From the weather forecast to the prognostic moisture content of dry agricultural crops

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From the weather forecast to the prognostic moisture content of dry agricultural crops

Proefschrift

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in de landbouw- en milieuwetenschappen
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Stellingen

1. De windsnelheid speelt bij het drogen van graan een veel belangrijker rol dan bij het drogen van gemaaid gras bestemd voor het inkuilen.
(Dit proefschrift)

2. Het maaitijdstip van gras kan de droogsnelheid beïnvloeden. Het maaien van gras bij een lage luchtvochtigheid in de namiddag vertraagt de droogsnelheid door een vroegtijdige sluiting van de huidmondjes.
(Atzema, A.J., 1994. Weather driven drying of perennial ryegrass. 21th Conference on Agriculture and Forest Meteorology, San Diego, California, USA, 7-11 March 1994: J15-J18)

3. Niet alleen buiten, maar ook voor gewassen in kassen is een weersverwachting belangrijk. Met een verwachting voor b.v. de globale straling kan een automatische kasklimaatregeling bijgestuurd worden.

4. Er wordt te weinig onderzoek verricht naar weersverwachtingen gericht op te velde staande landbouwgewassen. Dit blijkt uit de schaarse literatuur die over dit onderwerp aanwezig is.

5. De landbouwmeteorologie bestudeert alle meteorologische activiteiten die operationeel op het landbouwbedrijf gebruikt kunnen worden.

6. Dauw kan opgedeeld worden in dauwstijging en dauwval. De verhouding tussen deze twee processen wordt veroorzaakt door de hoogte van het gewas. Bij een gelijke gewasdichtheid geldt dat hoe hoger het gewas is, hoe groter de fractie dauwval is.
(Atzema, A.J., Jacobs, A.F.G., Wartena L., 1990. Moisture distribution within a maize crop due to dew. Netherlands Journal of Agricultural Science 38: 117-129)

7. Ten onrechte wordt er teveel waarde gehecht aan de dagelijkse maximum temperatuur daar deze meestal slechts een zeer korte tijd van de dag optreedt.

8. Met behulp van een thermohygrograaf verkrijgt men een goede indicatie van de droogsnelheid van droge en natte landbouwgewassen.

9. Bij de bestudering van planteziekten dient meer aandacht besteed te worden aan het microklimaat van de plant. Met behulp van specialistische weersverwachtingen kan het gebruik van gewasbeschermingsmiddelen teruggedrongen worden.

10. In het plantenfysiologisch onderzoek dient men aandacht te schenken aan de invloed van het weer op de gewasontwikkeling. Daarbij moet men vooral rekening houden met het verschil in de dagelijkse gang van de temperatuur van de bovengrondse delen en de sterk afwijkende worteltemperaturen.

11. De kamerbrede medewerking van het Nederlandse parlement aan het beperken van universitaire studies tot vier jaar is begrijpelijk als men bedenkt, dat het merendeel der academisch gevormde parlementsleden juristen zijn, en dat de studie Nederlands recht inderdaad binnen vier jaar op aanvaardbaar niveau kan worden voltooid.

12. Lichamelijke inspanning b.v. sport verhoogt de energie voor het werken. Hierdoor heeft men een betere nachtrust en kan men de dagelijkse problemen beter aan.

13. Het invoeren van de Engelse taal op een universiteit in Nederland vergroot de afstand tussen de universitair en andere opgeleiden. Deze invoering is daarom niet gewenst.

14. Het is niet wenselijk om in het begin van het promotieonderzoek je al bezig te houden met stellingen die gericht zijn op de maatschappij, omdat deze gedurende de jaren dat het onderzoek loopt, verandert.

Stellingen behorende bij het proefschrift van A.J. Atzema: From the weather forecast to the prognostic moisture content of dry agricultural crops.
Wageningen, 22 april 1994.

Van het concert des levens
krijgt niemand een program

Voorwoord

Het nat worden en weer opdrogen van gewassen heeft al jarenlang mijn belangstelling. Tijdens de studie Planteziektenkunde aan de LUW leerde ik Bert Wartena kennen. Hij was niet alleen hoogleraar Meteorologie, maar ook boer. Er was een gemeenschappelijke belangstelling. Aan het eind van mijn studie vroeg hij mij of ik belangstelling had voor het promotieonderzoek waarvan het resultaat nu voor u ligt. Het onderwerp trok me wel, maar aan het idee om na mijn studie het onderzoek in te gaan, moest ik wennen. Al snel bleek dat mijn aanvankelijke aarzeling om onderzoek te gaan doen onterecht was. Het onderzoek boeit me sterk. Hiermee wil ik Bert Wartena, pro(-)motor, dan ook hartelijk danken voor het geboden onderzoek, de kennis die ik opgedaan heb van de andere onderwerpen binnen de landbouwmeteorologie en het enthousiast maken van studenten om een vak landbouwmeteorologie te doen, waardoor ik meer hulp en gezelschap kreeg.

Van de Vakgroep Meteorologie wil ik iedereen bedanken (ook de studenten) die meegeholpen hebben aan dit onderzoek. Ook de rust en de vrijheid die de Vakgroep mij heeft gegeven, heb ik erg gewaardeerd. De instrumenten waren in goede staat en wanneer er iets stuk ging, werd dit snel verholpen. De drooglucht van gras op de Vakgroep werd door sommigen gewaardeerd, maar door de meesten voor lief genomen.

