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Soil productivity management and plant growth in the Sahel: Potential of an aerial monitoring technique

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Abstract

Spatial variability of plant growth has been a major problem for plant physiologists, agronomists, agro-foresters and soil scientists comparing or modelling treatment effects on acid sandy soils in the Sahel. While aerial photographs from aeroplanes or satellite images may provide valuable information for the surveying of large areas, their use for individual small experiments or farmers' fields has been limited due to high costs, restricted availability, and unsatisfactory resolution. As a simple alternative, a commercially available Zeppelin-type balloon, dragged on a rope by a camel, was fitted with an standard 35 mm camera and a remote control system. Flight altitude varied from 20 m to 500 m above ground. A ground-based camera mounted vertically on a tripod was used to center the Zeppelin over the target area. The high-resolution true colour negatives and colour infrared slides obtained by this device were used to unravel the history of farmers' management strategies for maintaining soil productivity, to monitor treatment effects and crop growth variability in an on-station experiment, and to visualize light absorption by photosynthesis in crops and trees. Such non-destructively collected data may serve as quick but reliable references for ground measurements in a wide range of experiments with loosely-spaced crops, bushes, and trees.

Introduction

Spatial variability in the growth of pearl millet (*Pennisetum glaucum* L.) is a striking feature on acid sandy soils of the Sahel and often hinders an effective analysis of field experiments (Wilding and Hossner, 1987). The causes of this micro-variability are still under investigation; however, small differences in available soil phosphorus (Wendt et al., 1993), surface crusting (Buerkert et al., 1995a; Chase and Boudouresque, 1987), and termite activity (Brouwer et al., 1992) have been identified as chemical and non-chemical factors contributing to it. In this context, non-destructive remote sensing techniques have a particular importance for detecting and monitoring the effects of soil productivity gradients on crop growth. At the regional scale, the availability of high resolution digital multispectral data taken from satellites of the Landsat TM (Thematic Mapper) and the SPOT (Satellite Pour l'Observation de la Terre) systems has successfully replaced aerial photographs. With a resolution of between 20 and 30 m, such data have been used to examine geologic features of the earth (Chavez, 1992), to map temperate forests (Zhu and Evans, 1992), and to study the spatial variation and composition of vegetation in different climatic zones (Frederiksen and Lawesson, 1992; Townshend and Justice, 1990; Tucker and Sellers, 1986). Within the limits of the given spatial resolution, satellite data have also been used to determine the biomass of barley (Kleman and Fagerlund, 1987), the leaf area index of bean, sunflower, sorghum, and millet (Redelfs et al., 1987), the lint yield of cotton (Wiegand et al., 1991), and growth parameters of soybean and corn (Thenkabail et al., 1994) at the scale of large fields in temperate climates. However, the limited resolution and high cost of the data have prevented a wider use of such remote sensing techniques by agronomists, plant physiologists, ecologists, and agro-foresters in the Tropics and sub-Tropics.

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At the individual plant or experimental plot level, non-destructive surveys and biomass measurements are at present conducted with radiometers, either hand-held or mounted on mobile platforms. Measuring the reflectance of red and infrared light from green crop canopies, these instruments have been successfully used to estimate the total above-ground biomass of maize and soybean (Tucker et al., 1979), alfalfa pastures (Mitchell et al., 1990), groundnut (Nageswara et al., 1992), and even the dry matter of young millet in the Sahel (Buerkert et al., 1995b). While such ground measurements of reflectances are quick and easy to take and may give accurate predictions of dry matter on a small scale, they are too time-consuming for larger experiments, for use in farmers' fields, and for extensive surveys of soil fertility patterns as reflected in plant growth variability. At this scale, low altitude aerial photography is still the most appropriate technique for documenting the effects of topographic features and previous management practices on crop growth in agricultural experiments (Denison et al., 1994) and for studying direct and indirect effects of management practices on the ecosystem (Smith et al., 1992). However, to obtain high-quality aerial photographs for a better understanding of soil-plant interactions or to regularly monitor crop growth, may be as costly as acquiring satellite data, and in remote areas or countries of the developing world it is often impossible. This research was therefore conducted to develop a simple, cheap, and robust technique of taking high-resolution aerial photographs at between 20 and 500 m above the ground. Made from commercially available components, the technique should allow the detection and interpretation of fertility gradients, the measurement of tree canopies, and the comparison of treatment effects on biomass development of crops in the West African Sahel.

