the mobility of cations within them. The cations in the Stern layer, although once assumed immobile, are now found mobile (Leroy and Revil, 2004) leading to the assumption of a dynamic Stern layer.

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DIFFUSION IN SOILS

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Synonyms

Gas diffusion in soil; Heat diffusion in soil; Soil water dispersion; Solute diffusion in soil; Water diffusion in soil; Water transport in unsaturated soil

Definition

Diffusion is a process that causes the spread of a constituent mass within the medium under gradient of

concentration. It originates from the random motion of particles (molecular diffusion). Diffusion equation describes well various spread processes of water, gases, solutes, and heat in porous media. In case of a porous material, diffusion coefficient is interpreted as dispersion coefficient with the value dependent on porous material structure. Diffusion equation allows to describe, in a simple manner, the transfer of mass or heat in porous media by inclusion of various effects into one parameter – dispersion coefficient.

Introduction

In soil, various diffusion processes occur. They comprise diffusive transport of heat energy, of gases, of solutes, as well as of water under unsaturated conditions. These processes are important for plant biomass production and for the state of the environment.

Equation of motion based on Newton's Laws connects acceleration and force into simple equation:

$$\vec{F} = m\vec{a} \quad (1)$$

where \vec{F} is vector of force m is mass \vec{a} is vector of acceleration.

Analyzing transport processes in microscale, one should consider various forces acting on each part of the system and forces acting among particular parts of the system:

$$\frac{d(m\vec{v})}{dt} = \sum \vec{F}_i \quad (2)$$

where \vec{v} is vector of flow velocity t is time.

This in fact leads to a partial differential equation of the second order in three-dimensional space. In case of porous material, it gives complicated equations that are not tractable in a practical way.

While considering the porous medium such as soil in a macroscopic scale one should take into account a representative volume of the medium to perform homogenization of its properties.

All factors that influence flow can be combined into one parameter that governs water movement. Describing water flow in the soil medium, one should consider water interaction with solid phase, gravity forces influence on flux, water internal friction, etc. Instead, all those effects are lumped into one parameter called diffusivity function or diffusion coefficient.

Moisture diffusivity in soil

This kind of reasoning lead to the Darcy's equation (1856) giving connection between macroscopic, saturated water flow velocity v , and pressure drop Δh over the sample length Δx :

$$v = K_{sat} \frac{\Delta h}{\Delta x} \quad (3)$$

Coefficient K_{sat} , called today saturated hydraulic conductivity, is a parameter that depends on the soil type and bulk density.

For unsaturated conditions, this equation is applicable in a modified form:

$$f_w = -K \frac{\partial \Phi}{\partial x} \quad (4)$$

where f_w is water flux K is hydraulic conductivity function Φ is pressure potential in the sample x is spatial coordinate.

In this equation, hydraulic conductivity function K is highly moisture dependent and is specific for a soil sample.

Above equations are based on the assumption that water potential gradient is a driving force causing water flow in the sample. Often, it is useful to consider water content gradient as a factor causing water flow. In such a case, the previous equation reads:

$$f_w = -K \frac{d\Phi}{d\Theta} \frac{\partial \Theta}{\partial x} \quad (5)$$

where Θ is a volumetric moisture content of the soil sample.

In this picture, new characteristic of the flux can be introduced, namely, diffusivity function D_w :

$$f_w = -D_w \frac{\partial \Theta}{\partial x} \quad (6)$$

It is visible from the comparison of above equations that:

$$D_w = K \frac{d\Phi}{d\Theta} \quad (7)$$

what means that the diffusivity is equal to water permeability K multiplied by the slope of the water retention curve $d\Phi/d\Theta$.

Moisture potential is usually considered as consisting of two different parts:

$$\Phi = h + z. \quad (8)$$

In this equation, h is a pressure part of the potential and z is gravitational part of the potential, represented in the equation by the elevation z over a chosen reference level. Pressure potential is dependent on moisture content, soil type and structure, while gravitational potential depends on gravitational forces.

In three dimensions, the equation for flux of water reads as follows:

$$\vec{f}_w = -K \left(\vec{i} \frac{\partial \Phi}{\partial x} + \vec{j} \frac{\partial \Phi}{\partial y} + \vec{k} \frac{\partial \Phi}{\partial z} \right). \quad (9)$$

Flux \vec{f}_w is treated here as a vector in three-dimensional space. Application of the equation for moisture potential leads to the equation:

$$\vec{f}_w = -K \left(\vec{i} \frac{\partial h}{\partial x} + \vec{j} \frac{\partial h}{\partial y} + \vec{k} \left(\frac{\partial h}{\partial z} + 1 \right) \right). \quad (10)$$

which shows clearly the influence of gravity force on the flux in vertical (z) direction.

When applying change of the variables to the diffusivity, the above equation reads:

$$\vec{f}_w = -K \frac{dh}{d\Theta} \left(\vec{i} \frac{\partial \Theta}{\partial x} + \vec{j} \frac{\partial \Theta}{\partial y} + \vec{k} \left(\frac{\partial \Theta}{\partial z} + \frac{d\Theta}{dh} \right) \right) \quad (11)$$

and the coefficient D_w :

$$D_w = K \frac{dh}{d\Theta} \quad (12)$$

is a moisture diffusivity function.

Application of the mass conservation law:

$$\frac{\partial \Theta}{\partial t} = -\text{div} \vec{q} \quad (13)$$

to the flux \vec{q} leads to the water diffusion equation:

$$\begin{aligned} \frac{\partial \Theta}{\partial t} = & \frac{\partial}{\partial x} \left(D_w \frac{\partial \Theta}{\partial x} \right) + \frac{\partial}{\partial y} \left(D_w \frac{\partial \Theta}{\partial y} \right) \\ & + \frac{\partial}{\partial z} \left(D_w \frac{\partial \Theta}{\partial z} \right) + \frac{dK}{d\Theta} \frac{\partial \Theta}{\partial z} \end{aligned} \quad (14)$$

with gravitational term $\frac{dK}{d\Theta} \frac{\partial \Theta}{\partial z}$.

In practice, diffusion coefficient depends on the moisture content and often, due to the spatial variability of the soil, is position dependent. This causes certain problems in the application of this model to real conditions.

This equation together with initial and boundary conditions form a complete system that describes fate of moisture content in a certain volume. Initial condition function defines initial values of the moisture content in each point of the volume under consideration, while boundary conditions define values of moisture and/or flux of water at the boundaries of considered volume at the time when moisture movement is calculated.

To determine the moisture content distribution in a medium in a certain time, it is necessary to solve the water flow equation.

The solution depends on the actual moisture conditions existing at the boundaries of the considered region and, on initial moisture conditions inside the considered region. Moisture flow equation is the second-order equation in spatial coordinates. One has to provide the value of moisture content and of moisture gradient at the boundary.

The factor containing the water hydraulic conductivity K in the equation originates from the gravity forces and is present only in the equation where vertical flow is applicable.

Solution of the diffusion equations

Usually, when diffusion coefficient depends on the moisture content, one has to solve the diffusion equation numerically due to complicated form of this function. In some cases, for simple diffusivity functions analytical solution is known. This is the situation for constant diffusion coefficient and for various geometries of modeled volume.

Dependence of water diffusion on moisture content

Diffusion coefficient of water in the soil is specific for a given soil. It depends on the status and moisture content. In order to be able to model various shapes of diffusion functions, many mathematical functions presenting empirical models have been used (Table 1).

Importance of gravity forces

Gravity forces are especially important under the conditions close to saturation when pressure head gradient is low. When pressure head gradient has a large value in comparison to unity, the gravity forces do not play a significant role in water flow. In such a situation, water can easily flow against the gravity from the deeper layers of the soil to the surface.

Calculation of moisture diffusivity

Moisture diffusivity can be calculated from the measurement results of transient moisture profiles of isothermal, horizontal water flow. Inverse analysis with the application of Boltzmann–Matano transformation is possible (e.g., Pachepsky et al., 2003). One dimensional diffusion equation for such a case has a form (e.g., Black et al., 1969; Lisle et al., 1987; Parlange et al., 1993):

$$\frac{\partial \Theta}{\partial t} = \frac{\partial}{\partial x} \left(D_w(\Theta) \frac{\partial \Theta}{\partial x} \right), \quad (15)$$

where Θ is volumetric water content, t is time of water absorption, and x is distance of monitored moisture content from the water exposed surface of the sample. Boundary conditions are constant with a step at the beginning of the process:

$$\Theta(0, t) = \Theta_1, \quad (16)$$

initial moisture in the sample is constant with a value:

$$\Theta(x, 0) = \Theta_2. \quad (17)$$

Application of Boltzmann transformation of variables that introduces variable:

$$\Theta(x, t) = \Theta(\eta) \quad (18)$$

with

$$\eta = \frac{x}{2\sqrt{t}}, \quad (19)$$

converts the partial differential equation into ordinary equation in a new variable:

$$\frac{d}{d\eta} \left(D_w(\Theta) \frac{d\Theta}{d\eta} \right) + 2\eta \frac{d\Theta}{d\eta} = 0 \quad (20)$$

with the boundary conditions

$$\omega(0) = \Theta_1, \quad (21)$$

$$\omega(\infty) = \Theta_2. \quad (22)$$

This equation can be solved by integration giving:

$$D_w(\Theta) = \frac{1}{2t_0(d\Theta/d\eta)\eta_0} \int_{\eta_0}^{\infty} \eta \frac{d\Theta}{d\eta} d\eta. \quad (23)$$

One should know the variability of moisture content in space and time $\Theta(x, t) = \Theta(\eta)$ from the experiment in order to apply this method.

