# Detection of *Heterodera avenae* infestations on winter wheat by radiothermometry

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SUMMARY

This study was an attempt to evaluate the potentialities of radiothermometry for the detection of infestations by the nematode *Heterodera avenae* Woll. in winter wheat (*Triticum aestivum* L.) cv. Arminda. Experiments were conducted on two strips after cultivation of resistant (cv. Panema) or susceptible (cv. Peniarth) oat varieties. The infestation levels on the two strips were different. Crops canopy temperature was measured with portable radiothermometers and a thermal infrared camera. The presence of nematodes in the root system markedly increased canopy stomatal resistance during the day. As a result, canopy temperature on a moderately infested plot at midday was higher by approximately 1 °C than on a lowly infested plot. Temperature difference between the two plots greatly varied with time of day, and therefore, cumulative temperature difference appeared to be more useful for detecting the presence of nematodes. Thermal images allowed precise delimitation of both moderately and lowly infested areas, and thus should be extensively applied to the detection of nematode attacks by remote sensing in large wheat fields.

RÉSUMÉ

*Détection d'infestations d'*Heterodera avenae *sur blé d'hiver par radiothermométrie*

Cet article a pour but de définir certaines potentialités de la radiothermométrie pour la détection d'infestations de nématodes (*Heterodera avenae* Woll.) sur blé d'hiver (*Triticum aestivum* L.) cv. Arminda. Le dispositif expérimental a été obtenu par culture de variétés d'avoine résistante (cv. Panema) ou hôte (cv. Peniarth). Il comporte deux bandes où les niveaux d'infestation sont différenciés. La température de surface des cultures est mesurée par des radiothermomètres portables et par une caméra infrarouge thermique. La présence du nématode dans le système racinaire provoque un accroissement sensible de la résistance stomatique du couvert au cours de la journée, et, par suite, la température de surface sur cette parcelle est supérieure d'environ 1 °C en milieu de journée, à celle de la parcelle faiblement infestée. L'écart de température entre les deux sites varie fortement au cours du temps et le cumul des différences de température apparaît plus intéressant pour diagnostiquer la présence du nématode. L'image thermique permet de délimiter avec une bonne précision la zone moyennement infestée de celle faiblement infestée et ouvre ainsi un vaste domaine d'applications pour la détection d'attaques de nématodes sur de larges emblavures.

Nematode parasitism affects water relations within the soil-plant-atmosphere continuum (SPAC) (Wilcox-Lee & Loria, 1987), and the symptoms usually observed resemble those caused by water stress due to soil water deficit (Evans, Parkinson & Trudgill, 1975; Meon, Fisher & Wallace, 1978; Meon, Wallace & Fisher, 1978; Kuc, 1978). From the soil to the atmosphere, absorbed water follows successive ways through the plant, *i)* first in the liquid phase between the soil and substomatal cavities, *ii)* then in the gazeous phase from the leaves into the air above the crop canopy. Water transport within the SPAC is mainly regulated by stomata opening, which is controlled by complex mechanisms in response to environmental variations (Jarvis & Morrison, 1981). These variations include climatic conditions and abiotic factors, e.g. salinity, water deficit or nutrient deficiency in soil (Marshall & Sagar, 1968), or biotic factors, e.g. various pests or pathogens (Ayres, 1981). Stomatal closure reduces stomatal conductance, thus causing gas diffusion to decrease, especially water evaporation from leaf surface. The evaporative deficit then modifies the energy balance above the crop canopy and, consequently, the sensible heat flux increases, and the surface temperature is higher. Thus, a difference in surface temperature between two neighbouring plots indicates a difference in water stress.