Materials and methods

Environmental conditions and land use

Test flights were conducted in August and September 1994 at ICRISAT Sahelian, Sadoré, Southwest-Niger (13°15'N latitude, 2°18'E longitude, and 240 m altitude) and at farmers' fields nearby. The soils of the area are derived from ancient dune sands (Bleich and Hammer, 1996) and have been classified by West et al. (1984) as *psammentic Paleustalfs*, sandy, siliceous, isohyperthermic according to the US soil taxonomic system (Soil Management Support Services, 1988) or as *Arenosols* (FAO – UNESCO, 1988). Because of the climatic and soil conditions, agriculture in this zone is limited to the short rainy season between May and September with an average total precipitation of 560 mm (Sivakumar et al., 1993). Weather conditions in this period are mainly influenced by the North-South movement of the Inner-Tropical Convergence Zone (ITCZ) which leads to convective fronts moving quickly in East-West direction. This causes rapid changes from bright sunshine to rainstorms with high rainfall intensities, especially in the second part of the rainy season, and makes aerial photography at low altitudes particularly difficult. In agricultural areas, the vegetation consists of an open parkland system where native trees such as *Faidherbia albida* and bushes are growing in fallow land, or fields planted with rainfed millet (*Pennisetum glaucum* L.), cowpea (*Vigna unguiculata* (L.) Walp.), and groundnut (*Arachis hypogaea* L.). Given the low soil fertility and the lack of use of mineral fertilizers, planting densities are very low, usually around 5000 planting hills (pockets) ha^{-1} or even lower (Bationo et al., 1992; McIntire, 1986).

Balloon, rope and safety valve

A commercially available Zeppelin-shaped balloon made with a 0.2-mm PVC envelope material (Ziegelmeier GmbH, Munich, Germany) was filled with 12 m^3 of hydrogen or helium and attached with an aluminium mountaineering carabineer through a small gyro-bearing to a 3-mm rope made of Dynema®. The rope weighed 2 g m^{-1} and was certified to have a maximum strength of 1800 N. With air temperatures between 20° and 40 °C, on the ground the average lift of the balloon for the rope and photographic equipment was about 40 N with a helium filling and 50 N with a hydrogen filling. To avoid the loss of the balloon and the attached equipment in case of a rope failure, a safety valve was constructed and fitted into the PVC envelope material (Fig. 1). The valve, which weighed 100 g, could be operated with the remote control and allowed rapid loss of the gas filling and a smooth landing of the equipment.

Photographic equipment and remote control

The photographic equipment consisted of a standard 35 mm reflex camera with automatic shutter speed adjustment (Nikon F-801s), a lens with a fixed focal length of 50 mm (Nikkor f:1.4) and an incorporated winder.

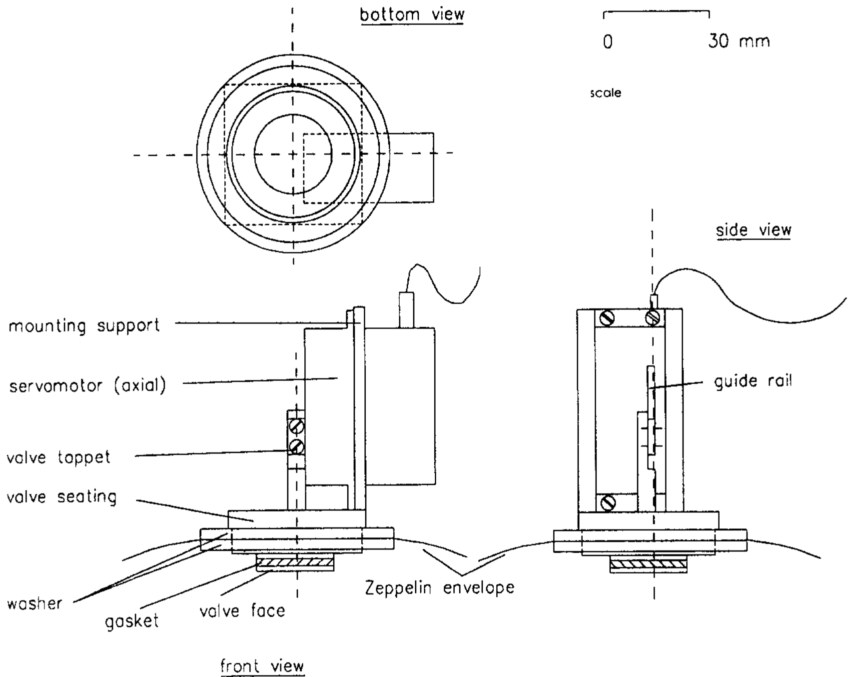


Figure 1. Schematic diagram of a remotely-controlled safety valve ftted into the PVC envelope. Operated with an axial servomotor ROBBE RS 15, the valve allows a rapid loss of the gas filling in case of a rope failure.

