VI

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5 Precision Agriculture

5.1 Image Sensing and Phytobiological Information

K. Omasa

Abstract. *Phytobiological information on plants and soils is useful in order to optimize mechanized and sustainable agricultural systems. In this section, promising image-sensing techniques for obtaining phytobiological information are briefly introduced, and the concept of a phytobiological information system (PIS) for plant production and sustainable agriculture is described.*

Keywords. *Imaging, Fluorescence, Phytobiological IT, Plant functioning, Spectral image, Sustainable agriculture, Thermal image, 3-D.*

5.1.1 Introduction

Precision agriculture has developed with the computerization of agricultural production systems and the networking of computerized control systems [1-3]. In the intelligent plant production system of controlled greenhouses, information on plant responses, measured by sensors, is used to optimize the system. In particular, information on shapes, components, and functions of living plants obtained by image instrumentation is effectively used for diagnosis and control of production processes. Such an approach is known as the "speaking plant approach (SPA)" [4]. Recent advances in biotechnology and micropropagation demonstrate the importance of developing the SPA to the level of cells and tissues.

Meanwhile, interest in sustainable and environmental agricultural engineering is increasing [3,5,6]. New types of agricultural engineering, including precision farming, recycle-type agriculture, and controlled agroforestry, may harmonize increases in plant production with environmental conservation and remediation in order to cope with global environmental problems. Hierarchical remote sensing from satellites, aircraft, vehicles, etc., is a powerful tool for the new type of agricultural engineering because it provides useful spatial information on the functioning of plants and agroecosystems. For example, spatial information from remote sensing used with precision farming results in more accurate farm work, with localized on-demand fertilizing and localized control of weeds and pests [3,7]. In particular, precision farming using autonomous vehicles needs to join with close-up remote sensing to obtain phytobiological information on plants and soils. It is also necessary for hierarchical remote sensing to verify remote sensing data from satellites and aircraft by exact phytobiological data from close-up remote sensing.

In this section, promising image-sensing techniques in image instrumentation and the close-up remote sensing for obtaining phytobiological information on plants and soils are introduced, and then the concept of the phytobiological information system (PIS) for using image sensing, including large-area remote sensing from satellites and aircraft, is described.

5.1.2 Image-Sensing Techniques for Obtaining Phytobiological Information

Table 1 shows typical image-sensing techniques for obtaining phytobiological information on plants and soils. Trends in image sensing techniques include hyperspectral, three-dimensional, and active sensing. Ordinary *multispectral* imaging is available for obtaining phytobiological information on color, pigments, shape, and growth of individual plants and parts; changes in water status in plants and soils; and soil properties [8-13]. *Hyperspectral* image sensing is capable of resolving several hundred spectral bands in the region from visible light to short-wave infrared and may make it possible to provide more phytobiological information by analysis of continuous spectral properties, compared with ordinary multispectral analysis. *Thermal infrared* imaging (a passive spectral imaging method) is effective for early detection of plant stresses as well as for measurement of surface temperatures of plants and soils [9,10,14]. Image analysis of the energy balance on the leaf and canopy provides phytobiological information on stomatal response and evapotranspiration [15-17]. *Fluorescence* image sensing methods (which are active methods), such as spectral analysis of steady-state laser-induced fluorescence (LIF), provide phytobiological information on changes in cell walls bound by fluorophores and on bleaching of plant pigments [18,19]. Analysis of chlorophyll *a* fluorescence induction is used not only for early detection of patchy changes in stomatal aperture and photosynthetic activity caused by biotic and abiotic stresses, but also for information about the development of the photosynthetic apparatus of attached leaves [20,21]. *Three-dimensional (3-D) surface imaging*, such as stereo-pair images and laser scanners (scanning range finders), makes it possible to remotely estimate 3-D structure and growth of plants and canopies

Table 1. Image-sensing techniques for obtaining phytobiological information on plants and soils.