Surface temperature can be measured remotely by radiothermometry. Remote sensing techniques using radiometers are concerned with the measurement of the radiative energy issued from a surface at specific wavelengths. Generally speaking, energy is reflected in the 0.4 to 2.5 µm range, or emitted above 3 µm, especially in the 7 to 15 µm range, the thermal infrared range of the electromagnetic spectrum where radiothermometers work. Atmospheric water vapour strongly absorbs electromagnetic infrared radiation, and only some wavebands remain transparent, among which the atmospheric window between 8-14 µm. A measurement in this spectral range, indicates a radiant, or apparent, temperature which nears the absolute temperature of the object (Fuchs & Tanner, 1966; Slater, 1980). Radiothermometry, i.e. remote measurement of temperatures, is used to measure water stress in crops (Blad & Rosenberg, 1976; Pinter *et al.*, 1979; Seguin, 1980; Idso *et al.*, 1981; Walker & Hatfield, 1983) and assesses crop water requirements (Stone & Horton, 1974; Jackson, Reginato & Idso, 1977; Mitchell & Hanks, 1985). Radiant temperature sensors are now commonly used and often easy to operate; they differ in their ability to produce thermal images or to be airborne (Lillesand & Kiefer, 1979). For this reason radiothermometry should be useful for detecting the activity of pests such as nematodes, that can alter water relations within the SPAC. Although research has been done using thermal infrared remote sensing to detect diseases (Jackson, 1986; Dieng, 1988; Eyal & Blum, 1989), this technique has not been hardly applied to the detection of nematode parasitism in crops. Only the investigations of Gebhardt (1984, 1986) have shown that radiothermometry can, under certain weather conditions, reveal the presence of nematodes in potato plants.

The aim of this study was to define the possibilities and limitations of radiothermometry. A series of experiments were performed on winter wheat infected with *Heterodera avenae* Woll., which causes various degrees of yield losses depending on weather conditions (Rivoal *et al.*, 1990; Rivoal, Doussinault & Hullé, 1990).

## Materials and methods

### Experimental design and plant material

The trial was located on a calcareous soil already described (Rivoal & Rivière, 1989). Because disturbance of water flow through plants is not specific to nematodes, experiments were conducted on two strips which differed only by their *H. avenae* infestation levels (Fig. 1). The experimental design consisted in two adjacent rows (6 × 60 m). They were separated by a central path to allow place for fertilizers and pesticides applications. Both rows were included in a long-term rotation trial started in 1982 (Table 1), and cropped predominantly with oats to control take-all due to the fungus *Gaumannomyces graminis* (Rivoal *et al.* 1990; Rivoal, Doussinault & Hullé, 1990). Growing of the resistant oat cultivar Panema resulted in almost total elimination of the nematodes in the low infestation row, whereas nematode population densities increased above the damage threshold in the moderately infested row due to the cultivation of the susceptible oat cultivar Peniarth (Rivoal *et al.*, 1990). The winter wheat (*Triticum aestivum* L.) cv. Arminda was sown on the two strips on 20 November 1987 and grown in accordance with the local farming practices.

Table 1

Crop rotations carried out at Argentan (F) to build an infestation differential for *Heterodera avenae*

| Year | Lowly infested strip | Moderately infested strip |
|---|---|---|
| 1982 | Oat cv. Panema (R)* | Oat cv. Peniarth (S) |
| 1983 | Wheat cv. Talent (S) | Wheat cv. Talent (S) |
| 1984 | Oat cv. Panema (R)<br>0.1 (0.13)** | Oat cv. Peniarth (S)<br>61.7 (16.53) |
| 1985 | Maize cv. LG11<br>0.0 (0.02) | Maize cv. LG11<br>15.3 (3.79) |
| 1986 | Oat cv. Panema (R)<br>0.1 (0.10) | Oat cv. Peniarth (S)<br>6.2 (2.75) |
| 1987 | Oat cv. Panema (R)<br>0.0 (0.05) | Oat cv. Peniarth (S)<br>33.9 (8.67) |
| 1988 | Wheat cv. Arminda | Wheat cv. Arminda |

* Resistant (R) and susceptible (S) cultivars.
** Means and standard deviations of infestation levels (larvae/g of soil) from five replicates (October, each year).