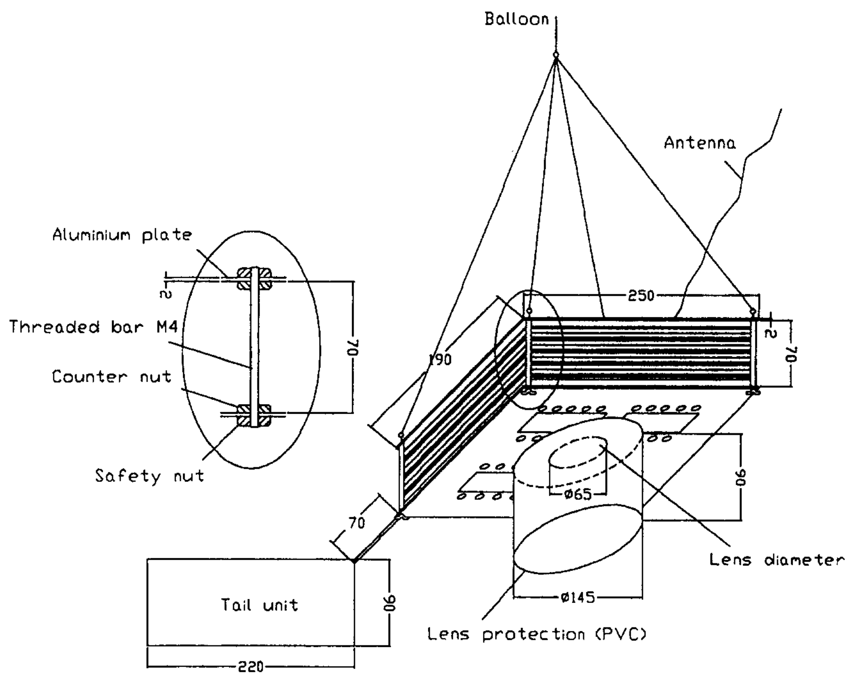


Figure 2. Schematic diagram of the custom-made aluminium case carrying the camera and the receiver of the remote control system.

The camera was fitted into a custom-made case from two perforated aluminium plates 200 × 250 × 2 mm (Fig. 2). Between the two plates, a 70 mm foam material protected the camera and the receiver of the remote control device. The case was suspended from the balloon on a single rope of 0.6 m length and allowed to

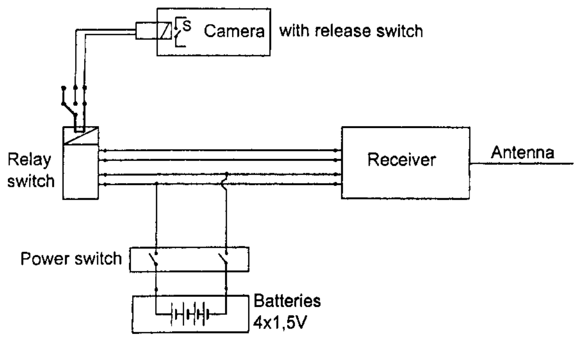


Figure 3. Schematic diagram of the electric circuits in the camera case. The receiver was a model GRAUPNER 16-channel Superhet C 16, and the relay switch a model S Robbe RSC 200.

turn around its vertical axis. At one corner of the case, an adjustable wind tail was mounted to position the case in relation to the wind direction at the commencement of each flight.

On the ground the camera was triggered through a commercially-available remote control system of 100 mW output power (J Graupner FM 314, Kirchheim-Teck, Germany) which operates at the 35 MHz waveband and contains eight channels, of which only one was used. The power supply of the system consisted of an external rechargeable lead battery (Panasonic LCR 12V 3.4P) which allowed an operation time of up to 20 h. In the initial system the receiver was connected with a relay switch to the release switch of the camera. This was mounted in the camera case and powered with four 1.5 V AA size alkaline batteries (Fig. 3). Subsequently, the release switch of the camera was activated mechanically with a radial servomotor. The 0.5 m standard antenna wire was extended to a total length of 3 m and suspended horizontally along the balloon, and vertically along the rope, to avoid shading of the antenna by the camera case. The weight of the equipment attached to the balloon was 1050 g for the camera, 820 g for the case, including the receiver and the wind tail, and 100 g for the antenna. Total costs were 5300 DM: 2500 DM for the Zeppelin-type balloon, 1300 DM for the camera, 500 DM for the remote control system, 400 DM for the rope of 500 m length, and 200 DM for batteries, materials and supplies. Running costs were about 100 DM per filling with H_2.