Image Sensing Techniques	Phytobiological Information
• Multi- or hyperspectral image sensing (near UV to near-infrared, including color)	• Color, shape, and growth of individual plants and parts, plant pigments, water status, soil properties
• Thermal image sensing	• Temperature, evapotranspiration, stomatal response
• Fluorescence image sensing (LIF, Chl fluorescence, etc.)	• Bleaching of plant pigments, movement of fluorophores in mesophylls, photosynthetic system
• 3-D surface image sensing (stereo, shape-from-x, laser scanner)	• 3-D surface structure and biomass of plants and canopy
• 3-D light microscopic imaging	• 3-D structure and functions of cells and tissues
• CT (X-ray CT, MRI, optical CT, etc.)	• 3-D structure and content, transfer and metabolism of biochemical components of/in tissues and plants

[22-25]. The *confocal laser-scanning microscope system* (a newly computerized light microscope system with a large working distance) and *CT* (computed tomography) techniques also provide information on 3-D structure and functions of and in cells, seedlings, and plants [10,26-29].

5.1.3 Multispectral or Hyperspectral Image Sensing

Reflectance spectra of plants and soils in the visible to short-wave infrared region (400 to 2,500 nm) include a large amount of phytobiological information [8,12,30,31]. Typical reflectance spectra of healthy and dead (dry) cucumber leaves and wet and dry loamy soils are shown in Figure 1. Absorption of photosynthetic pigments such as chlorophylls, carotenes, and xanthophylls in the leaf dominates the visible region from 400 to 700 nm [8,30,31]. Although each of the pigments has absorption maxima in the 300- to 500-nm region, only chlorophyll absorbs in the red region of 600 to 700 nm as well as the blue region. Leaf reflectance drastically increases in the region from 690 to 740 nm (red-edge) and keeps a high value to 1,300 nm (near-infrared), although the change in soil reflectance is slight. The near-infrared region is influenced by cellular structure and refractive indexes within the leaf. Absorption of water dominates the near-infrared and mid-infrared regions of 900 to 2,500 nm in healthy leaves and wet soil; and major absorption bands of water occur at 1,450 nm and 1,940 nm, and the minor absorption bands appear near 960 and 1,200 nm. Other biochemical components such as carbohydrates (starch and cellulose), protein, lignin, N, P, K, and Mg have absorption maxima in short-wave infrared region of 900 to 2,500 nm, although the molecular functional groups contributing to this are primarily limited to C-H, O-H and N-H [30]. However, note that optimum reflectance bands for estimating effects of water stress on plants and contents of biochemical components are not necessarily the absorption maxima [9,30,32].

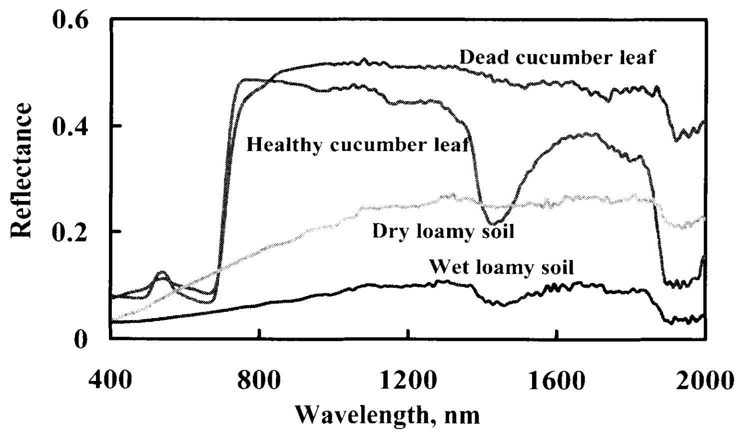

Figure 1. Typical reflectance spectra of healthy and dead (dry) cucumber leaves and wet and dry loamy soils.