Meteo Consult wil ik bedanken voor het gebruik van de VAX-computer en het maken van de weersverwachtingen. Moeilijke fouten tijdens het programmeerwerk loste Rik de Gier, werkzaam bij dit bedrijf, eenvoudig op. Voor vragen over de PC kon ik terecht bij Kees van den Dries van onze Vakgroep Meteorologie. Van beiden heb ik veel geleerd.

Het veldonderzoek van gras werd uitgevoerd op het IMAG proefbedrijf "De Vijf Roeden" in Duiven. Alle medewerkers en stagiaires wil ik hartelijk danken voor hun medewerking en de hulp voor en tijdens het inkuilen van gras. Het was een leuke groep mensen om mee te werken. Ook de akkerbouwers die hun percelen ter beschikking stelden voor het graanonderzoek, wil ik hartelijk danken. Wanneer niemand hiertoe bereid was had dit onderzoek niet uitgevoerd kunnen worden.

Het moge duidelijk zijn dat ik in een uitstekende werkomgeving heb mogen werken. Mede hierdoor liep het onderzoek goed. Zonder dat men het wist, heb ik in de laatste fase van het onderzoek steun gekregen van de "eetgroep" op SSR. Samen de maaltijd nuttigen, daarna een kopje thee of koffie en een gezellig gesprek doet mij goed. Ook de daaruit voortvloeiende activiteiten waardeer ik. Het leven bestaat niet alleen uit werken.

Uiteraard wil ik mijn ouders en mijn zus Jannie bedanken voor hun medeleven met mij. Ondanks de afstand van ruim 200 km, is het voor mijn vader en moeder geen enkel probleem om ook bij mij in Wageningen te komen. Jannie kwam in de eerste jaren van het onderzoek bijna dagelijks bij mij over de vloer. De laatste tijd is dit door de grote geografische afstand tussen ons wat minder vaak het geval, maar de belangstelling voor mij is er niet minder om.

Contents

Context and structure of this thesis

Forage conservation and harvesting cereals is a very weather dependent operation. Up to now the shortcomings of weather forecasts have been a major handicap to plan the timing of cutting grass destined for ensiling and the timing of harvesting cereals. The aim of the present research program is to forecast the moisture content of cut grass and mature grain. In this way the harvest can be planned carefully. This planning prevents a decrease of the quality of the products and minimizes cost. The moisture content of cut grass and mature grain can be calculated by models in which the input are standard weather elements and a few crop characteristics. This dissertation contains two parts. Part 1 (chapter 1-4) deals with cut grass destined for silage and part 2 (chapter 5-7) deals with mature grain just before the harvest.

Part 1

Chapter 1 describes the response of the drying of grass to the associated weather elements. The differences between grass species with respect to field drying is discussed together with the effects of swath treatments of the grass. The relationship between different air temperatures and grass temperature is examined.

In chapter 2 a simple grass drying model is presented. This model uses only three standard weather elements: air temperature, dew point temperature and precipitation. No crop characteristics are used. In dry weather the moisture content of grass is calculated hourly during daytime from 9.00 h to 19.00 h (local time) by determining the saturation deficit. Dew formed during the night is considered to be compensated by the drying of grass early in the evening and in the morning before 9.00 h. Roughly this model gives an indication of the forecast moisture content of cut grass.

Further research gives rise to a more complicated model which gives more accurate results. This model, described in chapter 3, uses some crop parameters and six standard weather elements. This model is based on the formula of Penman-Monteith and calculates the moisture content of grass 24 hours a day.

Forecasting the moisture content of grass is described in chapter 4. Now forecast weather elements provide the input of the model. Errors in the forecast weather elements can give errors in the forecast moisture content. Determination of the quality of forecasting the moisture content of grass on the forecast weather elements is discussed.

Part 2

Chapter 5 describes the response of the moisture content of wheat and barley to the associated weather elements. Both for wheat and barley the relationship between different air temperatures and surface temperatures to the ears is examined. The equilibrium moisture content of wheat and barley is discussed. Microclimate values are compared with standard weather data.

In chapter 6 a complicated model is presented that calculates the course of the moisture content of cereals, 24 hours a day. This model uses some crop parameters and six standard weather elements. This model is based on the formula of Penman-Monteith.

Forecasting the moisture content of wheat and barley is described in chapter 7. Now forecast weather elements provide the input of the model. The complexity of errors in the forecast weather elements is examined. The decrease of the quality of forecasting the moisture content of cereals with an increasing forecasting period is discussed.

Part 1

Grass and Forage Science (1993) Volume 48, 362–368

The effect of the weather on the drying rate of cut diploid and tetraploid perennial ryegrass (*Lolium perenne* L.) and diploid hybrid ryegrass (*Lolium perenne* × *L. multiflorum*)

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Abstract

The drying rate of cut diploid and tetraploid perennial ryegrasses (*Lolium perenne* L.) and a diploid hybrid ryegrass (*Lolium perenne* × *L. multiflorum*), and associated meteorological characteristics, were studied in the field for three successive years: 1988, 1989 and 1990. Meteorological elements measured were: air temperature (at 0·1 m and 1·5 m height), dew point temperature (at 1·5 m height), temperature within the grass sward, grass surface temperature, global radiation and wind speed (at 2 m height).