Nematode densities were determined before sowing by analysis of soil samples taken after ploughing from five 10 m² (2 × 5 m) areas on both rows with moderate and low infestation (Rivoal & Sarr, 1987; Rivoal *et al.*, 1990). Total dry matter above ground was estimated on 4 May 1988 from wheat plants sampled at the " 1-2

Table 2

Data concerning the experimental design cultivated with the winter wheat cv. Arminda. (Means are calculated from five replicates; average plant data are given for 0.20 m² areas; data followed by *a* or *b* are significantly different at P ≤ 0.05*)

| Plots | Infestation: Low | Infestation: Moderate | Signification: F | Signification: P |
|---|---|---|---|---|
| Stage 1-2 nodes (Feekes 6-7) | | | | |
| *Heterodera avenae* (nematodes/g. root) | 0.2 *a* | 23.8 *b* | 137.30* | 0.00 |
| Number of plants | 66.0 | 63.0 | 0.59 | 0.48 |
| Stem and foliage dry weight (g) | 60.7 *a* | 40.5 *b* | 63.39* | 0.00 |
| Root dry weight (g) | 5.1 | 4.5 | 2.42 | 0.19 |
| Harvest | | | | |
| Number of ears | 71.0 | 71.0 | 0.02 | 0.88 |
| Dry straw weight (g) | 117.1 *a* | 103.3 *b* | 7.41* | 0.05 |
| Dry grain weight (g) | 123.7 *a* | 112.9 *b* | 7.89* | 0.05 |

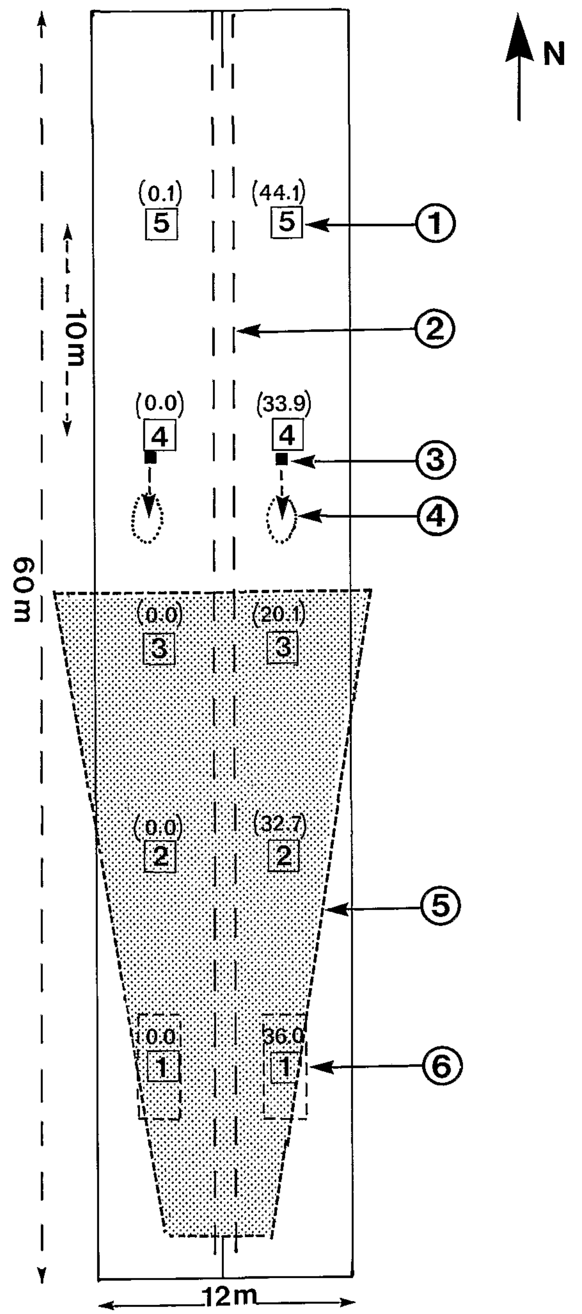


Fig. 1. Schematic representation of the experimental design carried out at Argentan (Orne, France) to detect *Heterodera avenae* infestations by radiothermometry : ① : Plot number; ② : Central path for tractor passage; ③ : Radiothermometers places; ④ : Ground resolution element; ⑤ : Approximate ground scene viewed by thermal infra red camera; ⑥ : Sampling area and densities of nematodes (larvae/g of soil).

nodes " stage (or " Feekes 6-7 "), from two 0.20 $m^2$ adjacent areas at the centre of the nematode sampling areas. Endoparasitic numbers of *H. avenae* were estimated in the roots taken at a depth of 15-20 cm. Wheat plants were harvested as sheaves from six 0.20 $m^2$ per plot and ears were cut and threshered. Table 2 shows yields as straw and grain dry weights.