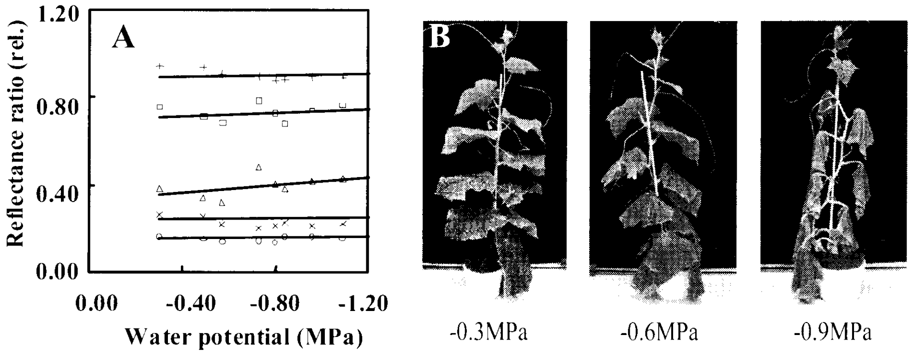

Figure 2. Changes in the reflectance band ratio of recoverable cucumber leaves with water potential above −1.2MPa (A) and the plants (B) [32]. Symbols in A: x = band ratio of 550 nm/850 nm; o = 680/850; + = 1,200/850; Δ = 1,450/850; □ = 1,650/850.

Spectral analysis of several bands with special reflectance features in the region from visible to near-infrared has been widely used for multispectral image sensing [9-11,33]. The use of the near-infrared region with high leaf reflectance allows easy separation of plants from the background soil. Spectral analysis of the visible region including color information (hue, saturation, lightness) is effective for separation of leaf, petal, fruit, and other parts of plants and their growth analyses. Leaf water status has been estimated using spectral reflectance [32,34-36]. The band ratio of 1,450 nm to 850 nm showed a good linear correlation (R^2 = 0.91) over a wide range of water potentials above −7.1 MPa, which was the water potential of a dry leaf, but only slight changes occurred in the band ratio of recoverable leaves with water potential above −1.2 MPa (Figure 2) [32].

Changes in plant pigment content have been assessed by ratios of spectral reflectance bands. For example, chlorophyll *a* content was estimated at R^2 = 0.90 by using a band ratio of 550 nm and 900 nm [9]. The change in red-edge also depends on chlorophyll content. Therefore, these analyses have been used to detect symptoms of nutrient deficiency and other injuries that cause changes in chlorophyll content [30,31]. Figure 3 shows a hyperspectral camera joined to a portable scanning range finder (lidar) and typical spectral reflectance and band ratio images of wheat plants cultured under different amounts of nitrogen fertilizer. The spectral reflectance images were measured at 1-nm intervals by the hyperspectral camera. As shown in Figure 1, the spectral reflectance in the visible region from 400 to 700 nm was small because of absorption by photosynthetic pigments in the leaf. In particular, the reflectance showed the minimum at the absorption maximum (680 nm) of chlorophyll *a*. In Figure 3, the band ratio of 550 nm to 900 nm had a good linear correlation with chlorophyll *a* content in the wheat field, and chlorophyll *a* content depends on the amount of nitrogen fertilizer, so this band ratio is effectively used to find the optimal amount of fertilizer.

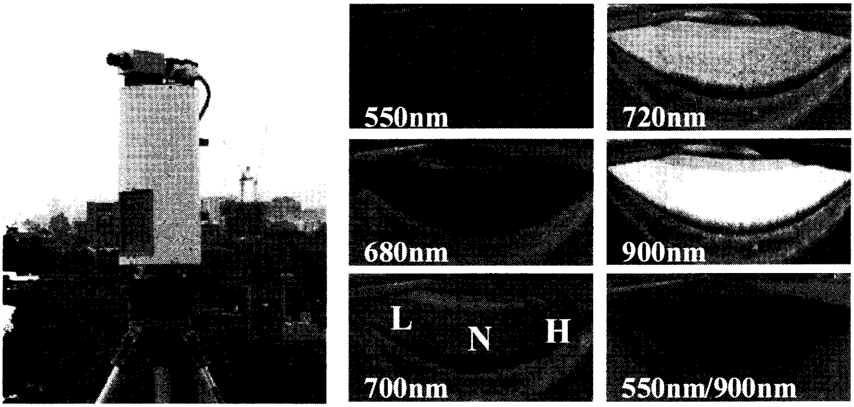

Figure 3. Hyperspectral camera (left) joined to a portable scanning range finder (lidar) and typical spectral reflectance and band ratio images (right) of a field of wheat plants cultured under different amount of nitrogen fertilizer (L = low, N = normal, H = high).