Diffusion processes in soil, beyond the diffusion of water under unsaturated conditions, as described above, comprise diffusion of heat, of gases, and of solutes. The diffusion equations for these agents are in all the cases similar (cf. Tables 2 and 3). In each case, the flux of the agent under consideration is proportional to the driving force of the process and to a coefficient characterizing the transport properties of the given material.

The driving force of water movement is the gradient of water potential (Darcy's law). The heat flux is driven by the temperature gradient (Fourier's equation). In case of diffusion of gases and solutes, the driving forces are the concentration gradients of the gases or of the solutes (First Fick's equation).

Diffusion in Soils, Table 1 Empirical equations relating water diffusivity to volumetric water content

Equation	Symbols meaning	Source
$D_w = a \frac{\Theta^b}{(\Theta_s - \Theta)^a}$	D_w – diffusion coefficient	Ahuja and Swartzendruber (1972)
$D_w = \frac{K_s}{\lambda a (\Theta_s - \Theta)} s^{3/2+1/\lambda}$	Θ_s – saturated volumetric water content	Mualem (1976)
$D_w = a \frac{\Theta^b}{(\Theta_s - \Theta)^a}$	Θ – actual volumetric water content	van Genuchten (1980)
	s – saturation of the soil	
	K_s – saturated hydraulic conductivity	
	α, a, b, λ – fitting parameters	

Diffusion in Soils, Table 2 Equations for water movement under unsaturated conditions in soil and heat transfer both under saturated and unsaturated conditions (modified from Bolt et al., 1966)

General notion	Water	Heat	Symbols
Flux	$f_w = -K(\partial\Phi/\partial x)$, Darcy (1856)	$f_h = -\lambda(\partial T/\partial x)$, Fourier (1822)	f_w – unit flux of water
Conservation equation	$\partial\Theta/\partial t = -(\partial f_w/\partial x) \pm q_w$	$\partial(c_v T)/\partial t = -(\partial f_h/\partial x) \pm q_h$	f_h – unit heat flux
Movement equation for soil profile	$\partial\Theta/\partial t = (\partial/\partial x)(D_w(\partial\Phi/\partial x)) \pm q_w$	$\partial T/\partial t = (\partial/\partial x)(D_h(\partial T/\partial x)) \pm q_h$	K – water permeability
			λ – heat conductivity
			Φ – water potential
			T – temperature
			x – distance
			t – time
			Θ – volumetric water content
			c_v – heat capacity
			q_w, q_h – source/sink terms
			$D_w = K_h(\partial\Phi/\partial\Theta)$
			$D_h = \lambda/c_v$

Diffusion in Soils, Table 3 Equations for gas and solute diffusion in soil (modified from Bolt et al., 1966)

General notion	Gas	Solute	Symbols
Flux	$f_g = -D_g(\partial C/\partial x)$, Fick (1855)	$f_s = -D_s(\partial C/\partial x)$, Fick (1855)	f_g – unit flux of gas
Conservation equation	$\partial[C(\varepsilon_g + B\Theta)]/\partial t = -(\partial f_g/\partial x) \pm q_g$	$\partial(\Theta C)/\partial t = -(\partial f_s/\partial x) \pm q_s$	f_s – unit solute flux
Movement equation for soil profile	$\partial C/\partial t = (\partial/\partial x)(D_g^*(\partial C/\partial x)) \pm q_g^*$	$\partial C/\partial t = (\partial/\partial x)(D_s^*(\partial C/\partial x)) \pm q_s^*$	B – Bunsen's coefficient of solubility
			C – concentration of the gas or solute
			Θ – volumetric water content
			x – distance
			t – time
			D_g – gas diffusion coefficient
			D_s – solute diffusion coefficient
			ε_g – air-filled porosity
			$D_g^* = D_g/(\varepsilon_g + B\Theta)$
			$D_s^* = D_s/\Theta$
			ΘC – amount of solute in a unit soil volume
			$[C(\varepsilon_g + B\Theta)]$ – amount of gas in unit soil volume
			q_g, q_g^*, q_s, q_s^* – source/sink terms

The properties of the diffusion medium are characterized by water permeability in case of water movement. In case of heat flux, it is the heat conductivity, while in case of gas and solute diffusion, it is the diffusion coefficient.

The similarities among the above processes become more evident after combination with the conservation equation. Then the equation gets the form of the second Fick's equation (Table 3) and material constant characterizing the properties of the medium acquires the dimension of square unit of length per unit of time (most often $\text{m}^2 \text{s}^{-1}$).

Thermal diffusivity in soil

The flow of heat in a soil is connected with many processes. Usually, it is not a simple heat conduction but involves also radiation heat transport, vapor transport with latent heat movement. In the simplest case, it is assumed that heat transfer undergoes conduction and can be

described with the diffusion equation. It is in fact the flow of thermal energy in the stable soil caused by temperature gradient.

Heat conduction equation comes out from the application of constitutive equation for the heat conduction in a matter, i.e., Fourier's law, $\vec{q}_h = -\lambda \nabla T$, that combines temperature gradient and heat flux in a linear manner with energy balance equation $dE/dt = \dot{Q} + \dot{W}$ that expresses energy conservation in the flow process, where \dot{Q} denotes heat flux term, \dot{W} represents work flux, and λ is the heat conductivity.

The application of both equations leads in the simplest case to (Hillel, 1982; Marshall and Holmes, 1988):

$$\frac{\partial T}{\partial t} = D_h \frac{\partial^2 T}{\partial x^2} \quad (24)$$

which has the form of diffusion equation for temperature distribution. The coefficient D_h is a thermal diffusivity

coefficient. One should keep in mind that despite of the form, this equation describes heat transport and not temperature transport.

Thermal diffusivity D_h can be calculated from the formula:

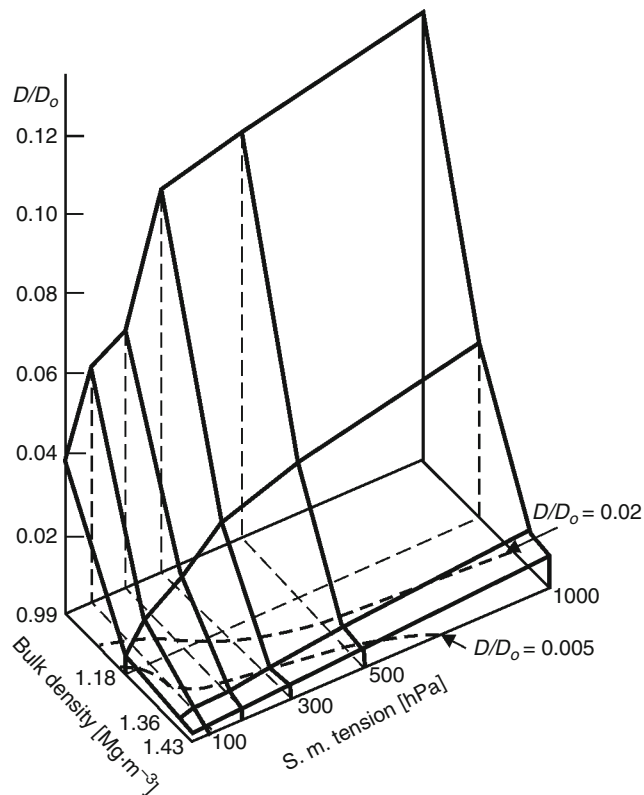
$$D_h = \frac{\lambda}{c_v} \quad (25)$$

where c_v is its heat capacity.

Thermal diffusivity of soils varies due to soil parameters variation. Moisture content is one of most important factors that change thermal diffusivity. Heat capacity of the soil is almost a linear function of moisture content, while thermal conductivity depends on moisture content nonlinearly (Figure 1). Thermal diffusivity has a maximum for certain moisture content, what is of high practical importance. Soil with the moisture content around this value will heat much quicker than soil with moisture far from that value. Optimal moisture allows to germinate seeds in spring significantly earlier.