Apart from the weather, the drying depended on the grass species and the yield. Hybrid ryegrass had a lower initial moisture content at cutting in the morning than perennial ryegrass. Also, the hybrid ryegrass dried faster than the perennial ryegrass. Within the same varieties a low yield dried faster than a high yield. Frequent tedding did not influence the rate of drying. The temperature within the grass swath approached the air temperature at 1·5 m. The grass surface temperature was greatly affected by global radiation. Increasing wind speed had an adverse effect on the drying rate of grass.

Introduction

The physical aspects of the drying process of cut grass are different from those of uncut grass. Water is lost from the plant as water vapour, from evaporating sites close to its surface. The ease with which water vapour can move away from the plant surface influences the rate of drying. Plant structures such as stomata and cuticle, therefore, play an important role.

Younger grass dries more quickly than mature grass at the same yield, and leaves dry faster than stems (Menzies and O'Callaghan, 1971; Jones, 1979). This phenomenon is partly due to the thicker cuticle on mature grass and stems. In leaves the bulk of the liquid water is closer to the surface in comparison with stems. Leaves also have numerous stomatal pores.

Soon after cutting, the continued loss of water results in stomatal closure. First, the stomata are visually closed, then they are physiologically closed. The stomata of Italian ryegrass (*Lolium multiflorum*) are visually closed 15 min after cutting, but the physiological closure of stomata occurs 30–40 min after cutting (Clark *et al.*, 1977). Hansen (1974) obtained average counts of 16 and 71 stomata per mm^2 for the abaxial and adaxial sides of Italian ryegrass leaves respectively. Similarly, in other *Lolium* species most of the stomata are situated on the upper (adaxial) surface on the lower slopes of the ridges. As well as the effect of water concentration on stomatal aperture, much of the swath will be subjected to low light intensity, which will also induce stomatal closure (Harris and Tullberg, 1980).

A function of the cuticle is conservation of water. The resistance of the cuticle of living grass is extremely high. After drying of grass, the cuticle tears and consequently the resistance of the cuticle decreases. Mechanical damage accelerates this process. Conditioning by a mower conditioner increases the drying rate (Glasbey, 1988; Lamond *et al.*, 1988).

A great deal of the energy necessary for evap-

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Table 1. The time of day (h) of mowing, tedding and ensiling in the tedding experiment

Date (1990)	Mowing		Tedding		Ensiling
	Day 1	Day 2	Day 1	Day 2	Day 2
3 May	15		16	12	17
17 May		7		9 11	16
30 May	19			9 12	16
15 June	11		12 16	11	15
12 July	9		11 16	11	16

oration of moisture is supplied by global radiation. During the day global radiation has a great influence on the grass temperature. At night the grass temperature decreases as a result of a net outgoing long-wave radiation (short-wave radiation is zero). Respiration plays a minor role. The energy released by respiration is equivalent to an increase in temperature of less than 2·5°C h^{-1} if the temperature of the grass is at least 25°C. At lower grass temperatures less energy is released (Wood and Parker, 1971).

The aim of the present research programme is to forecast the drying of grass by use of a weather-driven model. This paper describes only the response of the drying of grass to the weather elements. The drying rate is influenced by the grass temperature, which has to be estimated from the air temperature at 1·5 m height as measured at standard weather stations. Only then can the drying of grass be calculated by a model using the input of weather data. The model uses six meteorological elements, at hourly intervals (Atzema, 1992).

In this paper, the differences between grass species with respect to field drying are discussed together with the effects of swath treatments of the grass. The temperature behaviour of the grasses is also examined.

Materials and methods

During the growing seasons of 1988, 1989 and 1990, in eighteen periods from April to September inclusive, the drying of grass in the field was observed at the pilot farm of the Institute of Agricultural Engineering (IMAG) at Duiven in The Netherlands (51°57′ N, 6°02′ E). The experiments were carried out on sixteen different plots at the same location. The size of a plot varied from 1·3 to 2·7 ha. The grass species examined were diploid perennial ryegrass (*Lolium perenne* L.) (ten plots), tetraploid perennial ryegrass (*Lolium perenne* L.) (four plots) and diploid hybrid ryegrass (*Lolium perenne* × *Lolium multiflorum*) var. Barcolte (two plots). The perennial ryegrasses were a mixture of different varieties. All the grasses examined were in the vegetative state.

Grass was cut in the morning, the afternoon or the evening by a mower conditioner, which abraded the grass. After cutting the grass was tedded once or twice then windrowed just before ensiling.

During the field drying period, twelve samples of grass were taken every hour. The samples were dried in an oven at 60°C for 2 days to determine the moisture content. Just before ensiling the total mass of grass was weighed on a platform scale with a precision of 10 kg and yield per hectare was calculated.