Film material and filters

Initial tests with slow-speed high-resolution colour negative films rated at ISO 25 (Ektar 25, Eastman Kodak Company, Rochester) had shown that the shutter speeds used were too low for the sudden movements of the camera on windy days and led to blurred exposures. In subsequent tests, faster films rated at ISO 100 (Kodak GOLD and Kodak Ektar, Eastman Kodak Company for negatives; Agfachrome Professional 100, Agfa Gaevert AG for colour slides) were found to be more suitable. For colour infrared photography, the Ektachrome Infrared Film (Eastman Kodak Company) rated at Iso 100 was used with a multi-coated yellow-orange glass filter equivalent to Wratten No. 16 (Eastman Kodak Company) to block radiation below 0.54 μm wavelength. The maximum spectral sensitivity of the colour infrared film material was between 0.7 and 0.9 μm. Regardless of the film type, the diaphragm aperture of the camera was kept at 5.6 as recommended by the lens supplier for best resolution. Under the light conditions of the Sahelian rainy season, this allowed a minimum shutter speed of 1/500 s to be obtained.

Positioning of the camera

To obtain overlapping series of photographs for survey work on slightly undulated millet fields with thorny bushes, trees and fallow areas, the coil with the balloon rope was attached to the back of a dromedary camel (*Camelus dromedarius*) which was led by its rider in a straight line at a constant pace. To take pictures of a particular site (individual trees or an agricultural experiment), the balloon had to be centred on the target area. For this purpose, a second camera mounted on a tripod was placed in the centre of the site with its lens in vertically upward pointing position. Using radio communication, assistants carrying the coil with the balloon rope were guided to position the balloon in the camera's field of view.

Computation of a vegetation index from colour infrared photographs

To evaluate the colour infrared photographs, transparencies were scanned on a flatbed scanner at 1200 and 2400 dpi, and saved as TIFF files which contained the optical densities for the red, green, and blue range of transmitted light at the pixel level. Subsequently, computations were performed with the software package ImageProPlus (Media Cybernetics, Silver Springs, MD) to compute a vegetation index using the formula of Tucker and Sellers (1986) for the normalized difference vegetation index (NDVI):

$$NDVI = (NIR - R)/(NIR + R)$$

where NIR, the near-infrared component, corresponded to the optical density of the red band and R to the optical density of the green band, on the colour infrared transparencies. To enhance the contrast, the NDVI values normally between zero and one were expressed on a false colour scale ranging from zero to four with 15 steps. The converted image was saved as a TIFF file and then written to film.

Results

Overall performance of the system

During the test period in August and September 1994, the thermic conditions were very unstable, causing sudden movements of the balloon especially at altitudes above 200 m. In these situations, strong winds caused kite effects which led to tractive stresses on the ground of up to 500 N. Flight conditions were best between 9 and 11:30 a.m. but could be extended until 4 p.m. on cloudy days. However, balloon and equipment were sturdy enough to withstand turbulences leading to sudden plunges. Small holes in the balloon envelope were easily repaired on the spot with scotch tape, and after the flights with adhesive and patches of PVC material. The exact positioning of the balloon above a specific point typically required about 20 min, whereas taking overlapping photographs took 15 min per 1000 m ground distance.

Photographs of on-station experiments

For millet sown at a density of 10,000 pockets ha^{-1}, individual pockets could be well differentiated at booting stage, 60 days after sowing (Fig. 4). Treatment effects on plant growth and those strips where millet rows had been harvested previously for the determination of dry matter were also visible. However, for cowpea sown at 120,000 pockets ha^{-1}, and to a lesser degree also for groundnut sown at 80,000 pockets ha^{-1}, the identification of individual plants from an altitude of about 400 m was impossible.

Photographs of farmers' fields

The aerial photographs of traditional millet fields document farmers' settlement behavior and explain some of the striking patterns of spatial variability in millet growth which could not be interpreted from the ground (Fig. 5A and B). Patches of bare soil surrounded by tall millet plants resulted from the foundations of houses where clay had been applied to avoid the penetration of water during rainfall events. The photographs also revealed that the increase in millet growth immediately after the shift of houses to a new site lasted about three years before the dry matter development of millet on settlement areas became similar to that of surrounding land (Fig. 5B).

Colour infrared photographs and NDVI computations

Compared to the true colour picture (Fig. 6A), the colour infrared photograph (Fig. 6B) of a transect in a farmer's field including a traditional grass house, a *Faidherbia albida* tree, millet plants, and a mango tree (*Mangifera indica*) allowed a clear differentiation in the photosynthetic activity of the different objects. Even millet plants growing under the *F. albida* tree could be identified. The computation of NDVI values from the red and green spectral densities on the infrared photograph, and their conversion into false colours (Fig. 6C), further increased the contrasts and enhanced the resolution in areas of particularly high photosynthetic activity such as the canopy of the mango tree.