Diffusion of gases

Concentration diffusion plays an essential role in the gas exchange within soil. The diffusive flow f_g of a gas within a porous medium is described by the first Fick's law.



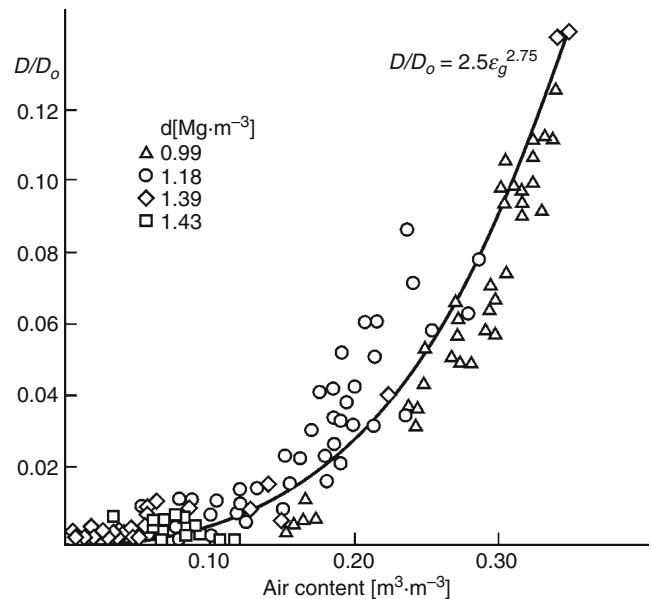
Diffusion in Soils, Figure 1 Dependence of relative gas diffusion coefficient in a loamy textured Chernozem Rendzina (Bezek, Poland) on soil moisture tension and bulk density (modified from Stępniewski, 1981).

$$f_g = -D_g \frac{\partial C}{\partial x} \quad (26)$$

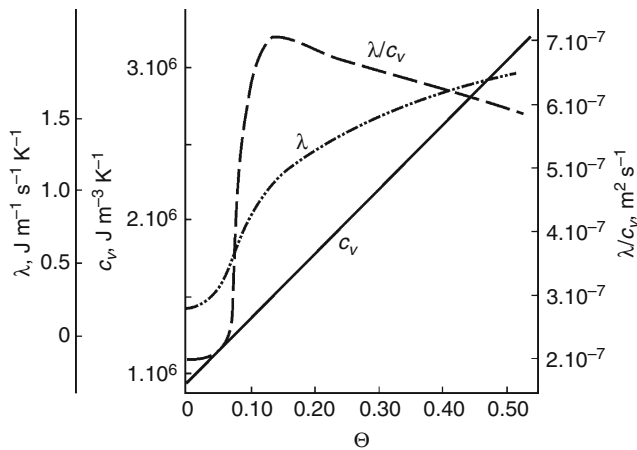
The change of the concentration of gases with time is described by the second Fick's law, containing also the sink/source term (Table 3).

Coefficient of gas diffusion in soil D_g depends on the kind of the diffusing gas, on the temperature and pressure, as well as on the content of air-filled pores, and their tortuosity, continuity, and shape. These, in turn, depend on the spatial arrangement of soil particles and distribution of water. The diffusive properties of soil medium usually are characterized by relative diffusion coefficient D_g/D_o , where D_o is the diffusion coefficient of the same gas in free atmospheric air under the same temperature and pressure conditions. The D_g/D_o value does not depend on the temperature, pressure, or the kind of the diffusing gas (e.g., Kristensen et al., 2010).

The dependence of relative gas diffusion coefficient on soil bulk density and on soil moisture tension is presented in Figure 2, and that on air-filled porosity ϵ_g – in Figure 3. The value of D_g/D_o in soil is usually below 0.2. As it can be noticed, it increases with soil moisture tension, and rapidly decreases with soil bulk density. It should be emphasized that gas diffusion coefficient in porous media does not depend on the size of the pores, as long as the pore diameters are greater than the mean free path of the molecules of the gas under consideration (Glinski and Stępniewski, 1985). This limit is the pore diameter of 0.10 μm . In the case of soil, pores of that size are emptied of water at soil moisture tension above 3 MPa ($pF > 4.5$),



Diffusion in Soils, Figure 2 Relationship of D/D_o to air-filled porosity ϵ_g , of the same as in Figure 1 loamy textured Chernozem Rendzina at different bulk densities d (modified from Stępniewski, 1981).



Diffusion in Soils, Figure 3 Thermal conductivity λ , heat capacity c_v , and thermal diffusivity $D_h = \lambda/c_v$ versus volumetric water content for a sandy soil of 50% total porosity and 3.5% organic matter content (modified from Van Duin, 1956).

i.e., at moisture contents below the permanent wilting point. It means that diffusion of gases within macropores ($>30 \mu\text{m}$) and mezopores ($30\text{--}0.2 \mu\text{m}$) usually containing plant available water does not depend on the pore size. It was demonstrated that the magnitude of gas diffusivity (as well as that of thermal diffusivity) is more sensitive to the porosity than to the scale dependency inherent in fractal structures (Anderson et al., 2000).

D_g/D_o usually shows a curvilinear relationship versus e_g , as shown in Figure 3. It can be described by an empirical power model in the form:

$$\frac{D_g}{D_o} = \gamma e_g^\mu \quad (27)$$

where γ and μ are empirical coefficients characterizing the diffusion medium.

It should be kept in mind that gas diffusion in soil comprises not only the macroscale diffusion within the entire soil profile, but also microscale and approximately spherical diffusion within particular aggregates, as well as longitudinal and radial diffusion within the plant root tissues (e.g., Gliński and Stepniewski, 1985; Cook and Knight, 2003). Due to soil heterogeneity and importance of microscale diffusion processes, the composition of air within the intra-aggregate pores may differ from that in the inter-aggregate pores. The former pores contain less oxygen and more carbon dioxide compared to the inter-aggregate pores (e.g., Zausig et al., 1993; Højberg et al., 1994; Horn, 1994; Horn and Smucker, 2005).

Diffusion of solutes

Diffusion of inert, nonreactive solutes in soil can be described by the first and the second Fick's equations presented in Table 3. Unlike the diffusion of gases, the diffusion of solutes takes place in the liquid phase of the soil.

Due to this, the diffusion coefficient depends on the continuity and tortuosity of the pores filled with water and increases with the degree of saturation with waters.

In case of reactive solutes which can undergo processes of adsorption, dissociation, ion exchange, and chemical reactions, these processes have to be taken into consideration within the sink/source term.

Summary

Diffusion processes in soil comprise transport of water under unsaturated conditions, transport of gases in liquid and gaseous phase, transport of heat in all the three phases, as well as transport of solutes within liquid phase. The flux per unit cross-sectional area and per unit time is proportional to driving forces of these processes which are the gradients of water content, of gas concentration, of temperature, and of solute concentration, respectively, as well as to the parameter called diffusion coefficient (dimension $\text{m}^2 \text{s}^{-1}$), characterizing properties of the medium in which the diffusion process takes place. Combination of these equations with the conservation law gives the formulas of the second Fick's equation type for all the fluxes with the source/sink term. It should be underlined that under field conditions diffusion processes are usually coupled one with other or with mass flow processes caused by infiltration and lateral flow of water as well as by gas movement due to pressure gradient.

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Cross-references

[Air Flux \(Resistance\) in Plants and Agricultural Products](#)
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DILATANCY

The tendency of a body under shearing stress to expand as it deforms. This property is typical of sandy soils and powders, as a result of the sliding and rolling of particles over one another along the shearing plane.

DISCHARGE

The volume of water flow through the stream or open channel past a point in a given time period.

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Glossary of Soil Science Terms. Soil Science Society of America. 2010. <https://www.soils.org/publications/soils-glossary>

Cross-references

[Water Balance in Terrestrial Ecosystems](#)

DISPERSION

The tendency of clay particles in an aqueous suspension to either clump together into flocs or to separate from one another and thus disperse in the fluid medium, depending on the composition and concentration of the electrolytes in the ambient solution.

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Cross-references

[Flocculation and Dispersion Phenomena in Soils](#)

DISPERSIVITY

The ratio of the hydrodynamic dispersion coefficient (d) divided by the pore water velocity (v); thus $D = d/v$.