In 1989, twelve samples were also taken just before cutting. This grass was cut with scissors. In 1990 different treatments were carried out within the same plot. After cutting, the whole plot was tedded. Next, after some hours, part of the plot was tedded once or twice more, part was windrowed and part was dried without any further field conditioning. Table 1 shows the time of mowing, tedding and ensiling in the tedding experiment and Table 2 shows the time of the differ-

Table 2. The time of day (h) of mowing, tedding, windrowing and ensiling in the windrowing experiment

Date (1990)	Mowing		Tedding		Windrow		Ensiling
	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 2
3 May	15		16			12	17
17 May		7		9		11	16
30 May	19			9		12	16
15 June	11		12		16		15

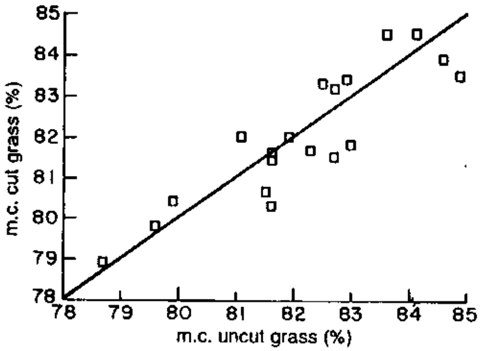

Figure 1. The initial moisture content (m.c.) of cut grass versus the moisture content of uncut grass.

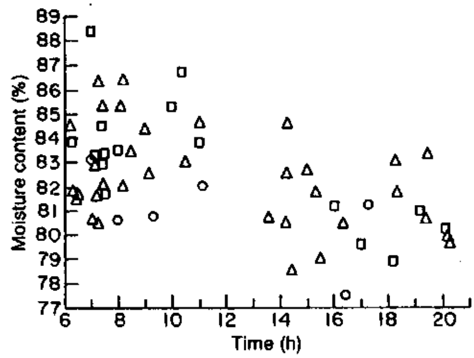

Figure 2. The initial moisture content (m.c.) at different times of the day. △, *Lolium perenne*, diploid; □, *Lolium perenne*, tetraploid; ○ *Lolium perenne* × *Lolium multiflorum*, diploid.

ent field treatments in the experiment on windrowing. The width and height of the windrow were 0·90 m and 0·35 m respectively. The width between two windrows was 4·0 m. The differences between the three parts were compared hourly.

Standard meteorological data were taken hourly from the weather station at Deelen at a distance of 15 km from the experimental site. The temperatures at 0·1 m and 1·5 m height were taken from the meteorological station at Wageningen at a distance of 25 km from the experimental site. Meteorological data were also taken on the experimental plots. The air temperature and the dew point temperature (both at 1·5 m height) were measured with a psychrometer (Assmann). The temperature within the grass sward was taken with a mercury thermometer. The grass surface temperature was measured with a Heymann infrared radiation meter. The wind speed (at 2 m height) was taken with a cup anemometer (type Deuta).

Results and discussion

Grass species

On average there was no significant difference in the air temperature and dew point temperature (both at 1·5 m height) between the experimental plot, the weather station at Deelen and that at Wageningen. Also, the moisture content of uncut grass did not differ from that of grass cut at the same time (Figure 1, 1989 data).

Figure 2 shows the initial moisture content of perennial ryegrass (diploid and tetraploid) and hybrid ryegrass (diploid) at cutting, at different times of the day during the months of April to September. The moisture content of grass at mowing varied from about 78% to 88%. Initial moisture content varied with the time of mowing, the grass species used, the stage of maturity and the nitrogen and water application. For young grass, the application of nitrogen, dew and rain preceding cutting increases the moisture content at the time of cutting (Wilman & Owen, 1982).

Owen and Wilman (1983) found that diploid hybrid ryegrass (*Lolium perenne* × *Lolium multiflorum*) had a low moisture content at cutting compared with diploid perennial ryegrass (*Lolium perenne*) when cut in the morning. Tetraploid varieties had a higher moisture content at cutting than the diploids (Owen and Wilman, 1983). Figure 2 also shows this phenomenon when herbage was cut in the morning, but when cut in the afternoon it appeared that the initial moisture content of the tetraploid ryegrass was not higher than that of the diploid. Table 3 shows the initial moisture content of different varieties of ryegrass when cut in the morning as compared with the afternoon. The average moisture contents at cutting in the morning and in the afternoon were 83·4 ± 1·9% and 80·7 ± 1·7% respectively.

Plots with a low herbage mass dried faster than plots with a high herbage mass and diploid var-

Table 3. Initial moisture content (%) of different varieties of ryegrass when cut in the morning or in the afternoon

Variety	Morning cut	Afternoon cut
Perennial diploid	83·2 ± 1·9	81·1 ± 1·7
Perennial tetraploid	84·3 ± 1·9	80·1 ± 1·0
Hybrid diploid	81·6 ± 1·2	79·3 ± 2·6

Table 4. The moisture content (%) and the amount of water (kg ha⁻¹); at the start and at the end of the drying period, of perennial ryegrass varieties at two different dry matter yields (kg ha⁻¹)