The analysis of wheat at the 1-2 nodes stage (Feekes 6-7) confirmed the differences in nematode infestation level in cv. Arminda roots between moderate and low infestation rows. *H. avenae* did not modify the numbers of wheat plants, but significantly affected total aerial dry matter. At harvest ear numbers were similar in both rows, but straw and grain yields were significantly reduced ($P \leqslant 0.05$) in the moderately infested strip (Table 2).

## Stomatal resistance

Leaves stomatal resistance was measured with a diffusion porometer (Model MK III, Delta-T, Cambridge). The porometer was calibrated several times a day so as to operate under the same temperature and relative humidity conditions as those in the vicinity of the leaves. The plants tested were selected within approximately 1 $m^2$ areas near plot No. 3 on the low infestation strip, and plots No. 1 and No. 4 on the moderate infestation strip (Fig. 1). Measurements were made on both leaf sides (amphistomous plant) and were carried out alternately on each row over a period of 5 min to reduce the variations due to climatic factors. The wheat canopy stomatal resistance ($r_c$) is obtained by the relation :

$$r_c = \frac{1}{LAI} \sum_i \left[\frac{1}{r_{li}}\right]^{-1}$$

where *LAI* is the leaf area index, and $r_{li}$ the equivalent stomatal resistance of a single leaf noted " *i* ".

## Radiant surface temperature

Canopy radiant temperatures were measured using two types of device :

- two portable radiothermometers (Model Heimann KT15, 8-14 µm, with a 20° field of view) were placed 3 m above canopy surface. Viewing was focused with a 45° incidence to an elliptic 2.4 $m^2$ area located in the centre of each strip (Fig. 1). It was oriented to the south according to the direction of wheat rows, thus minimizing shading effects at midday when temperature difference between the two strips was greatest (Boissard & Guyot, 1983). Measurements were performed simultaneously on the two strips at 30 s intervals and averaged every 5 min. This procedure allowed calculation of temperature difference between the two rows (differential radiothermometry).

• a thermal infrared camera (Model AGA 680, 25° lens, video spatial resolution = 2.5 mrad, 5.5 × 5.5 cm pixel at the centre of the image). The camera was fixed onto a crane at 11 m above crop canopy, and was adjusted to an angle of 30° from horizontal so as to show the two experimental rows in the same thermal image.

### Environmental conditions

Physiological and physical measurements on wheat canopies were made on June 17 and 23, 1988, when cv. Arminda was at the end of flowering (Feekes 10-5-3).

The weather conditions recorded at the local meteorological station, 30 km away from the experimental site, on the two days of measurements, are given in Table 3.

## Results

The stomatal resistance of the *H. avenae* moderately infected plants was always greater than that of plants with low level of infection throughout the day (Fig. 2), and was almost twice higher between 10:00 h and 17:00 h (Solar Time = ST) when radiant temperature was measured. During this time, the greater amplitude exhibited in the moderately infested plot could be due to variations in infestation level between plots (values are the means of the measurements from two plots) and also between wheat plants within the same plot.

Differences in radiant temperature during the day are given in Fig. 3. These differences remained positive, indicating that surface temperature was higher on the moderately infested plot. The radiant temperature difference greatly varied with time, but remained most often between 0.5 and 1.0 °C with a maximum at 1.3 °C. Thus plant water stress due to *H. avenae* was reflected in the two measurements of canopy stomatal resistance and canopy radiant temperature.