Some vegetation indexes obtained from the red and the near-infrared spectral regions made it possible to estimate net primary production (NPP) and leaf area index (LAI) as well as to extract vegetation information from the background, such as soil [...,31,37]. Hyperspectral analysis may be able to provide more phytobiological information on productivity and stresses of plants, biochemical and mineral components in living plants and soils, and classification of species, parts of plants, and soil types.

5.1.4 Fluorescence Image Sensing

Fluorescence image sensing is an active sensing technique. Phytobiological information is obtained by measuring the fluorescence emitted from fluorophores in living plants under irradiation with actinic light [18-21].

Figure 4 shows an excitation and emission matrix of steady-state fluorescence of a healthy cucumber leaf. When the leaf is irradiated with visible light (about 380 to 600 nm), fluorescence with very strong intensity in the spectral range of about 660 to 770 nm is emitted from chlorophyll *a*. Blue and green fluorescence is emitted from cell wall-bound phenolics, compounds in vacuoles and other fluorophores excited by ultraviolet rays and reabsorbed by photosynthetic pigments such as chlorophylls, carotenes, and xanthophylls [19,38]. Therefore, spectral analysis of steady-state fluorescence in the ultraviolet to red region (300 to 800 nm) has been used for early detection of changes in plant pigments, cell structure, and membranes [18,19,38,39]. Laser-induced fluorescence (LIF) may be effective for remote monitoring of the above-mentioned change [17,39]. Use of extrinsic fluorescent probes makes it possible to observe structures and movements of components in cells and tissues [26]. However, we should pay attention to the ambiguity of fluorescence and its dependence on the environment.

Chlorophyll *a* fluorescence also has been used for investigation of the photosynthetic system, and is a powerful tool for noninvasive analysis of photosynthesis [40,41]. Image sensing of chlorophyll fluorescence quenching in leaves gives nonuniform photosynthetic responses in adjacent tissues and can allow identification of

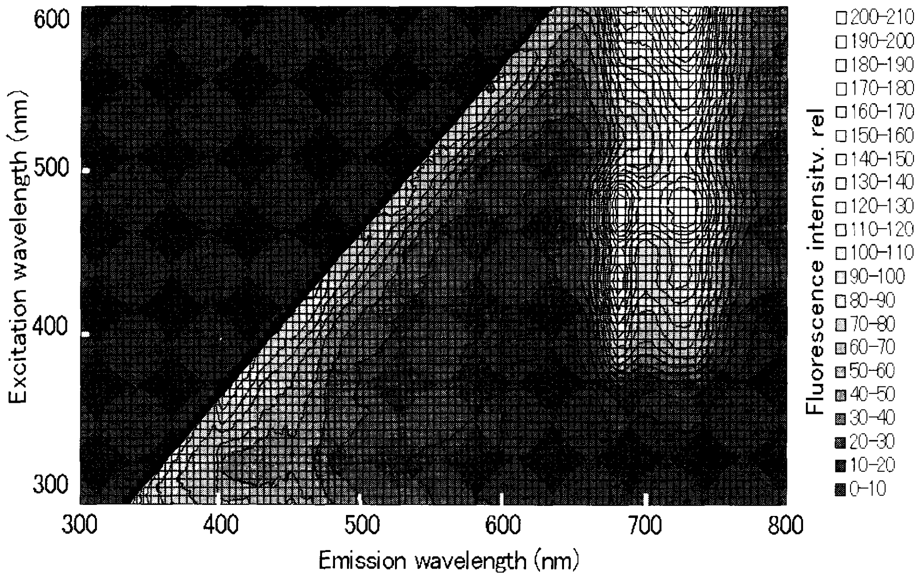

Figure 4. Excitation and emission matrix of steady-state fluorescence of a healthy cucumber leaf.

sites of inhibition within the photosynthetic apparatus. Originally developed by Omasa et al. [42] and Daley et al. [43], the techniques are used for early detection of changes in patchy stomatal response and photosynthetic activity caused by abiotic stresses such as air pollutants, low concentration O_2, water deficit, UV light, chilling, agricultural chemicals and biotic stresses [42-49].