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DIURNAL STRAINS IN PLANTS

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Synonyms

Circadian rhythm in fluctuations of diameter; Daily plant organ radius variations; Diurnal changes in plant organ diameter; Diurnal fluctuations in size

Definition

Diurnal strains in plants:

- Diurnal – having a daily cycle
- Strain – a deformation produced by stress

Periodic reversible shrinkage and irreversible and/or reversible swelling of plant tissues. This process is a function of the changing levels of tissue hydration. Tissue hydration during natural day/night cycles in plants which have lost their leaves (late autumn, winter and early spring) depends on water accessibility and temperature, whereas in plants with leaf, tissue hydration additionally depends on the transpiration rate which is connected with air humidity, wind speed, CO₂ concentration, etc. Swelling of tissues is caused by hydrostatic pressure and mainly occurs at night. In contrast, during the day tissues shrink because of decrease in turgidity caused by transpiration. The measurable effect of this process is the decrease in the tangential strain. The strain is a response to the mechanical stress imposed on the plant cell walls by changing water pressure. The nature of the strain generated by changes in water pressure depends on the properties of the cell wall and it can be elastic, viscoelastic, and plastic. There are different phenomena which generate tangential strains in plant organs: variations in hydrostatic pressure, variations in osmotic pressure, variations in temperature, and growth of the tissues.

Historical perspective

Reversible shrinkage of plant organs was first reported during periods of temperatures below the freezing point (Hoffmann, 1857; Sachs, 1860). Wiegand (1906) described the swelling of tree branches during thawing and described a much bigger extension of the bark than of the xylem. This reversible seasonal deformation was attributed to the elastic properties of plant tissues. One of the first pieces of information concerning diurnal decrease in the size of a plant organ (orange fruit) was reported by (Bartholomew, 1923). However, initially the mainstream research in diurnal strains was connected with systematic observations of the radial growth of trees. Development of new tools and methods of observation helped to identify a daily rhythm of shrinkage and swelling of tree trunks (MacDougal, 1924; Reineke, 1932).

The first rapid increase in research on this phenomenon started in the late 1950s and lasted till the middle of the 1970s of the last century (Ninokata and Miyazato, 1959; Kozłowski and Winget, 1964; Klepper, 1968; Klepper et al., 1971; Molz and Klepper, 1973; Pereira and Kozłowski, 1976). During this time, the mechanism of diurnal variations in size of different plant organs was identified and described. However, the phenomenon was seen as a side effect of transpiration and water accessibility without any significant function. Since that time, both the recognition of the mechanism as well as the understanding of the role of diurnal strains in plant organs has expanded considerably.

Mechanism of diurnal strains fluctuation

During the early evolution of land plants, the problem of water loss due to direct exposure to dry air had to be solved (water stress). It was resolved on the physiological level by enhancement of osmotic adjustment and on the

structural level by the development of epidermis. However, evolution of a non-permeable epidermis would create new problem with gas exchange. The compromise which was achieved and enabled adaptive radiation of land plants was the evolution of stomata.

Although water is lost during the day, osmotic adaptation helps the plant to survive a short period of water stress. During the night, water is replenished in greater quantity than the amount lost, which generates a mechanical stress. The side effect of these two consecutive stresses is cyclic deformation of plant organs.

During the vegetative season when the sun is rising (1) stomata open (2) (Wronski et al., 1985; Herzog et al., 1995). Temperature steadily increases afterward (3), whereas the relative humidity of the air decreases (4). In this way, preferable conditions for high rate of water transpiration (5) are established (Lövdahl and Odin, 1992). Transpiration causes a decrease in water potential in water conduits (6) and eventually leads to water tension (7) in Soil-Plant-Atmosphere Continuum (SPAC). Water tension is a reason for the decrease in hydration of an apoplast (8), which actually means decrease in water potential of the apoplast and ultimately measurable shrinkage of the xylem (9). In this way, a steep gradient of water potential between apoplast and symplast (10) is created (Molz and Klepper, 1972) and in consequence, water flows from turgid cells (living cells of the symplast with high water potential) toward apoplast and water conduits (11) (with lower water potential). Cell-wall pressure (turgidity) pushes water outward in the living cells, effectively decreasing cells' water potential. Loss of water causes a decrease in turgidity (12) and stabilizes the water potential inside the cell at the apoplast water potential level. Loss of turgidity causes shrinkage of living tissues (13) (Yoshida et al., 2000; Tyree and Zimmermann, 2002; Alméras et al., 2006), and the below-threshold value is recognized by a living system as a water stress (14) (Molz and Klepper, 1973). During the day, the mechanism of restoration of the initial water status in cells leads to osmotic adjustment (15). This means that the water stress turns on an adaptational reaction, which decreases osmotic potential, lowering cell water potential (16), and thus preventing outward water movement. Osmotic adjustment allows for maintenance of relatively greater volume at low water potential and it helps to stop decline in turgidity.

As a rule, the process of adaptation toward water stress is overshoot (17) (Beloussov and Grabovsky, 2006) – excessive decrease of water potential in the symplast causes water movement into living cells, though in plant conduits water tension has a very low water potential (refilling under water stress due to osmotic adaptation [18]). It happens when the day is very long and the osmotic adaptation passes through the constraints of water tension.

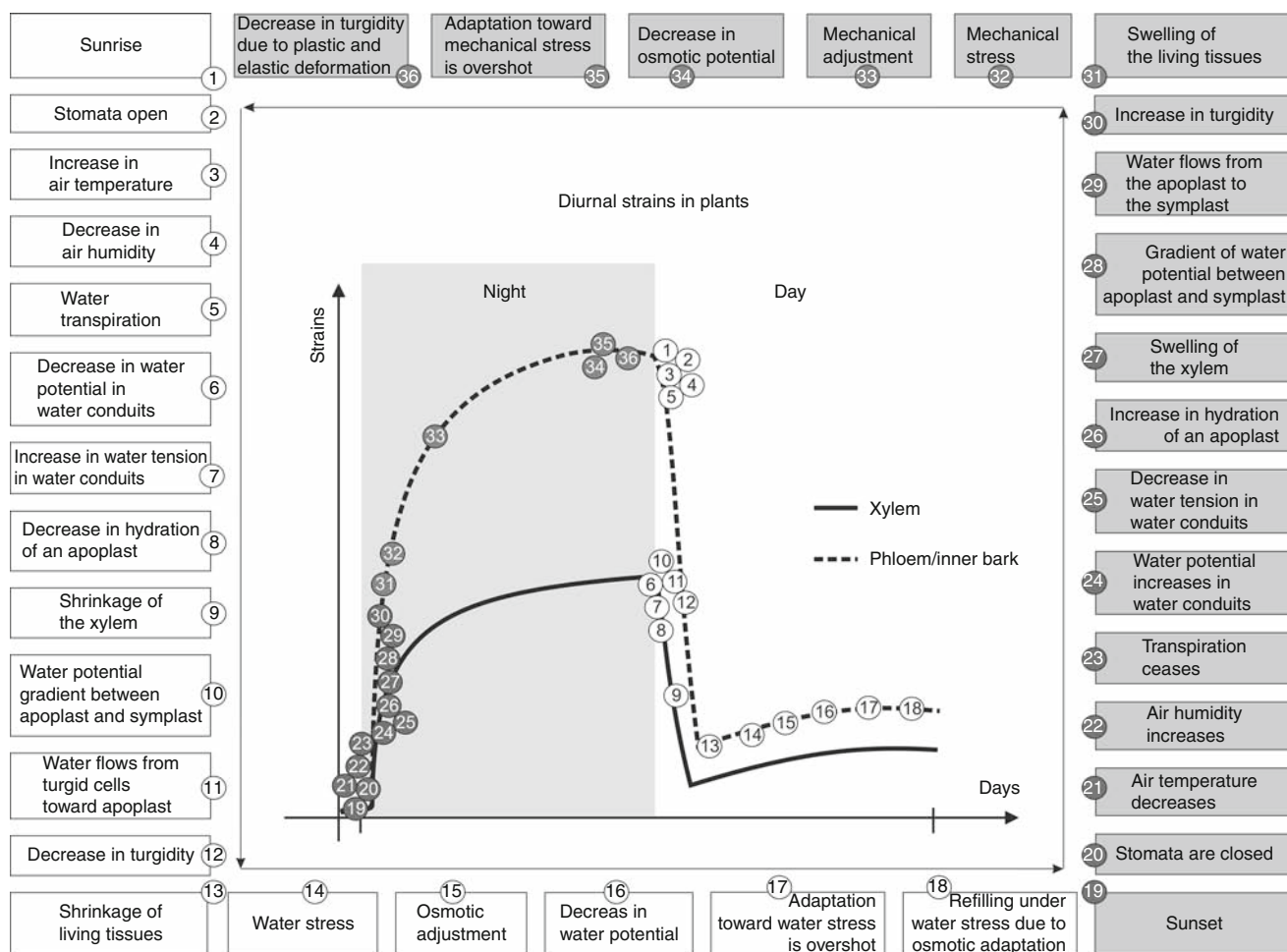
This adaptation to water stress is ended sharply at sunset (19) when stomata are closed (20) (Wang et al., 2008). During the night, air temperature decreases (21) and air humidity increases (22) (Lövdahl and Odin, 1992). In such circumstances transpiration ceases (23). In plant