Contrary to a visible image (Fig. 5A), the thermal

Table 3

Weather conditions recorded at the local meteorological station (Alençon) on the two days of measurements

| | Insulation duration (h) | Air temperature (° C)* | Relative humidity (%)* | Wind speed (m.s$^{-1}$)** | Precipitation (mm) |
|---|---|---|---|---|---|
| June 17 | 7.0 | 16.1 | 78 | 5.4 | 0 |
| June 23 | 14.6 | 15.4 | 67 | 4.4 | 0 |

(*) 2 m above ground.
(**) 10 m above ground.

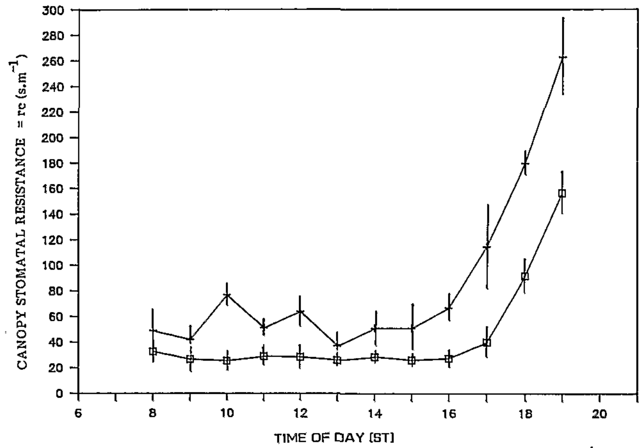


Fig. 2. Diurnal course of canopy stomatal resistance (s.m$^{-1}$) on the low (□) and moderate infestation (+) rows (June 23, 1988).

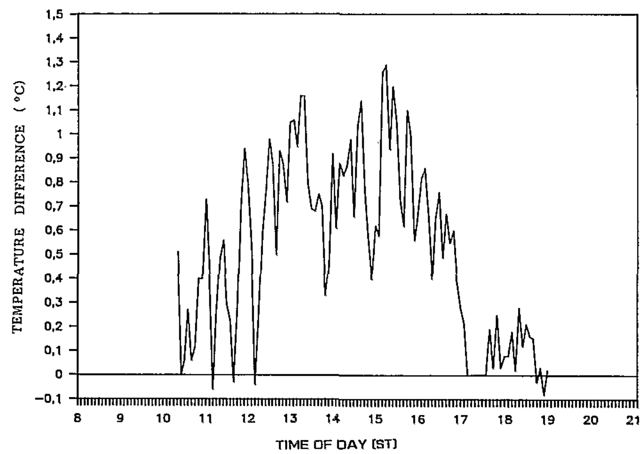


Fig. 3. Diurnal course of temperature difference (°C) between the moderate and the low infestation rows (June 23, 1988).

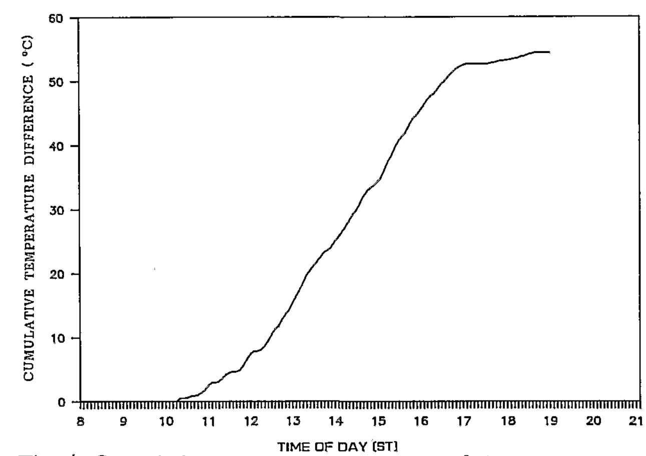


Fig. 4. Cumulative temperature difference (°C) with a 5 min calculation step, between the moderate and the low infestation rows (June 23, 1988).

image (Fig. 5B) shows two different areas with the left and central parts in a prevailing green colour (low infestation row) and the right part with prevailing blue and red colours (moderate infestation row). These colours are indicative of the radiant temperature of crop canopies (0.25 °C per colour level) according to the scale for thermal images (Fig. 5B). The two strips show temperature difference of 0.5 to 1 °C.