Figure 5 shows a photograph and images of nonphotochemical quenching (NPQ) and quantum yield (Φ_{PSII}) of PSII electron transport of an attached cucumber leaf 2 days after application of $^1/_{1000}$ diluted solution of an herbicide (Nekosogi-ace) in soil. The result indicates decreased electron transport from PSII caused by DCMU (3-(3,4-dichlorophenyl)-1,1-dimethylurea) in the herbicide at sites near veins with no visible injury 2 days after the treatment and consequently inhibition of *trans*-thylakoid proton

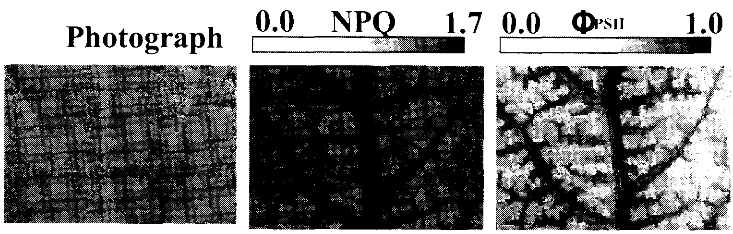

Figure 5. Photograph and images of NPQ and Φ_{PSII} of an attached cucumber leaf at 2 days after application of an herbicide (Nekosogi-ace) in soil [49].

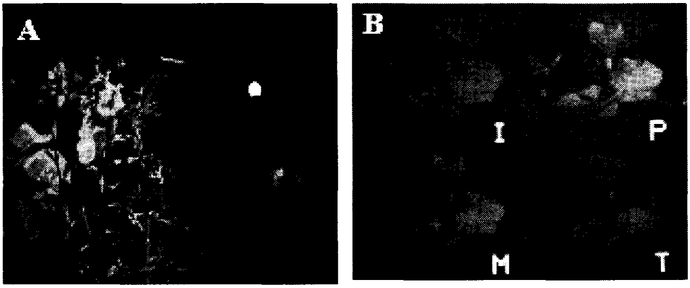

Figure 6. LIF imaging system (A) and images (B) of chlorophyll fluorescence transients [45].

gradient formation and decrease in CO_2 assimilation. The techniques can also be used to analyze and diagnose the development of the photosynthetic apparatus of attached leaves and cultured tissues [50-52]. Recently, field-portable imaging systems [48,53] for NPQ analysis and an LIF imaging system (see Figure 6) for remotely measuring chlorophyll fluorescence transients have been developed.

5.1.5 Thermal Image Sensing

Water evaporates from mesophyll cell walls in the substomatal cavity and diffuses into the atmosphere through the stomata and boundary layers of leaves and canopies. Carbon dioxide (CO_2) for photosynthesis, as well as air pollutants, enters the leaf in the opposite direction [54,55]. When the thermal environment (air temperature, humidity, radiation, air current, etc.) is maintained relatively constant, leaf temperature provides phytobiological information such as stomatal response, transpiration, and absorption of CO_2 (photosynthesis) and air pollutants [9,10,14-17].

Thermography systems often have been used to remotely measure changes in temperature of plants and canopies (including soil) as a surrogate for stomatal conductance (= 1/stomatal resistance) and gas exchange [9,14,17,56-58]. In the latter half of the 1970s, a thermography system joined with a computer was developed for image analysis of leaf temperature [14,56]. Consequently, Omasa et al. [15,59,60] quantitatively evaluated spatial distributions of stomatal resistance, transpiration rates and absorption rates of air pollutants all over the attached leaf from leaf temperature. Recently, such a quantitative study has been noticed as a research field of thermal image sensing although it is difficult to analyze quantitatively the energy balance on all leaves of plants [16].