Grass variety	Date (1989)	Yield of dry matter	Moisture content		Amount of water		Water loss
			Start	End	Start	End	
Diploid	17 May	3000	82·0	64·3	13700	5400	8300
Diploid		2800	80·4	57·1	11500	3700	7800
Diploid	5 July	4350	81·8	64·9	19500	8000	11500
Diploid		3740	80·6	59·4	15600	5500	10000
Tetraploid	12 June	3840	84·3	67·6	20600	8000	12600
Tetraploid		3590	84·5	66·3	19600	7100	12500
Diploid†	26 May	2660	83·2	65·8	13200	5100	8100
Tetraploid		2480	81·7	68·7	11100	5400	5600
Diploid	12 June	4310	84·5	60·4	23500	6600	16900
Tetraploid		3840	84·3	59·2	20600	5600	15000
Diploid	12 June	4310	84·5	67·3	23500	8900	14600
Tetraploid		3590	84·5	66·3	19600	7100	12500
Diploid	12 July	3450	81·5	52·6	15200	3800	11400
Tetraploid		2700	83·5	54·2	13700	3200	10500
Tetraploid	22 April	2900	83·3	71·4	14500	7200	7300
Diploid†		2200	81·0	64·9	9400	4100	5300
Tetraploid	8 May	3900	83·4	71·4	19800	9800	10000
Diploid		2700	81·6	63·4	12000	4700	7300

† Hybrid ryegrass was used.

ieties dried faster than the tetraploid varieties (Table 4). Also, the hybrid ryegrass dried faster than the perennial ryegrass. Using different varieties from our experiments Owen and Wilman (1983) found the same relative differences. So, within the same varieties, a low mass dries faster than a high mass. A low mass of a diploid variety dries very fast when compared with a high mass of a tetraploid variety, but the relative drying rates of diploid and tetraploid varieties depended on the difference in mass of the two varieties. At equal masses the diploid varieties lost more water than the tetraploids, while the hybrid ryegrass lost more than perennial ryegrass. Crops with a high mass lost more water than those with a low mass, but it could happen that the moisture content of the high mass remained higher than that of the low mass.

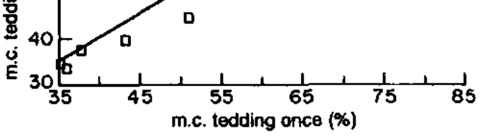

Figure 3. The moisture content (m.c.) of grass tedded more than once versus that tedded once (1990 data).

Swath treatments

In agreement with Spencer *et al.* (1990), the present results suggest that tedding grass more than once a day does not influence the drying rate. Figure 3 compares the moisture content of the plot that was tedded more than once a day with the plot that was tedded only once. After the initial tedding, the density of the spread swath became less, but it did not do so when tedding was repeated within a few hours. The weather and herbage mass (Table 5) were quite variable, so the decision to ted once or more than once did not depend on the weather or mass.

On the other hand, windrowing influenced the final moisture content considerably. Figure 4 shows that grass in windrows had a higher moisture content than that in spread swaths. Similar results were obtained by Glasbey (1988) and Lamond *et al.* (1988). The pathway to water loss from within the windrow is considerably longer than that within a spread swath.

Table 5. The mean air temperature T_a, dew point temperature T_d, wind speed and global radiation in the afternoon (from 12.00 to 17.00 hours inclusive) and the amount of fresh grass

Date (1990)	T_a 1·5 m (°C)	T_d 1·5 m (°C)	Wind speed 10 m ($m s^{-1}$)	Global radiation ($J cm^{-2} h^{-1}$)	Mass of fresh grass ($t ha^{-1}$)
3 May	23	6	6	290	17·7
17 May	18	9	6	210	19·8
30 May	20	3	2	260	6·2
15 June	15	6	2	120	22·1
12 July	23	15	3	260	23·7

Grass temperatures

During the day, especially when the sun is shining, the temperature at the surface of the grass is higher than the temperature within the swath. The surface temperature rises or falls immediately in response to global radiation and determines the temperature within the swath. Figure 5 shows an example of the change in temperature within the swath in relation to variations in the global radiation and the surface temperature. The swath is mainly heated (and cools down) in response to the surface temperature. Grass with a high temperature dries faster than that at a low temperature if the other drying conditions remain the same.

Figure 6 shows the relationship between the grass surface temperature and the temperature within the swath during the day. The surface temperature was nearly always higher than that within the swath, except early in the morning, when the surface temperature was low as a result of negative net radiation.

At a standard weather station, neither the surface temperature of the grass nor the temperature within the swath is measured. However, the air temperature is measured at 1·5 m height, and at some weather stations the air temperature is also measured at 0·1 m height. Figure 7 shows that the temperature within the swath approached the temperature at 1·5 m height ($r = 0·90$) so the air temperature at 1·5 m height can be used in models instead of the temperature within the grass.

Figure 8 shows the relation between the grass surface temperature and the temperature at 0·1 m height ($r = 0·92$). The influence of global radiation on the grass surface temperature was greater than that of the air temperature at 0·1 m height. At a low temperature, early in the morning, the grass surface temperature was lower than that of the 0·1 m air temperature. The reverse occurred when a high temperature was caused by high global radiation in the afternoon.

The relationship between the grass surface temperature and global radiation is shown in Figure 9. The correlation coefficient was only 0·62, because the grass surface temperature depends not only on global radiation, but also on the wind speed and moisture content of the grass. The best linear fit was:

$$y = 0·064\,x + 10·4 \qquad (1)$$

where x is the global radiation and y is the grass surface temperature.