Discussion

The use of balloon techniques for aerial photography dates back to the beginning of the 20th century with the photographs of the famous prehistoric stone monuments in Stonehenge, England (Capper, 1907). In semi-arid climates such techniques have recently been used in Syria (ICARDA, 1991) and Niger (Hebel, 1995) but the set-ups were very costly or fragile, and the pictures obtained were put to documentary rather than analytical use. The set-up described here is, in contrast, sturdy, easy to handle, and inexpensive. The low operational costs make it suitable for regular monitoring of continuous natural processes such as the growth of crops and trees. For safety reasons, filling the balloon with helium rather than hydrogen is recommended. This also allows short-term between-flight storage of the filled balloon in buildings. However, care should be taken not to over-extend the storage period, as about 10% of the hydrogen or helium filling is lost per day by diffusion through the PVC foil and small amounts of air continually permeate from the outside and reduce the lift of the balloon.

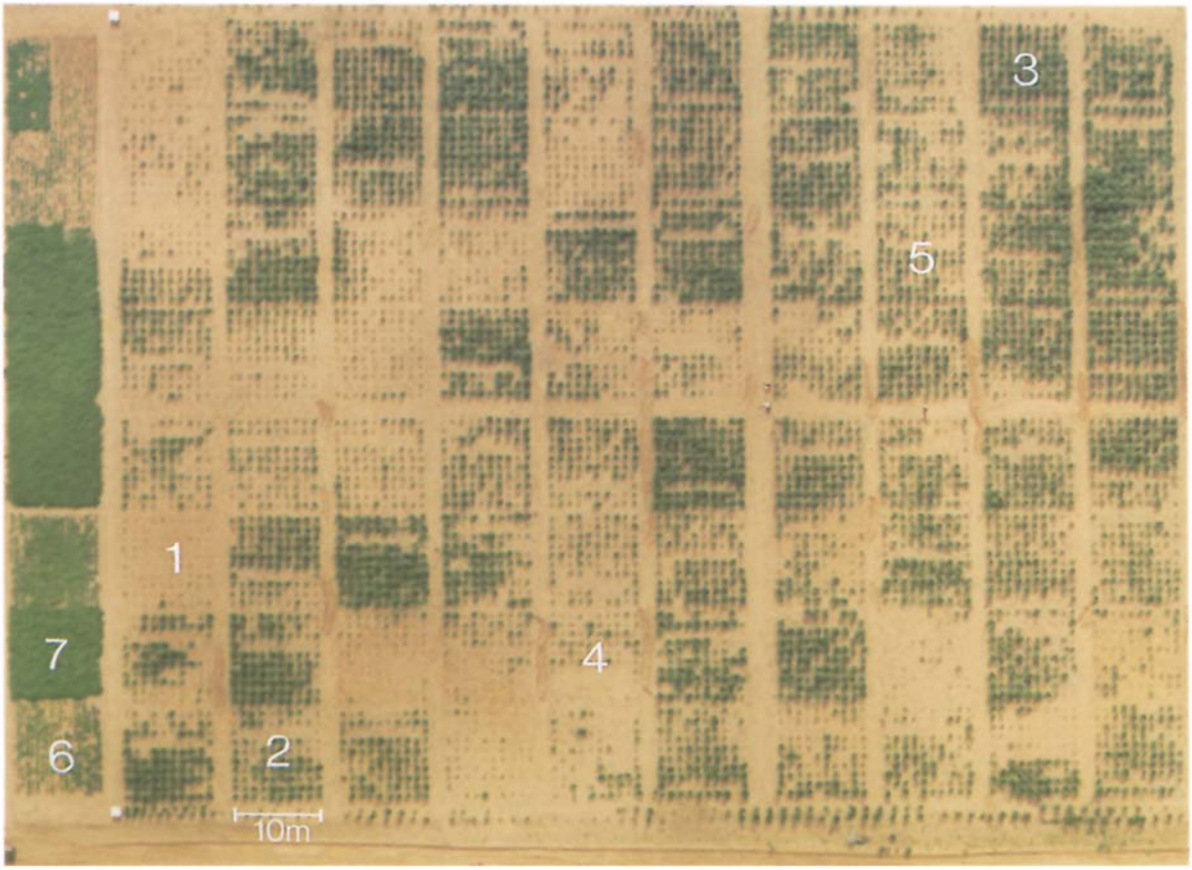


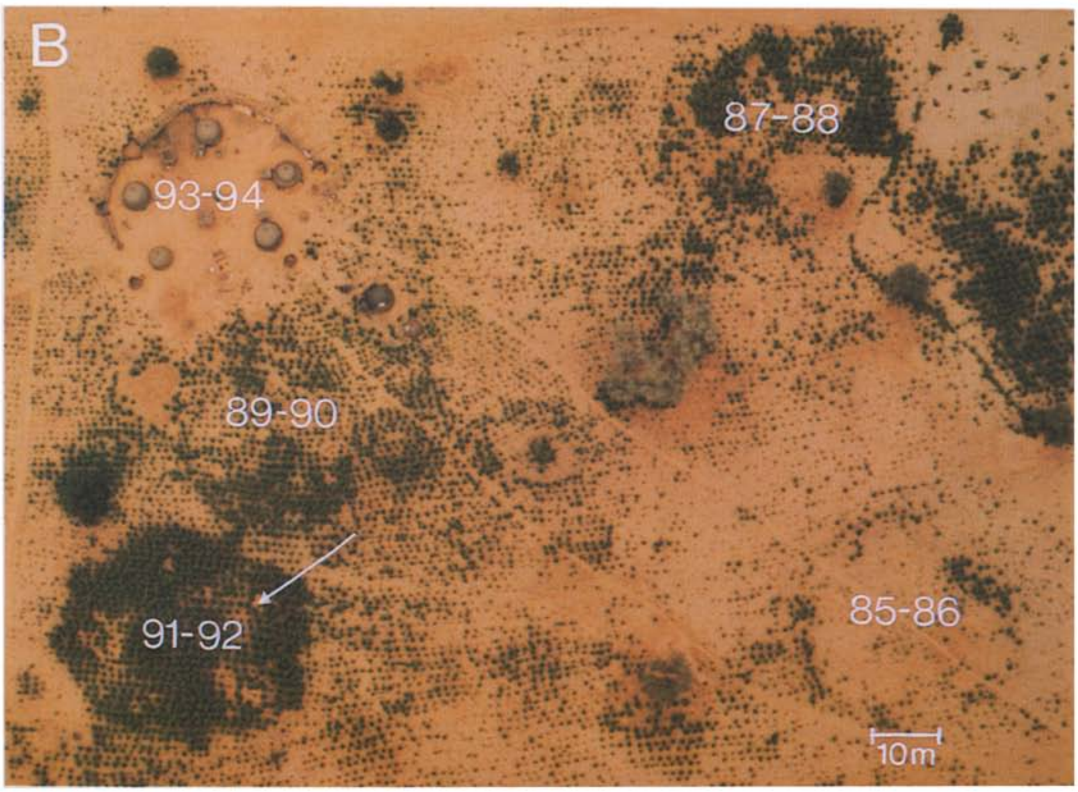
Figure 4. Aerial photograph of an on-station soil fertility experiment with millet at ICRISAT Sahelian Center 60 days after sowing taken from an altitude of about 300 m above ground. Numbers indicate (1) bare control plot without application of mineral fertilizers, (2) plot with millet crop residues (CR) surface mulched at 2,000 kg ha^{-1} but without mineral fertilizers, (3) plot with 13 kg P ha^{-1} and CR surface mulched at 2,000 kg ha^{-1}, (4) plot with 500 kg CR ha^{-1} and no P fertilization on a hard pan, and (5) plot with the same treatment as (4) but close to a former tree. Also note the plots planted with groundnut (6) and cowpea (7) at the left of the photograph.