It is also very difficult to spatially evaluate stomatal conductance and transpiration rates of plants and canopies under growing conditions in the field. However, a thermal image can provide information for early detection of plant stresses (see Figure 7), because stomatal closure occurs before the appearance of visible injury, and for screening of plants with high growth under steady-state thermal environments [9,17]. Helicopter-borne remote sensing using a thermal camera was effective for early detection of environmental stress of canopies [17]. Microscopic thermal images provided information on responses of stomata at sites between veins of rice plants [61].

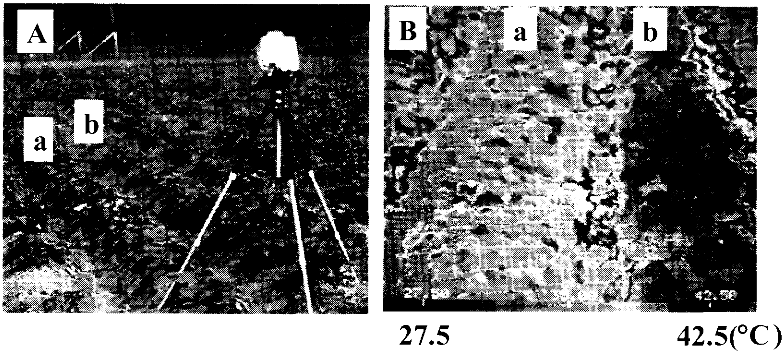

Figure 7. Effects of stomatal closure on leaf temperature of sweet potato plants in a plowed field. A, photograph; B, thermal image; a, closed stomata; b, open stomata. Air temperature 30°C.

5.1.6 Three-Dimensional Image Sensing

The three-dimensional (3-D) image-sensing technology for measurement of surface architecture can be broadly divided into two categories: *passive techniques*, which reconstruct a 3-D shape image (i.e., range image or depth image) from stereo-paired images or from monocular images by shape-from-x methods, and *active techniques*, which obtain a 3-D shape image by irradiance of objects with electromagnetic waves such as laser light [22-25,27]. Active technology provides exact 3-D images of objects without clear texture, compared to passive technology, and may give more useful phytobiological information, although it is usually more expensive.

Figure 8 shows a passive 3-D color CCD camera developed by us and a 3-D texture mapping image of a flowering plant calculated from a series of nine color images obtained by changing focus planes of the camera using a modified shape-from-focus

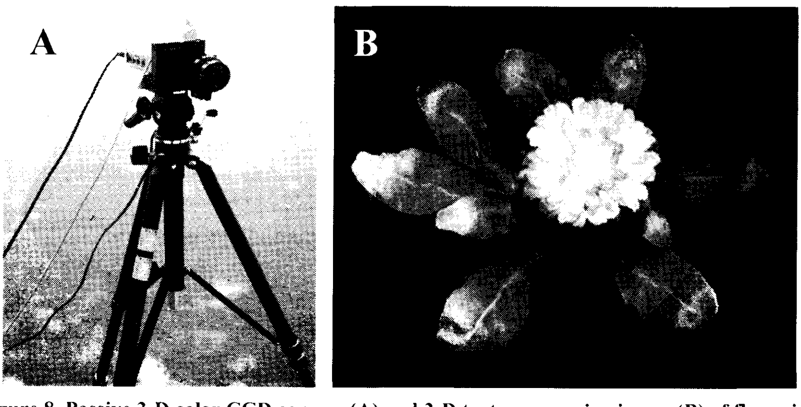

Figure 8. Passive 3-D color CCD camera (A) and 3-D texture mapping image (B) of flowering (pot marigold) plant calculated by a modified shape-from-focus (MSF) algorithm.

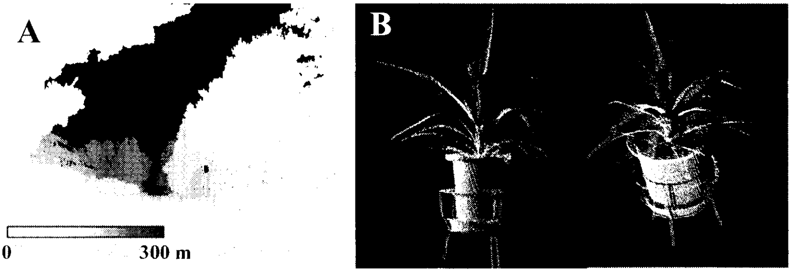

Figure 9. Range image (A) of street trees and 3-D view (B) of a potted plant measured by scanning range finders.