The difference between the actual grass surface temperature and that calculated from equation (1), was small when the wind speed was low and

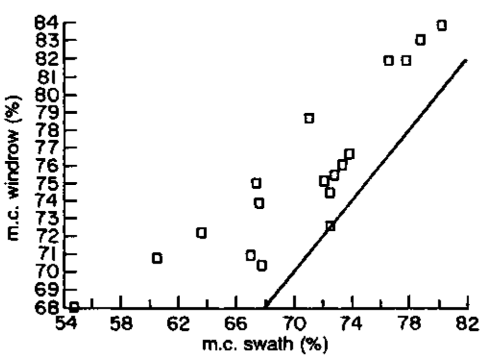

Figure 4. The moisture content (m.c.) of grass in windrows versus that in spread swaths.

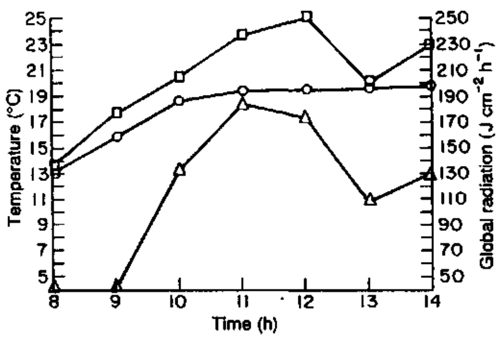

Figure 5. The course of the grass surface temperature, the temperature within the swath and the global radiation (9 May, 1990). □, grass surface temperature; ○, temperature within the swath; △, global radiation.

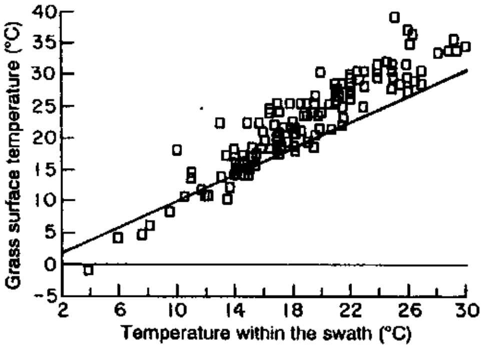

Figure 6. The grass surface temperature versus the temperature within the swath. The line represents equality.

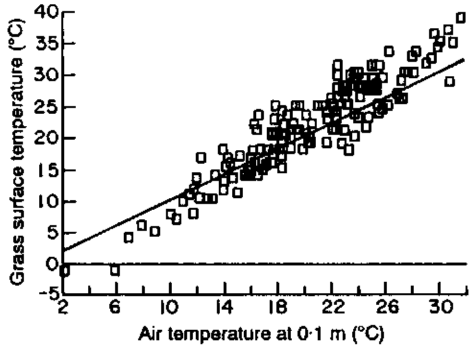

Figure 8. The grass surface temperature versus the air temperature at 0·1 m. The line represents equality.

the moisture content high. Figure 10 shows the influence of wind speed and the moisture content of the grass on the grass surface temperature. The difference between the actual grass surface temperatures and the grass surface temperature as calculated by equation (1) using only the global radiation at a given wind speed and moisture content of the grass is plotted vertically (z-axis) in Figure 10. The moisture content of the grass (%) and the wind speed ($m\ s^{-1}$) are given on the x-axis and y-axis respectively. A high wind speed reduces the grass surface temperature, while a low moisture content increases the grass surface temperature. Thus a high wind speed decreases the drying rate. Thompson (1981) also noted the adverse effect on the drying rate from an increasing wind speed.

Conclusions

In general, the moisture content of grass at the time of cutting was 3% higher when cut in the morning than when cut in the late afternoon. Hybrid ryegrass had a lower initial moisture content at cutting compared with perennial ryegrass, and diploid varieties dried faster than tetraploids at the same mass. Within the same varieties, a low mass dried faster than a high mass. Tedding the grass more than once a day did not influence the drying rate.

The temperature within the swath approached the air temperature at 1·5 m and the air temperature at 0·1 m was a good indicator of grass surface temperature. The grass surface temperature was greatly determined by and responded rapidly to the global radiation, but it was influenced by the wind speed and the moisture content of the grass. A low moisture content of the grass increased the grass surface temperature. A high wind speed had an adverse effect on the drying rate of the grass.

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Thanks are due to co-workers, trainees and J. H. Ettema at the pilot farm of the Institute of Agri-

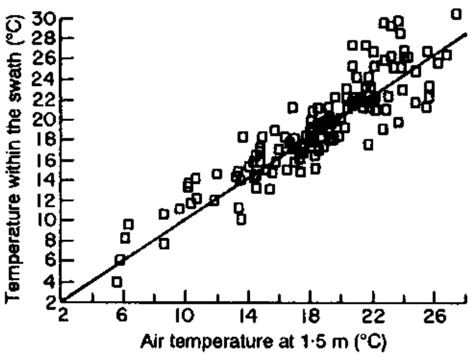

Figure 7. The temperature within the swath versus the air temperature at 1·5 m. The line represents equality.

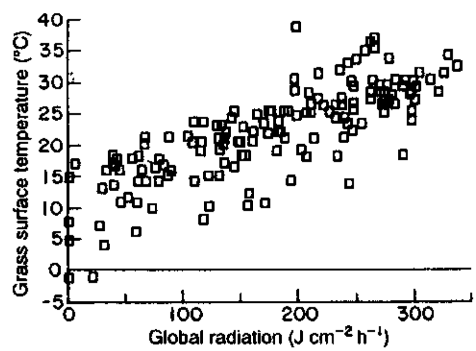

Figure 9. The grass surface temperature versus the global radiation.