water conduits water potential increases (24), causing a decrease in the water tension (25). This means rehydration of the apoplast (26). In consequence, swelling of the xylem elements (27) occurs (Mengel and Kirkby, 2001). Higher water potential in water conduits and lower water potential of living cells produce water potential gradient (28) and causes water flow from the apoplast to the symplast (29) (Molz and Klepper, 1972). Rehydration of living cells causes increase in turgidity (30), which at the tissue level is a basis for swelling (elastic and plastic deformation) of living tissues (31) (Yoshida et al., 2000; Tyree and Zimmermann, 2002; Alméras et al., 2006). The water recharging mainly occurs from sunset to midnight (Wang et al., 2008). In this way, during the first few hours of the night, mechanical stress inside the plant is generated (32) (Stankovic et al., 1998). One of the adaptive mechanisms to this stress is mechanical adjustment (33) (cell growth, cell-wall relaxation, schizogenous space formation, or schizolisogenous space formation [Evert and Eichhorn, 2006]). The second adaptive mechanism to this stress is decrease in osmotic potential (34) (osmotic

adjustment). In consequence, adaptation to mechanical stress prevents an uptake of water into living cells, but again this adaptation process is overshoot (35) (Belousov and Grabovsky, 2006) at the end of the night and a small decrease in turgidity can be observed due to mechanical adaptation (i.e., plastic deformation) (36). This happens when the night is very long and mechanical adaptation relaxes tensional stress. Living tissues are vulnerable toward incoming daily water imbalance. On the next day, the whole process starts from the beginning (1) (Figure 1).

Measurements and applications

Diurnal strain measurements are nondestructive and can be monitored continuously with different types of dendrometers. The simplest technique is application of a caliper or one of the linear variable differential transformers (LVDT sensors) based on strain gauges (Ninokata and Miyazato, 1959; Klepper et al., 1971; Okuyama et al., 1995; Yoshida et al., 2000; Daudet et al., 2005). New noninvasive techniques are still developing. One of



Diurnal Strains in Plants, Figure 1 Mechanism of diurnal strains fluctuation. Numbers between 1 and 18 represent processes and events during the day and numbers from 19 to 36 symbolize processes and events during the night.

the most promising techniques which allows truly noninvasive measurements is digital image correlation (DIC) (Sutton et al., 2000). A second new technique is Electronic Speckle Pattern Interferometry (ESPI) (Jones and Wykes, 1989). Optical methods are inherently nonintrusive and noncontacting. They are highly also sensitive and provide full-field measurement data.

Diurnal strain measurements are potentially a powerful tool for studying (Alméras, 2008):

1. Tree physiology, i.e., helps to obtain information about:
 - (a) Tree water status (Klepper et al., 1971; So et al., 1979; Ueda and Shibata, 2001)
 - (b) Water transport (Zweifel et al., 2000; Sevanto et al., 2002)
 - (c) Transpiration rate (Herzog et al., 1995)
 - (d) Spatial and temporal patterns of physiological activity (Sevanto et al., 2002)
 - (e) Cambial growth dynamics (Kozłowski and Winget, 1964; Deslauriers et al., 2003)
 - (f) Wood morphogenesis (Okuyama et al., 1995; Abe and Nakai, 1999)
 - (g) The transport of sugar in phloem (Sevanto et al., 2003; Daudet et al., 2005)
 - (h) The rate of embolism in a stem (Hölttä et al., 2002)
 - (i) Embolism removal (Zwieniecki and Holbrook, 1998)
 - (j) The reduction in wood conductivity in senescent trees (Ueda and Shibata, 2002)
2. Practical applications, such as:
 - (a) Correcting continuously recorded dendrometric data (Kozłowski and Winget, 1964; Deslauriers et al., 2003)
 - (b) Estimating transpiration (Herzog et al., 1995)
 - (c) Establishing irrigation scheduling (Goldhammer and Fereres, 2001; Remorini and Massai, 2003)
 - (d) Detecting the effects of pathogens on plant water status (Cohen et al., 1997)

Summary

Daily shrinkage in plant organs is generally related to the variation in water potential. Plant organs shrink during the day because plants lose more water by transpiration than they can take up. The higher the water stress, the more the water lost during the day. At night, when there is little loss of water, plant organs will increase in diameter because of the uptake and storage of water. Since the living cells are much more elastic than wood cells, diurnal plant organ fluctuations are mainly influenced by changes of the thickness of living tissues. Therefore in stems of woody plants, the shrinking and swelling take place mainly in a ring of phloem outside the xylem. Both the shrinkage and swelling of the cells, tissues, or organs are the effects of stress. Shrinkage is caused by daily water stress, whereas swelling is caused by nocturnal mechanical stress. Whenever a change of local stress is applied to cells or tissue, they respond by actively generating forces

directed toward the restoration of the initial stress value (adaptation), but by overshooting it. This causes cyclic deformations which partly are irreversible. The irreversible part of deformation is called growth.

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 Weather, Effects on Plants

DNA IN SOILS: MOBILITY BY CAPILLARITY

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Synonyms

Vertical advection

Definitions

DNA. Deoxyribonucleic acid that carries the genetic information in the cell and is capable of self-replication and synthesis of RNA (ribonucleic acid) in a process called transcription. DNA consists of two long chains of nucleotides twisted into a double helix and joined by hydrogen bonds between the complementary bases adenine and thymine or cytosine and guanine.

Soil. The top layer of the Earth's surface, consisting of rock and mineral particles mixed with organic matter. It plays an irreplaceable role in the biosphere because it governs plant productivity of terrestrial ecosystem and allows the completion of the biogeochemical cycles through its inhabiting microorganisms. The main characteristics are the domination of the solid phase, the presence of aqueous and gaseous phases, and its capacity of reactions by surface-active particles.

Vadose zone. Also termed the unsaturated zone, it is the portion of Earth between the land surface and the phreatic zone or zone of saturation (“vadose” is Latin for “shallow”). Water in the vadose zone has a pressure head less than atmospheric pressure, and is retained by a combination of adhesion (*funicular groundwater*) and capillary action (*capillary groundwater*).

Advection. A transport mechanism of a substance with a fluid in motion. An example of advection is the transport of solutes (DNA, pollutants) in the soil water flow.

Capillarity. The flow of liquids through porous media, such as the flow of water through soil. The capillary fringe is the subsurface layer in which groundwater seeps up from a water table by capillary action to fill pores. If pore size is small and relatively uniform, it is possible that soils can be completely saturated with water for several feet above the water table. Alternately, the saturated portion

will extend only a few inches above the water table when pore size is large. In smaller pores of the soil, water is held against the force of gravity by capillary forces and is called capillary water. This constitutes the only available source of water to plants.

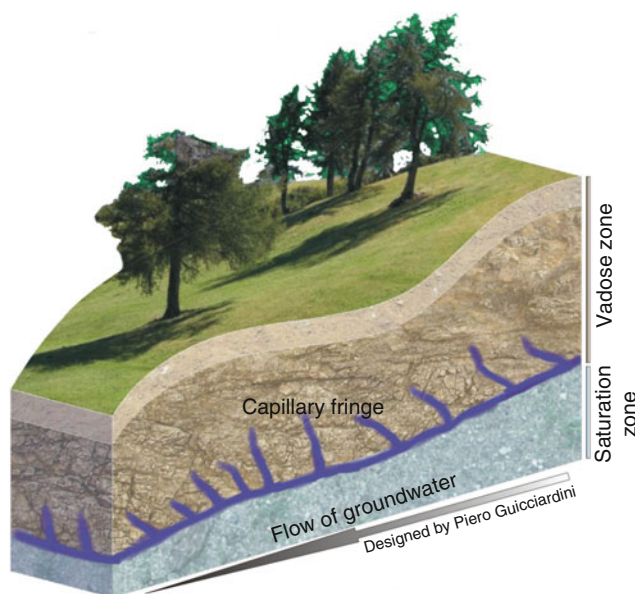
Real-time PCR. It allows for the detection of PCR (Polymerase chain reaction) amplification during the early phases of the reaction and this provides a distinct advantage over traditional PCR detection. Traditional methods use agarose gels for detection of amplicons at the final phase of the PCR reaction. Real-time PCR detects the accumulation of amplicons during the reaction and the data is measured at the exponential phase.