Thermal images have the advantage of showing the spatial variability of radiant temperature in plant canopies. In this study, they demonstrated that advective energy transfer occurred above the rows bordering the low infestation strip. Indeed, the surface temperature increased by 0.5 °C at the edge of the low infestation strip (blue colour on the left of the image). This phenomenon, called " plot border effect ", means that some energy is transferred as sensible heat by wind, from a low evaporating area, e.g. a path kept free from weeds with higher air temperature, to the adjacent crop canopy. The contrast between moderate and low infestation areas was determined with a good accuracy by the two-coloured processing (Fig. 5C) and appropriate choice of the threshold temperature between the two plots.

## Discussion

Implementing radiothermometry for detecting nematodes requires that the two adjacent plots be available. This prerequisite soon turns out to be a limitation to monitoring of irrigation, because an adequately irrigated plot cannot conceivably be maintained near water stressed areas. For this reason, investigations based on radiant temperature differences have not be used (Jackson, 1982). In contrast, this situation is of interest for plant protection because neighbouring plots with differ-

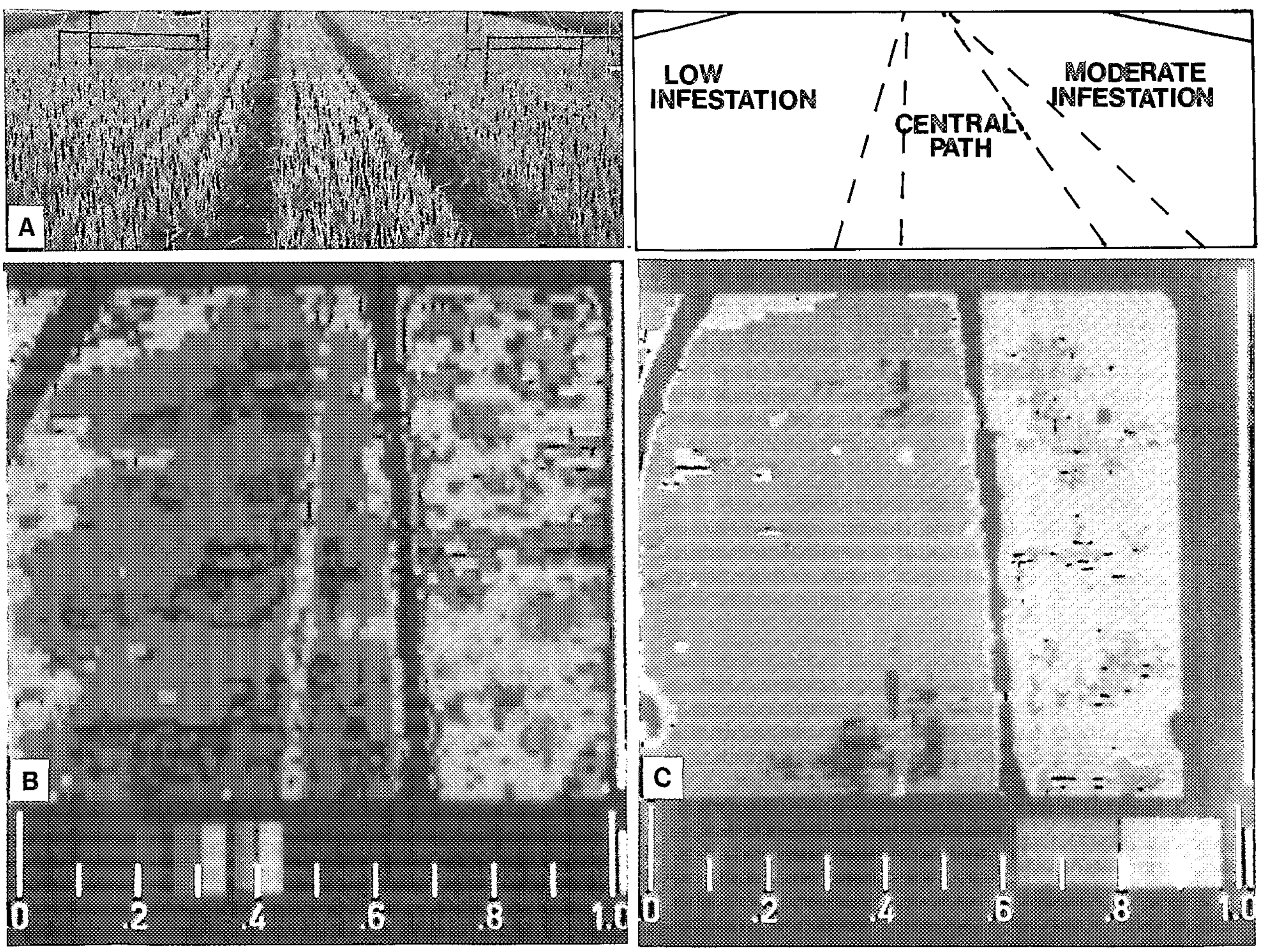


Fig. 5. Views of the cv. Arminda canopies : A : Visible image of the experimental site (Argentan (F), June 23, 1988); B : Thermal image of the site composed of five level colors with 0.25 °C per level [June 17, 1988; 16h (ST)]; C : Thermal image of the site composed of two level colors with 1 °C per level [June 17, 1988; 16h (ST)].

ent infestation levels are common. On experimental sites, a control plot is often available for comparison with nearby plots (Taylor, 1967). The same holds for natural field conditions when moderately or highly infested patches form clearly delimited areas among less infested ones (Gair, 1964; Caubel, Duchesne & Rivoal, 1975; Caubel *et al.*, 1978; Esmenjaud, Marzin & Rivoal, 1987). In such cases, radiothermometry appears to be a valuable method for airborne remote sensing of nematode infestations in large cereal-growing areas where conventional sampling techniques may be unreliable and too expensive.

Surface temperature difference (STD) represents an indirect indicator of water stress in plots. Therefore, it does not measure plant water status, but the effect of the change in water status caused by the nematode invasion of plant root system, as it is also the case every time stomatal resistance or plant growth are affected. Variations in STD due to water stress caused by pests or pathogens have been little investigated so far. However, O'Toole *et al.