(MSF) algorithm [29]. This algorithm was well-suited for processing images of objects with clear texture but it was ill-suited for those with a glossy texture. This limitation was mitigated by illumination of objects with a checked pattern.

Figure 9 shows a range image of street trees and a 3-D view of a potted plant measured by scanning range finders (see Figure 3) using laser light of near-infrared range with large reflectance of leaves. The range images were obtained by measuring time-of-flight of laser light for the street trees and by a principle of triangulation for the potted plant. Omasa et al. [24] also estimates 3-D canopy structure and ground surface using a newly developed helicopter-borne scanning lidar system capable of scanning the entire canopy with a laser beam of small footprints (below tens of centimeters).

Meanwhile, the *confocal laser-scanning microscope (CLSM)* has been generally used to obtain information on the 3-D architecture of cells and tissues at high magnification [26,27]. In this system, the 3-D image is typically constructed by stacking numerous two-dimensional (2-D) images, which are obtained at constructive confocal planes. The CLSM has fluorescence imaging capability, especially using extrinsic fluorescent probes, and it can provide information on 3-D architecture and movements of biochemical components in cells and tissues as monochromatic or pseudo-color images. However, using the CLSM for *in situ* observation of cells and tissues over a wide magnification range under natural growing conditions is difficult. This problem results because, in this situation, the laser is operated at a narrow working distance and must be adjusted, thereby affecting the physiological reactions of the target cells. We have therefore developed a new computerized CCD video light microscope system with a wide working distance for obtaining 3-D natural color measurements of shape and growth of intact plants/cells under various growing conditions and over a wide magnification range [29]. This system was applied to 3-D measurement of intact petunia seedlings after providing a water supply to the seed.

Magnetic resonance imaging (MRI) and x-ray CT systems provide information on 3-D structure and functions of/in cells, seedlings, plants, and harvests. For example, root systems, difference in water contents in the soil, and water movements in the plants were three-dimensionally measured by MRI and x-ray CT [10,28,61]. These systems are also used for structural and functional research of harvests such as fruits and vegetables (Figure 10).

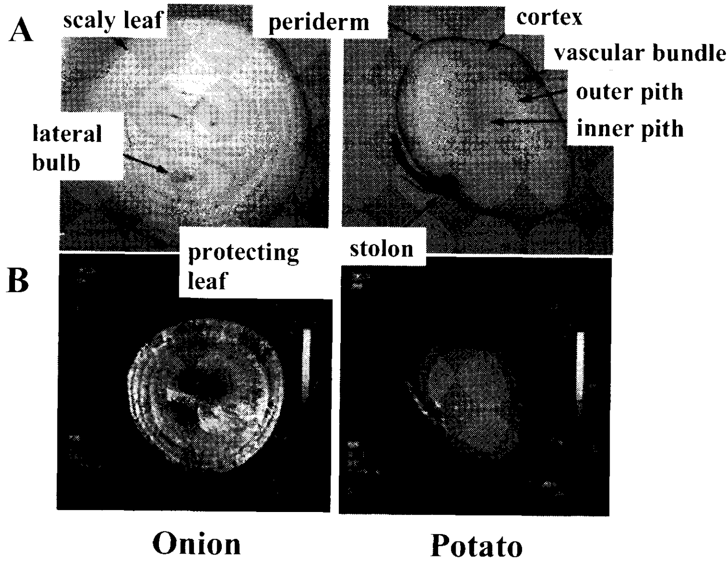

Figure 10. Section photographs (A) and MRI images (B) of onion and potato.