Introduction

The total soil DNA (tDNA) includes both intracellular (iDNA) and extracellular DNA (eDNA), with the latter originated from the former by active or passive extrusion mechanisms or by cell lysis. The eDNA can represent a relevant fraction of tDNA and thus a significant portion of the entire soil metagenome. Studies on the ecological relevance of eDNA in soils have concerned the gene transfer through transformation and interaction between eDNA molecules with the reactive surface of clay minerals, humic substances, and sand particles (Nielsen et al., 2006). Only recently has the attention been directed at the role of eDNA in the formation of bacterial biofilm in soil (Böckelmann et al., 2006) and at the possibility that eDNA can be transported by water through the soil profile (Agnelli et al., 2004). The key role of transformation in evolutionary terms justifies to continue the investigation on the fate of extracellular DNA in soil (Pietramellara et al., 2007). Extracellular DNA is also an important source of nitrogen and phosphorous, which are recycled by bacteria for the synthesis of new DNA; it might participate in gene transfer and, thus, in microbial evolution (de Vries and Wackernagel, 2004). Researches demonstrate that transgenes can move beyond the intended organism and into the surrounding environment, and it can be subjected to vertical advection if in the water solution (Dighton et al., 1997; Poté et al., 2003; Ceccherini et al., 2009b) that is in the vadose zone (Figure 1) of soil (Arias-Estévez et al., 2008). The extracellular DNA can be transported in the soil water flow also by horizontal movements, in fact, using soil column systems, the vertical and horizontal movements of a target sequence were monitored and quantified via real-time PCR in microcosm (Ascher et al., 2009) and *in field* experiments (Ceccherini et al., 2009a).

The extracellular DNA in soil

The release of DNA in soil is still poorly known and, for this reason, it is interesting to briefly discuss on what is known on the release of DNA from bacteria, fungal cells, and plant cells in soil. Conditions causing cell death are important for the release of DNA molecules; in prokaryotic and eukaryotic cells, the release can occur by physical



DNA in Soils: Mobility by Capillarity, Figure 1 Some different forms of soil water.

or spontaneous damage of the cell, by pathogen-induced cell lysis and necrosis or by active extrusion (Levy-Booth et al., 2007). Many genera of environmental bacteria, such as *Acinetobacter*, *Bacillus*, *Micrococcus*, release DNA during growth in liquid media (Lorenz and Wackernagel, 1994; Paget and Simonet, 1994), and this release can be stimulated by the presence of other organisms (Matsui et al., 2003). Here some examples are reported to give concise information to the readers. During biofilm formation by *Pseudomonas aeruginosa*, active DNA extrusion involved acylated homoserine lactone signaling molecules and was inhibited by halogenated furanone (HF). The DNA extrusion can also occur by membrane vesicle lysis, a process regulated by quorum sensing (Allesen-Holm et al., 2006). The breaking of bacterial cell walls and membranes can also occur by autolysis with release of DNA and RNA (Nishimura et al., 2003).

The release of DNA from fungal cells has been less investigated than that from bacterial cells despite 70% of the DNA in soil being of fungal origin (Borneman and Hartin, 2000).

Several studies have investigated the persistence of plant DNA in the terrestrial environments (Widmer et al., 1996; Lynch et al., 2004) but the release of DNA from plant roots and plant debris is still poorly understood. This release can occur after autolysis and decomposition of wilting tissues, by mechanical disruption of tissues or by enzymatic degradation of cell structures by plant pathogens. It is well known that chlorophyll, proteins, and RNA molecules are enzymatically degraded during leaf senescence (Green, 1994), and this probably also occurs for the DNA molecules.

Only few reports have studied the release of DNA from plastids or mitochondria. Probably, their DNA is more protected than the chromosomal one against degradation by cytoplasmic nuclease activity, due to the presence of the organellar membranes (Nielsen et al., 2006). However, some authors (Ceccherini et al., 2003) reported a 98% loss of a chloroplast *aadA* gene in ground tobacco leaf material after 72 h as compared to a 56% loss of total DNA. Finally, during the decomposition of dead cells and tissues, conditions such as rapid desiccation, low temperatures, high salt concentrations, or low pH values, can affect the activity of the endoenzymes, increasing the persistence of both cells or tissues and their DNA (Hofreiter et al., 2001).

However, DNA released into the soil environment, both after cell death and by active extrusion, rarely is present as a pure molecule. Generally the DNA is released in the extracellular environment together with proteins, glucides, lipids, which could be considered as constitutional organic components (COC), and with RNA and cellular wall debris (CWD); this kind of DNA was termed “dirty eDNA” (Tamayo et al., 1999; Pietramellara et al., 2007).

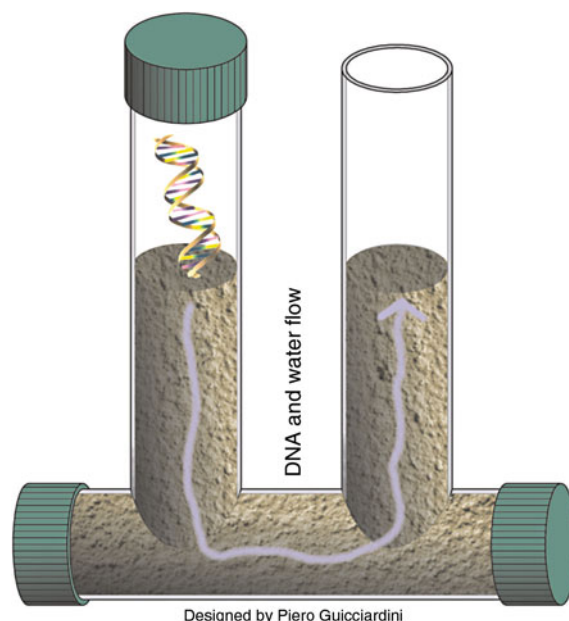
The capillarity

Soil capillaries are characterized by a rapid transport of water and solutes through the soil. These flows occur in macropores such as root and earthworm channels, mouse burrows, fissures, and cracks. Through preferential flow, there is transport of dissolved organic matter, like extracellular DNA, following vertical advection movements, and this soil area shows higher microbial biomass than the soil matrix, with an enhanced turnover of soil organic matter and nutrients (DiCarlo et al., 1999). A significant aspect of the majority of the studies on soil ecology is the lack of a dynamic soil system with water movement. Therefore, information on the transport of eDNA and on its potential transforming ability in subsurface soil is lacking. Moreover, plants get most of their water from capillary water retained in soil pores after gravitational water has drained and surface tension (suction) holds capillary water around the soil particles. As water is removed by plants or by evaporation from the soil surface, the films of water remaining around the soil particles become thinner and are held by the soil particles more tightly. This underlines the interest of some authors to monitor the movements and thus the fate of eDNA, using simulating or natural soil systems.

One of this kind of studies, addressing the possibility that DNA could move vertically in the capillary fringe, monitored the 35S-*nptII* sequence by PCR. DNA was added as a water solution at the bottom of the unsaturated soil column. After the addition, capillary water rose 4 cm within the soil column and the target DNA was detected up to that height. After a second wetting (12 h later), the target sequence was detected up to the top of the soil column (10 cm). However, after a third wetting

(24 h later), the marker sequence was only found at heights from 0.5 cm to 4 cm. Results clearly showed the vertical movement of DNA due the capillary rise and suggested the possibility of DNA degradation within the soil column (Ceccherini et al., 2007). Moreover, using simulating systems, the movements of a target sequence, belonging to *bt*-maize MON810, were quantified via real-time PCR. The genomic DNA was added at the top of unsaturated soil columns (Figure 2). The presence of the sequence in the eDNA fraction extracted from representative parts of the soil columns, demonstrated the DNA drifts in vertical and horizontal directions following the water solution motions. The high yields of the target sequence quantified in the eDNA also pointed out the efficiency of the eDNA extraction method (Ascher et al., 2009).

To complete this brief description, it is interesting to report some studies about solute movements by the gravitational pathway in soil. In a first case, unsaturated soil columns were used to examine the release and transport of DNA content of a tomato leaf, which was introduced into a column system after being dried at 35°C for 3 days. DNA from column leachate water was extracted and analyzed and tomato sequences detected by specific PCR amplification. Analysis using agarose gel electrophoresis showed degradation of DNA after its passage through unsaturated soil columns. The presence of tomato genes in the leachate water suggested a potential release of DNA from leaves and a potential transport of DNA over considerable distances in water-unsaturated soil. Consequently, transport of plant DNA in the vadose zone is



DNA in Soils: Mobility by Capillarity, Figure 2 Representation of a column system used to show the vertical and horizontal fluxes of a DNA solution in soil.

indicated, and also the risk that the DNA may reach the groundwater (Poté et al., 2007). In a second case, the study addressed the possibility that a target sequence of transgenic *bt*-maize could be detected *in field* where the crop was growing. The rhizosphere eDNA was extracted at different times, representative of maize growing stages and the target sequence was quantified via real-time PCR. This molecular approach revealed to be suitable for specific detection of target DNA, supporting the persistence of DNA *in field* (Ceccherini et al., 2009a).