For short-range aerial surveys of crop growth or tree inventories, the attachment of the balloon to a camel moving steadily in one direction allowed complete coverage by a series of overlapping photographs. However, sudden changes in wind direction and speed can led to unforeseen drifts of the balloon and make it diffcult to properly overlay the individual photographs. Therefore fixed reference points, such as the white markers in the on-station experiment (Fig. 4), should be established in the area before the flights to minimize these disadvantages of a balloon system for survey work.

Compared with images from conventional and ultralight aircraft, the described set-up afforded the advantage of higher resolution, which allowed the precise identification of individual millet plants (Fig. 4) and the analysis of tree canopies (Fig. 6). Also, the images obtained from the balloon were exactly to scale and allowed a direct comparison of the surface size of objects over the entire picture. Compared with a low-

Figure 5. Photographs of spatial variability in millet growth on farmers' fields in southwest Niger. (*A*) Millet growth variability around a hardpan observed at the ground level. (*B*) Aerial photograph showing residual effects of changes in soil productivity due to farmers' settlement activities. Numbers indicate the years during which the settlement of the farmers remained at a particular site. The picture was taken 75 days after sowing from an altitude of about 400 m above ground. The white arrow indicates the hardpan shown in Figure 5A. Such hardpans within the boundaries of former settlement areas are the result of clay applications to the foundations of the five houses belonging to the one extended family. Note that the increases in millet growth in former settlement areas lasted about three years.