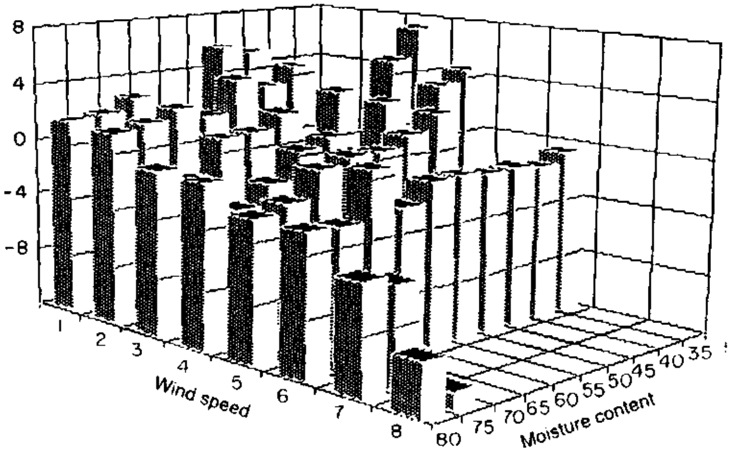

Figure 10. The difference between the actual grass surface temperature and the calculated temperature (°C) (vertically). The moisture content of the grass (%) and the wind speed (m s^{-1}) are given on the *x*-axis and the *y*-axis respectively.

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References

Atzema A.J. (1992) A model for the drying of grass with realtime weather data. *Journal of Agricultural Engineering Research*, **53**, 231–247.

Clark B.J., Prioul J.-L. and Couderc H. (1977) The physiological response to cutting in Italian ryegrass. *Journal of the British Grassland Society*, **32**, 1–5.

Glasbey C.A. (1988) Effects of conditioning, swath structure, and weather on the drying rate of mown grass. *Biometrics*, **44**, 283–288.

Hansen G.K. (1974) Resistance to water flow in soil and plants, plant water status, stomatal resistance and transpiration of Italian ryegrass as influenced by transpiration demand and soil water depletion. *Acta Agriculturae Scandinavica*, **24**, 83–92.

Harris C.E. and Tullberg J.N. (1980) Pathways of water loss from legumes and grasses cut for conservation. *Grass and Forage Science*, **35**, 1–11.

Jones L. (1979) The effect of stage of growth on the rate of drying of cut grass at 20°C. *Grass and Forage Science*, **34**, 139–144.

Lamond W.J., Spencer H.B., Glasbey C.A. and Haughey D.P. (1988) Field wilting and drying of grass in a cool moist climate. *Research and Development in Agriculture*, **5**, 23–28.

Menzies D.J. and O'Callaghan J.R. (1971) The effect of temperature on the drying rate of grass. *Journal of Agricultural Engineering Research*, **16**, 213–222.

Owen I.G. and Wilman D. (1983) Differences between grass species and varieties in rate of drying at 25°C. *Journal of Agricultural Science, Cambridge*, **100**, 629–636.

Spencer H.B., Lamond W.J., McGechan M.B., Graham R. and Moore A.B. (1990) Moisture and dry matter losses in field and wind tunnel trials of grass wilting with frequent mechanical disturbance. *Journal of Agricultural Science, Cambridge*, **115**, 203–207.

Thompson N. (1981) Modelling the field drying of hay. *Journal of Agricultural Science, Cambridge*, **97**, 241–260.

Wilman D. and Owen I.G. (1982) Effects of stage of maturity, nitrogen application and swath thickness on the field drying of herbage to the hay stage. *Journal of Agricultural Science, Cambridge*, **99**, 577–586.

Wood J.G.M. and Parker J. (1971) Respiration during the drying of hay. *Journal of Agricultural Engineering Research*, **16**, 179–191.

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A simple prognostic model for the drying of grass

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1. Introduction

Several agricultural products can be harvested after a natural drying process has reduced the moisture content. A low moisture content often determines the quality of the product and contributes to the profit of the production, because through natural drying the costs of artificial drying are reduced.

Farming claims a planning of work, where prognostic drying models are very helpful. They forecast the moisture content of agricultural products some days ahead. In literature several diagnostic models have been described (Agena et al., 1968; Brück et al., 1969; Dyer et al., 1977; Hill, 1976; Hill et al., 1977; Rotz et al., 1985; Thompson, 1981). With a weather forecast these drying models can be combined to prognostic drying models. In the present paper one model will be discussed (Agena et al., 1968). It is a simple model with only three standard weather elements: air temperature, dew point temperature and precipitation. Despite the limitation of only three weather elements, this model mostly yields realistic results.