Conclusions

The importance of natural transformation in evolutionary terms represents a valid reason to improve the investigation on the fate of extracellular DNA in soil. Several authors have demonstrated that there is a sharp discrepancy between its biological efficiency and its persistence; fragments of target DNA were detected after a long time in soil but no transformations were determined, probably because the genetic information originally present in the complete DNA molecule could be lost by degradation. Availability of water in soil is an important factor driving microbial activity. In bulk soil, bacterial cells occur mainly adsorbed to surfaces, refractory to movement, interacting only with partners in their immediate vicinity, unless they are transported by the soil water solution. Thus, water flow by capillarity induced by plant uptake and evaporation from soil surface, enhancing microbial and eDNA movements, can promote cellular activities with possibilities of horizontal gene transfer.

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Cross-references

Biofilms in Soil
 Microbes and Soil Structure
 Microbes, Habitat Space, and Transport in Soil
 Soil Functions
 Soil Water Flow
 Surface and Subsurface Waters

DOUBLE LAYER

See *Electrical Double Layer (Diffuse Layer, Double Layer)*

DRAINAGE

Outflow of water from the soil, either naturally or artificially. Surface drainage refers to the downslope flow of excess water from the soil surface. Subsurface (groundwater) drainage refers to the removal of water from within or below the soil, generally involving the lowering of the water table.

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Cross-references

Irrigation and Drainage, Advantages and Disadvantages

DRIP IRRIGATION

An irrigation method which allows water and fertilizers to drip slowly to the root system of plants. Either onto the soil surface or directly onto the roots. This method provides farms the most efficient way to grow crops in water scarce areas.

Cross-references

Irrigation and Drainage, Advantages and Disadvantages
 Irrigation with Treated Wastewater, Effects on Soil Structure

DROUGHT

An extended period of dry weather which, as a minimum, can result in a partial crop failure or an inability to meet normal water demands.

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Library of Congress Cataloging-in-Publication Data Environmental engineering dictionary and directory/Thomas M. Pankratz <http://www.docstoc.com/docs/2845196/CRC-Press>

Cross-references

Drought Stress, Effect on Soil Mechanical Impedance and Root (Crop) Growth

DROUGHT STRESS, EFFECT ON SOIL MECHANICAL IMPEDANCE AND ROOT (CROP) GROWTH

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Definition and introduction

While there is no doubt that limited water availability decreases root growth, it is often assumed that this is the main cause of decreased growth in drying soil. However, this may not always be the case. Many laboratory experiments on water stress use growth media where the mechanical impedance remains low and constant as its matric potential becomes more negative. For example, roots are often grown in vermiculite, where water content is adjusted to give a required matric potential, or in solutions such as PEG that are adjusted to a required osmotic potential (Whalley et al., 2000). However, as the water potential of the root environment becomes more negative, not only does the elongation rate decrease but also the pressure that roots are able to exert on their surroundings (Whalley et al., 1998). While this effect on root growth pressure may not be relevant to elongation through media with negligible impedance, it is relevant to elongation through strong soil. In fact, root growth pressure is far more sensitive than the rate of elongation (through low-impedance media) to water potential. As the matric potential of most soils becomes more negative, its strength increases greatly. There are relatively few studies that consider both soil strength and water potential, but those that do conclude that soil strength has a greater effect on root growth and penetration than soil water potential (e.g., Mirreh and Ketcheson, 1973; Yapa et al., 1988; Whalley et al., 1999). A difficulty of such experiments is that it is difficult to control soil water status and mechanical impedance independently (Whalley et al., 2000). To fully understand the effects of high soil strength on root elongation,

the relationship between soil water status and soil strength must be understood.

Soil strength and soil water status

For loose soil, with a bulk density less than about 1.4 g cm^{-3} , effective stress (product of degree of saturation and matric potential) gives a common relationship between penetrometer pressure and soil water status for a wide range of soils (Figure 1). Soil strength increases rapidly with soil drying, and even relatively wet soils are found to be strong even though they had not been compacted. In denser soils, however, empirical models that predict penetrometer resistance depend on soil type (e.g., Hernanz et al., 2000). Although good models to predict the penetration resistance of soil exist (Farrell and Greacen, 1966), in practice they are difficult to use because they need such extensive soil characterization. The following pedotransfer function to predict soil penetrometer resistance, Q , from soil density, ρ , degree of saturation, S , and matric potential Ψ

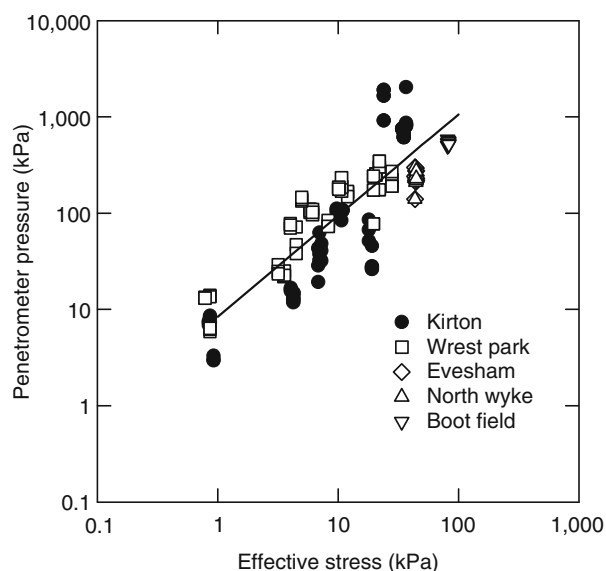
$$\log_{10} Q = 0.35 \log_{10}(|\Psi S|) + 0.93 \rho + 1.26 \quad (1)$$

was developed for a large number of Canadian soils (Whalley et al., 2007). This has the advantage that details of particle size distribution and organic matter content are not needed and data from moisture sensors can be used to predict penetrometer resistance, provided bulk density is known. An anomalous prediction of Equation 1 is that, as soil becomes increasingly dry and S approaches zero, the soil is predicted to become weaker, decreasing from

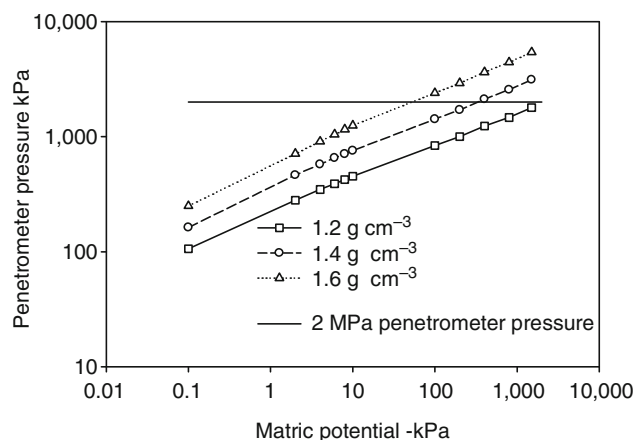
a maximum. For sand-kaolinite mixtures, this has been shown to be the case (Mullins and Panayiotopoulos, 1984) and beach sand also behaves in a similar manner. However, in agricultural soils strength does not decrease from the maximum, probably because of cementation by biological exudates and mineral precipitation as soil dries. Since Equation 1 was fitted to data from agricultural soils for $\Psi > -1.5 \text{ MPa}$, this anomalous behavior has been taken into account empirically. One of the implications of Equation 1 is that when soil is dense, high penetrometer pressures will be reached in much wetter soils than is the case for loose soil (Figure 2). Field data from Whalley et al. (2006) confirms that in the field, high soil strength occurs in relatively well-watered environments (see Figure 3). Penetrometer pressures in excess of 2 MPa were found in soil maintained at matric potentials of approximately -80 kPa .

Root elongation rate and soil strength

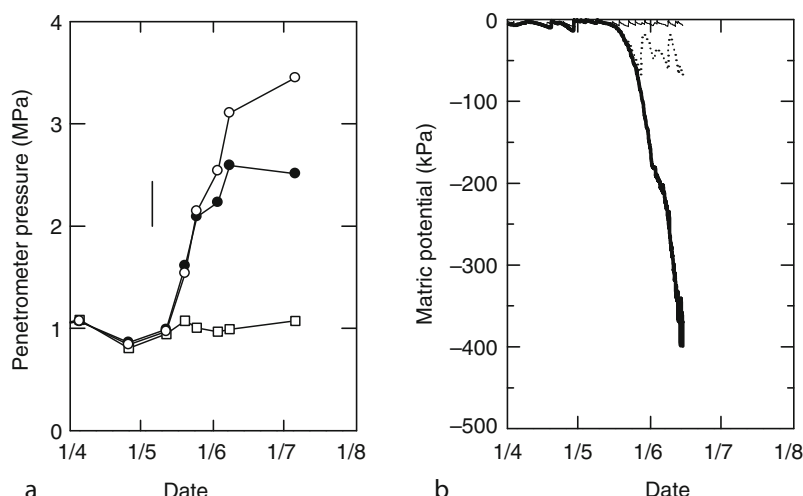
Penetrometer pressures between 2 and 3 MPa are commonly cited as a threshold to root elongation. However, root elongation rate decreases approximately linearly as soil strength increases (Bengough and Mullins, 1991). There has been a considerable research effort directed at understanding the elongation rate of roots growing in soils of various strengths. A seminal paper is that of Greacen and Oh (1972), who set out how the difference in pressure due to soil strength and cell turgor was accommodated by the cell wall. This model is appealing in its simplicity, but unfortunately it is inconsistent with physiological measurements. Passioura and Fry (1992) proposed a solution to allow ephemeral changes to elongation rate, due to set increases in turgor, as observed experimentally in algal



Drought Stress, Effect on Soil Mechanical Impedance and Root (Crop) Growth, Figure 1 Resistance to a rotating penetrometer plotted against effective stress for five different soils. (From Whalley et al., 2005). Resistance to a rotating penetrometer is considered to be a good approximation to the resistance to root penetration.