A


B
87-88
93-94
89-90
91-92
85-86
10m

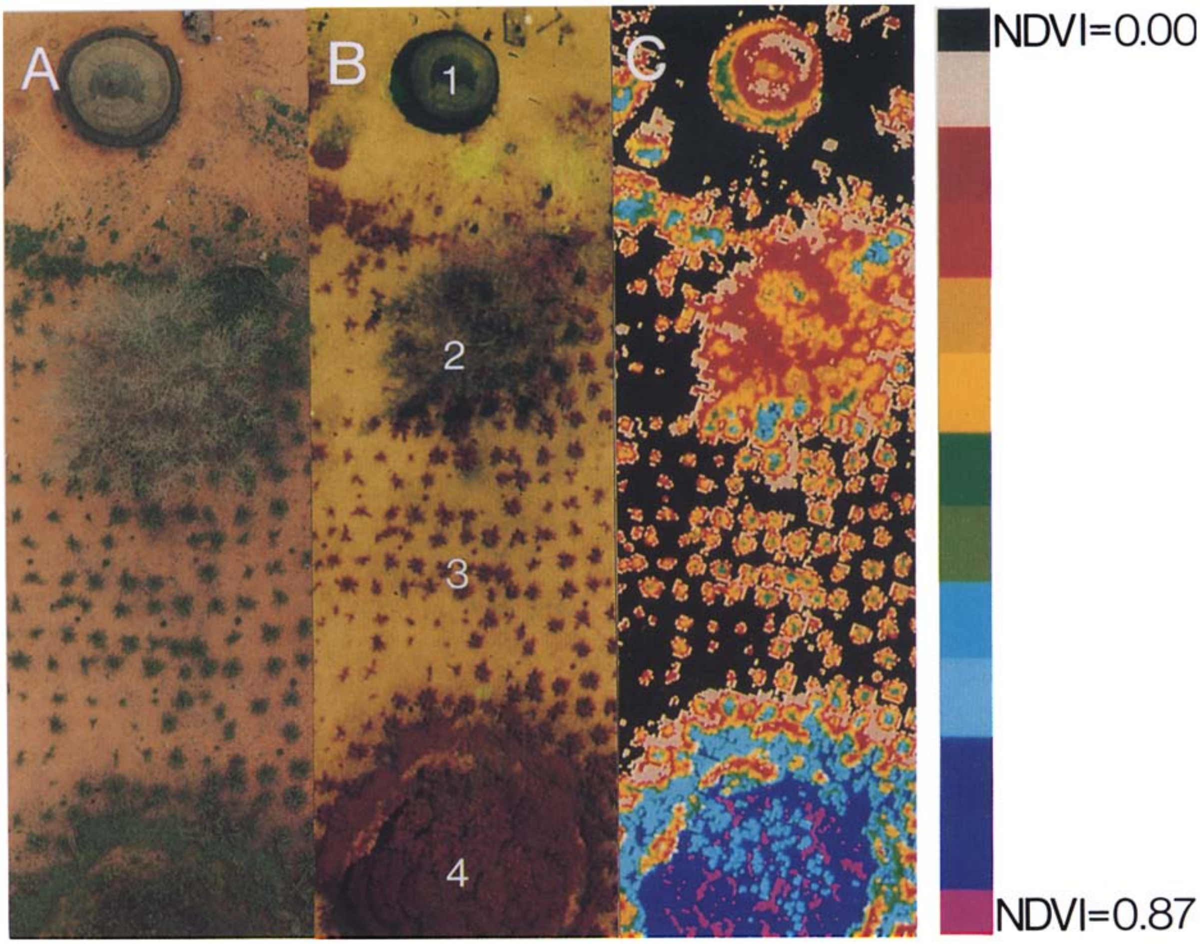


Figure 6. (*A*) Aerial true colour and (*B*) colour infrared photograph taken from an altitude of about 100 m above ground. The photographs show a transect with (1) a farmer's grass house, (2) a *Faidherbia albida* tree, (3) millet plants 75 days after sowing, and (4) a mango tree. (*C*) A false colour normalized difference vegetation index (NDVI) has been calculated from the optical densities of the red and green bands in the colour infrared photograph shown in Figure 6B to increase contrasts and reveal patterns of photosynthetic activities in plant canopies.

flying ultralight aircraft which was used to take high resolution photographs from the same experimental areas in 1993 (data not shown), the balloon set-up was much more flexible. It allowed photographs to be taken in the middle of the rainy season, when calm periods between weather fronts may last for only a few hours.