* (1984) showed that a crop water stress index based on surface temperature data could be more sensitive than physiological indicators to control irrigation. Moreover, water relations are very often modified before plant growth and canopy structure exhibit some disturbance (Jackson, 1986; Gebhardt, 1986; Dieng, 1988). This early diagnosis of nematode parasitism gives some advantages to radiothermometry over other existing methods.

STD greatly varies at the experimental site with such climatological factors, as solar radiation (Wiegand & Namkan, 1966), and to a lesser extent, wind speed (Okuyama, 1975). As a result, quantifying this term in this form is difficult, and radiothermometrical data must, therefore, be taken over a period of time. For example, cumulative temperature difference (CTD) (Fig. 4), which reflects the persistence of water stress, yields more stable and precise responses than STD. The mean slope of the CTD curve could provide a simple quantification of the difference in water status between two plots under given climatic conditions.

These results open up prospects for a wide range of applications :

- radiothermometry is especially useful for research and experimentation. It is non-destructive and can estimate the consequences of nematode infestation on plant water status before any symptom can be visually detected. Surface temperature measurement can help the understanding of plant physiology and plant responses to environmental constraints.

- radiothermometry also constitutes a valuable technique for agricultural advisory services, and will be particularly helpful in sensing cultivated areas where crops exhibit disturbed water relations. It is of special interest for detecting nematode parasitism since infestation extends from limited spot-like areas (Caubel *et al.*, 1978) and water movements within the SPAC are often affected before any symptom is actually visible.

However, ground temperature difference between two areas recorded by radiothermometry are not necessarily indicative of parasitism, and this technique must therefore be associated with complementary ground measurements to document the presence and particular cause of the stress.

Ground or airborne thermal infrared remote sensing methods appear to be well adapted to some agronomic requirements at the farm or restricted agricultural zone scale. This remote sensing technique is appropriate for filling the gap resulting from the present inadequate performances of satellites, because it has a good ground resolution within this wavelength range and permits increased repeatability, which is of necessity under the climatic conditions in western Europe.

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