Drought Stress, Effect on Soil Mechanical Impedance and Root (Crop) Growth, Figure 2 Relationships between penetrometer pressure and matric potential calculated with Equation 1 using water release characteristic data for a silt soil. The horizontal line indicates a penetrometer resistance that is becoming too high for root elongation. As a dense soil dries, this penetrometer resistance is reached at a much higher value (i.e., in a wetter soil) in comparison with the loose soil. (Redrawn from Whitmore and Whalley, 2009.)



Drought Stress, Effect on Soil Mechanical Impedance and Root (Crop) Growth, Figure 3 The mean penetrometer resistance at a depth of 20 cm (a), the matric potential at a depth of 20 cm plotted against time (b) due to soil drying by wheat. The effects of three treatments are shown. These were well watered (open squares on the left panel and faint black line in right panel), drying limited to -80 kPa (closed circles on the left panel and dotted line in right panel), and finally rain fed (open circles on the left panel and heavy black line in right panel). The vertical line on the panel (a) is the SED (standard error for the difference). Note that when soil dries to -80 kPa, the penetrometer resistance exceeds 2 MPa. (Redrawn from Whalley et al., 2006.)

cells. To our knowledge this model has never been applied to root elongation which is probably because too much detailed information on cell-wall stiffening as a response to external stresses is needed.

Root penetration at boundaries

Roots can grow into rigid pores smaller than their nominal diameter (Bengough et al., 1997; Scholefield and Hall, 1985). In ryegrass, Scholefield and Hall (1985) found that this ability was limited by the size of the root cap and the stele, but Bengough et al. (1997) reported that the stele of maize roots did narrow in response to radial constriction. In soil, roots will often exploit cracks, voids, and large pores, or enlarge smaller pores by displacing soil particles. On encountering strong soil, root cell division and elongation are decreased (Eavis, 1967). Root diameter just behind the apex increases, and the production of lateral roots can be increased and also commences closer to the apex (Atwell, 1988). The increase in root diameter in response to impedance is caused by cortical cells enlarging radially rather than axially, with a corresponding change in the orientation of the cellulose microfibrils in the cell walls (Veen, 1982).

Thicker dicot roots have been observed to penetrate compacted subsoil in the field better than thinner monocot roots (Materechera et al., 1991, 1992). In both pea and lupin, 59% of the roots that reached the compacted layer were able to penetrate it, whereas in wheat and barley the root penetration was only 33% and 36%, respectively. The same authors found that species with thicker roots had better penetration of the subsoil, and particularly that the extent of thickening in the high-impedance treatment

Drought Stress, Effect on Soil Mechanical Impedance and Root (Crop) Growth, Table 1 Bending stiffness of roots of Azucena and Bala which had been grown either in strong (Impeded) or in weak (control) sand. The data was Log transformed before REML (analysis using the method of residual maximum likelihood) and the SED (standard error for the difference) is 0.1359. The back transformed bending stiffness in N mm^{-1} is shown in brackets. (Taken from Clark et al., 2008a.)

	Control roots	Impeded roots
Azucena	-1.606 (0.2000)	-1.765 (0.1712)
Bala	-2.698 (0.0673)	-3.607 (0.0271)

relative to the control was important. It was also suggested that thicker roots gave better penetration because they would be more resistant to buckling (Barley and Greacen, 1967). In rice, genetic variability in root penetration into strong layers has been associated with genetic control of root diameter (Clark et al., 2008a). Although, greater bending stiffness in rice was associated with better penetration of strong layers, Clark et al. (2008a) noted that the process of penetration of a strong soil reduced bending stiffness (Table 1). This was thought to be due to cell-wall relaxation, which is implicated in the development of growth pressure (Clark et al., 1996).

An important observation by Clark et al. (2008b) is that the penetration of roots into a strong layer can be increased if there is a spatial gradient in soil strength. When there was a spatial gradient in strength, the penetration ability of Bala (a poor performing rice line) to penetrate a wax layer was similar to the better-performing Azucena in the absence spatial gradient in soil strength.

Summary

The most important message to take is that increases in soil strength sufficiently large to impede root elongation can occur after only a moderate degree of soil drying. In Figure 3, it can be seen that at matric potentials of around -80 kPa, which would normally be considered well watered for field-grown crops, penetrometer pressures in excess of 2 MPa were recorded. In such conditions root elongation is limited by high soil strength and not by the lack of water availability.

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Cross-references

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DRYING OF AGRICULTURAL PRODUCTS

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Definition

Drying is the process of the removal of water (moisture) from hygroscopic materials at low to medium moisture contents (normally $<30\%$ wet basis) by means of evaporation. When the moisture content of the agricultural products is high (usually $>50\%$ wet basis) the process of

removal of moisture is referred to as dehydration. The examples of the products that are dried include cereals, oilseeds, legumes, and some processed foods; and examples of the products that are dehydrated include fruits, meats, and vegetables (Pabis et al., 1998; Sokhansanj and Jayas, 2006).

Process

Drying/dehydration is one of the most important postharvest treatments being adopted worldwide to reduce the spoilage and increase the shelf life or storage durability of agricultural products. Removal of moisture is a complex simultaneous heat and mass transfer process but treating it as such is not sufficient because end use characteristics or quality of the product cannot be handled this way. Moisture from inside the hygroscopic materials moves to the surface and then it evaporates to the surrounding atmosphere. This movement in moisture is caused by the gradient of water vapor pressure being high inside the materials to being low outside the materials. The movement of moisture could be by liquid diffusion, vapor diffusion, capillary flow, or a combination of these features. Usually the moisture gradient is established by application of heat from external sources. The process can be done at atmospheric pressures but can also be done under vacuum, and similarly the process can be done at a range of temperatures. The selection of the process temperature and pressure depends on the end use quality of the dried/dehydrated products. Heat is transferred to the product by a heating medium usually hot air or superheated steam, this heating medium also carries the moisture away from the product. Sometimes heat can be applied by contact such as by mixing hot sand with granular material or by coating a liquid product on a rotating drum whereas at other times heat could be applied through radiation, for example, in infrared dryers or through volumetric heating, for example, in microwave dryers. Drying of products using solar radiation (sun drying) is the simplest and oldest form of drying; however, sun drying is weather dependent and is slow, therefore other sources of heat are used. Depending on the heat source, operating pressure, and operating mechanism, dryers are classified as hot air, infrared, microwave, vacuum, freeze, flash, superheated steam, spouted bed, fluidized bed, and spray. The dryers are also classified based on the relative flow of material and the heating medium as concurrent flow, counter flow, cross flow, or mixed flow.

Challenges in drying agricultural products

Most dehydrated products are rehydrated prior to consumption; therefore, the texture and taste of the product

after rehydration are important quality parameters. Since agricultural products are sensitive to the heat (temperature), improper drying may cause the thermal damage to the product and the product may be spoiled or quality of end product may be poor. Under-drying will reduce the shelf life and over-drying will result in loss of mass, more power consumption, and thus economical losses. Drying characteristics of various agricultural and biomaterials are different and are also influenced by growing region, growing season, and weather conditions; therefore, it becomes necessary to study drying characteristics of the specific product for design of proper and efficient dryers.

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Cross-references

[Aeration of Agricultural Products](#)
[Hysteresis in Foods](#)
[Solar Drying of Biological Materials](#)
[Water Effects on Physical Properties of Raw Materials and Foods](#)

DURIPAN

A subsurface soil horizon that is cemented by illuvial silica, usually opal or microcrystalline forms of silica, to the degree that less than 50 percent of the volume of air-dry fragments will slake in water or HCl.

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Cross-references

[Claypan and its Environmental Effects](#)

DYNAMIC LOAD

A load connected with the elastic deformations of a body (e.g., soil, grains, fruits) subjected to time-dependent external forces.

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