High resolution aerial photographs of treatment effects in on-station experiments with millet may serve not only as a reference for a representative sampling scheme of plants but also allow differences in treatment responses across replicates to be documented (Fig. 4). In this case, the development of biomass photographed at 45 days after sowing reflected well the total dry matter of millet at maturity as well as revealing some effects of the land-use history prior to 1983, when the land lay fallow for eight years (Buerkert et al., 1995a). However, such use of aerial photographs at the individual plant level should not be generalised, as it diminishes with decreasing planting distance and a more proliferate crop growth such as that of groundnut or cowpea (Fig. 4, left).

Spatial variability in millet growth (Fig. 5A) has been related to differences in phosphorus availability (Wendt et al., 1993), but is often difficult to explain by differences in soil chemical parameters alone (Buerkert et al., 1995a; Geiger and Manu, 1993), and without a clear understanding of its causes it often appears to be random in nature. The use of high resolution aerial photographs in the on-farm survey made it possible to document nearly a decade of farm management practices, and the resulting effects on crop growth (Fig. 5B). Talks with the respective farmers confirmed that they knew about the fertilizing effect of small animals and household refuse in the immediate proximity of their settlements. Often lacking other means to improve the low fertility of the fields, it was their practice to place their houses at the sites of lowest productivity and to move on after a few years to the next spot of low millet yield. The photographs were also able to reveal the tapering-off of soil productivity after recultivation of a settlement area. It should be noted that an even quicker decline in the residual effects of crop residue application as a means of improving soil fertility for millet has been shown by Rebafka et al. (1994) in an on-station experiment. Such rapid decreases in soil productivity after the application of organic amendments are of little surprise, given the high moisture and temperature conditions during the rainy season and the low buffering capacity of the prevailing acid sandy soils. Documenting and better understanding the spatial variability in millet growth through aerial photographs also has important implications for the design of agricultural experiments. Rather than increasing random variation in a superimposed experiment, clearly defined areas of different soil productivity, such as shown in Figure 5B, can be used to place treatments in well-chosen blocks of rather uniform crop growth. This allows the experimenter to test treatments in a chronosequence of residual effects of traditional settlement and soil management practices.

The basic principles of densiometric measurements of film dyes are well-known and have been extensively reviewed by Leamer et al. (1975) and Scarpace (1978). However, to determine conclusively to what degree aerial photographs from a balloon can be used to non-destructively monitor biomass development of millet and other types of vegetation in the Sahel requires further testing. The presented steps from true colour over colour infrared to NDVI images (Fig. 6) merely show the potential of this procedure. A calibration of the NDVI values with ground truth data of plant biomass is necessary, and for applications across larger areas a standardization for differences in soil reflectance caused by variation in moisture would be desirable. However, it remains doubtful if a simple rigid transformation of the NDVI into a soil-adjusted vegetation index (SAVI) and the subsequent determination of a reflectance-based crop coefficient K_{er} as proposed by Bausch (1993) for corn would provide much help in standardizing reflectance measurements in millet of the Sahel.

Whatever the results of further research in this area, colour infrared photography has two major advantages compared to true colour photographs. First, it has been shown recently that colour infrared photography is much less affected by dust aerosols which may hamper the transmission of light in the visible spectrum in dry areas such as the Sahel (Chavez, 1992; Egan, 1994). Colour infrared images may also offer much higher contrasts between plant canopies and the surrounding soil than do true colour pictures (Fig. 6). Such increases in contrast may be helpful for counting individual plants and measuring their surface area, advantages which seem particularly relevant to agroforestry research, particularly if it seeks to monitor the canopy diameter of trees.

Conclusions

The simple technique of taking aerial photographs in the Sahel with a balloon allows the spatial variability in millet growth to be documented, contributes to its explanation, and permits better-designed agricultural experiments on acid sandy soils. During the vegetative growth phase of widely-spaced millet plants, true colour or colour infrared images may also be used to estimate plant parameters such as plant density and leaf area index. For this purpose, color infrared photographs may even be more helpful, but further research with calibration against ground truth data is required to clarify the precision of such estimates. The results also indicate that the use of such aerial photographs in more narrowly-spaced or sprawling crops, such as groundnut or cowpea, may be limited to the visual documentation of differences in soil productivity or treatment effects at a given time.

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