5.1.7 Phytobiological IT

Figure 11 shows a conceptual flow of phytobiological IT for plant production and sustainable agriculture. A phytobiological information system (PIS) is a management system that functions in database and model analysis. This system is connected with

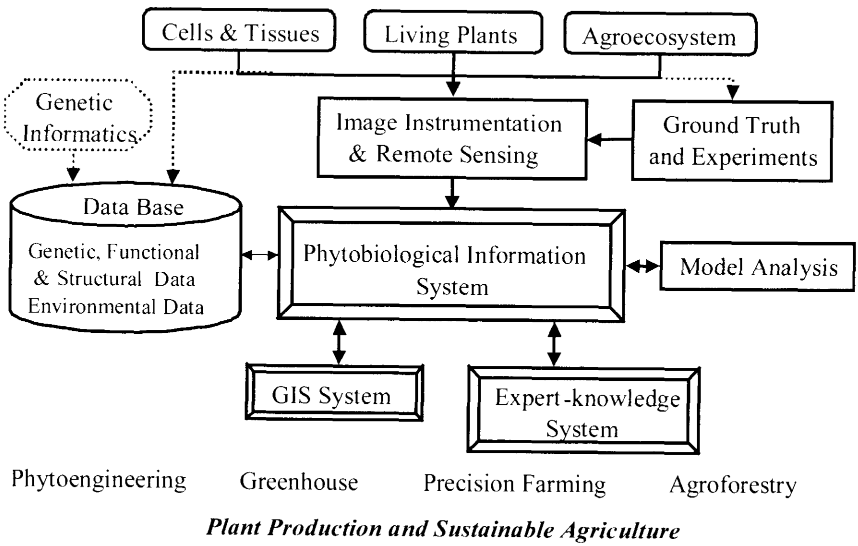

Figure 11. A conceptual flow of phytobiological IT for plant production and sustainable agriculture.

other geographic information systems (GIS) and expert-knowledge systems via network systems such as the Internet. In the system, phytobiological information on cells to agro-ecosystems obtained by imaging sensing techniques (including wide-area remote sensing described in Section 5.2) should be used, along with results of model analysis and phytobiological and environmental information obtained by other methods, to achieve both increasing plant production and optimizing use of water, fertilizers, and chemicals for sustainable agriculture. This information may also be used for improvements in farm management, in training of farmers and researchers, and in capability of machinery and control systems for phytoengineering, greenhouses, and precision farming. Results of model analysis using remote sensing data may provide a guide for agroforestry planning. Joining genetic informatics to this information may make it useful in the fields of genetic screening and eco-biomonitoring.

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5.2 Remote Sensing from Satellites and Aircraft

K. Omasa, K. Oki, and T. Suhama

Abstract. *This section introduces useful sensors for remote sensing from satellites and aircrafts using hyperspectral, hyperspatial, active, and 3-D observations. We also introduce recent advances in agricultural remote sensing including applications in sustainable agriculture such as precision farming, agroforestry, and land conservation.*

Keywords. *Hyperspectral sensor, Land conservation, Land use, Lidar, Precision farming, Remote sensing.*

5.2.1 Introduction

Remote sensing from satellites and aircraft has been widely used for applications in agriculture [1-3]. In particular, passive optical sensors mounted on aircraft, Landsat, and SPOT (the French Systeme Probatoire d'Observation de la Terra) have allowed applications such as prediction of crop production and land use change. Recent advances in agricultural remote sensing are applications in sustainable agriculture, such as precision farming, agroforestry, and land conservation. These closely relate to applications in forest, ecosystem, hydrology, and environmental management [3-5].

Meanwhile, technical trends in remote sensing from satellites and aircraft are hyperspectral, hyperspatial, active, and 3-D observations [5-11]. Although ordinary satellite optical sensors, such as the Landsat Thematic Mapper (TM) and SPOT High Resolution Visible (HRV), have been limited to less than ten spectral channels, the Hyperion on Earth Observing-1 (EO-1) launched by NASAin November 2000 provides a high resolution hyperspectral imager capable of resolving 220 spectral bands (from 0.4 to 2.5 μm) with a 30-m spatial resolution. A hyperspatial QuickBird satellite launched in October 2001 provides panchromatic (PAN) images with a spatial resolution of