2. Methods

2.1. The model

The receptivity of the air for water vapour depends on the saturation deficit which determines the field drying of cut grass. The base of the model is the sum of the hourly values of the saturation deficit. Only during daytime from 7.00 UTC to 16.00 UTC the model calculates the dry matter content of grass. Dew formed during the night is considered to be compensated by the drying of the grass early in the evening from 16.00 UTC and in the morning before 7.00 UTC. When the daily precipitation is more than 0.9 mm the dry matter content decreases by reducing the saturation deficit. If the daily precipitation is more than 10 mm the excess of water is considered to fall on the ground and so it does not decrease the dry matter content further. In the latter case the model calculates as if the amount of water is 10 mm. The dry matter content of grass (D_g) can be calculated hourly by:

$$D_g=14.89+0.2338\Sigma(e_s-e_a-f)-2.526*10^{-4}(\Sigma(e_s-e_a-f))^2 \qquad (1)$$

Notation

D_g	Dry matter content of grass	%
e_a	actual vapour pressure	Pa
e_s	saturated vapour pressure	Pa
f	precipitation factor	

2.2. Realised dry matter content

To compare the model results with the field drying of grass, samples of cut grass were taken. In the growing season of 1988, field conditions were observed at the pilot farm of the Institute of Agricultural Engineering (IMAG) at Duiven in The Netherlands (51°57'N, 6°02'E). Here, plots of grass were as large as those on a common farm, because the aim of this pilot farm was to test agricultural tools. From May to September, inclusive, during the drying process samples of drying grass were taken in triple, every two hours: the first sample just after cutting and the last one just before ensiling. Samples were weighed before they were dried in an oven at 60°C for two days. After drying the samples of grass were weighed again. Just before ensiling the total mass of grass was weighed on a platform scale. So, the yield can be calculated. On the pilot farm a weather station was installed.

2.3. Prognostic dry matter content

To calculate the forecast dry matter content of cut grass one or more days before cutting, the model has been used, too. Now forecast weather elements (air temperature, dew point temperature and amount of precipitation) were needed. These standard weather elements have to be forecast one or more days ahead.

3. Results

The diagnostic dry matter content calculated with realised weather elements, is not exactly a copy of the realised dry matter content of the samples taken in the field, because the model uses only three weather elements. In figure 1 the diagnostic dry matter content has been compared with the realised dry matter content. On the average, the diagnostic dry matter content is higher than the realised ones. Wind speed and the amount of grass are elements that are missing in the model. Also, other weather elements or crop parameters may play a role in the obtained dry matter content. The correlation coefficient and the slope of the regression line is 0.75 and 0.36, respectively.

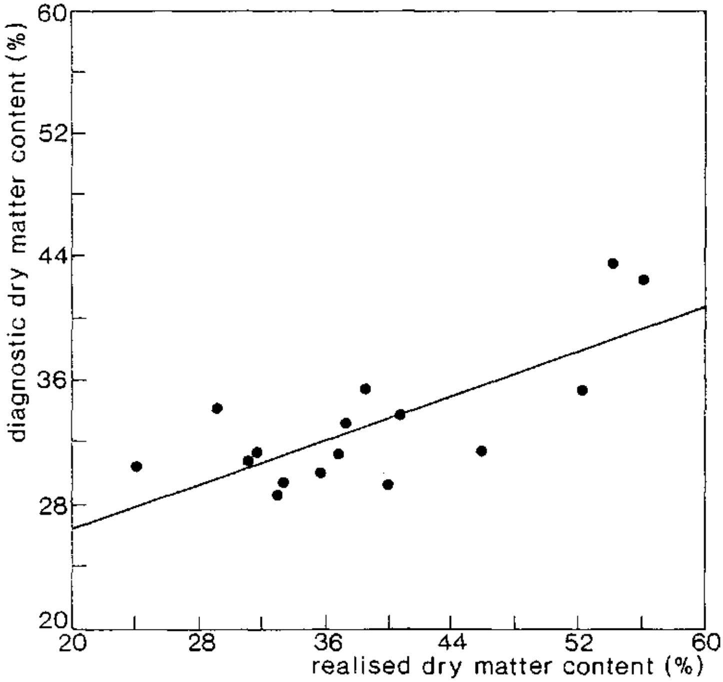

Figure 1: The linear regression line between the diagnostic dry matter content calculated by the model and the realised dry matter content in the field.

To exclude the difference of other weather elements than used in the model the realised dry matter content of different plots of grass on the same day has been plotted during the day. The results are shown in figure 2 together with the diagnostic dry matter content (solid line) calculated by the model.

Four plots of grass were sampled. In two plots (1 and 3) the yield of dry matter was high, 2600 and 2800 kg ha^{-1}, respectively. Moreover in these plots the dry matter content was low: 33.3 and 31.7%, respectively. In the other two plots (4 and 2) the yield of dry matter was less with 1800 and 1900 kg ha^{-1}, respectively, but the dry matter content was higher in nearly the same drying time (45.9 and 36.8%, respectively). In plot 1 (high yield, low dry matter content) hybrid ryegrass (*Lolium perenne x L. multiflorum*) was used. The outlook of the grass of plot 1 was coarse. That is probably the reason that the yield was great. Plot 2 has the same cultivation as plot 1, but it was sown with perennial ryegrass, only. Therefore the outlook was fine and the yield was less. The area of both plots was 2.7 ha.

In September 1987 plot 3 (1.0 ha) and plot 4 (1.3 ha) were sown with perennial ryegrass. The first yield was gathered on 6 May 1988, the day the samples were taken. The yield was different, because plot 4 was sown one week later than plot 3.

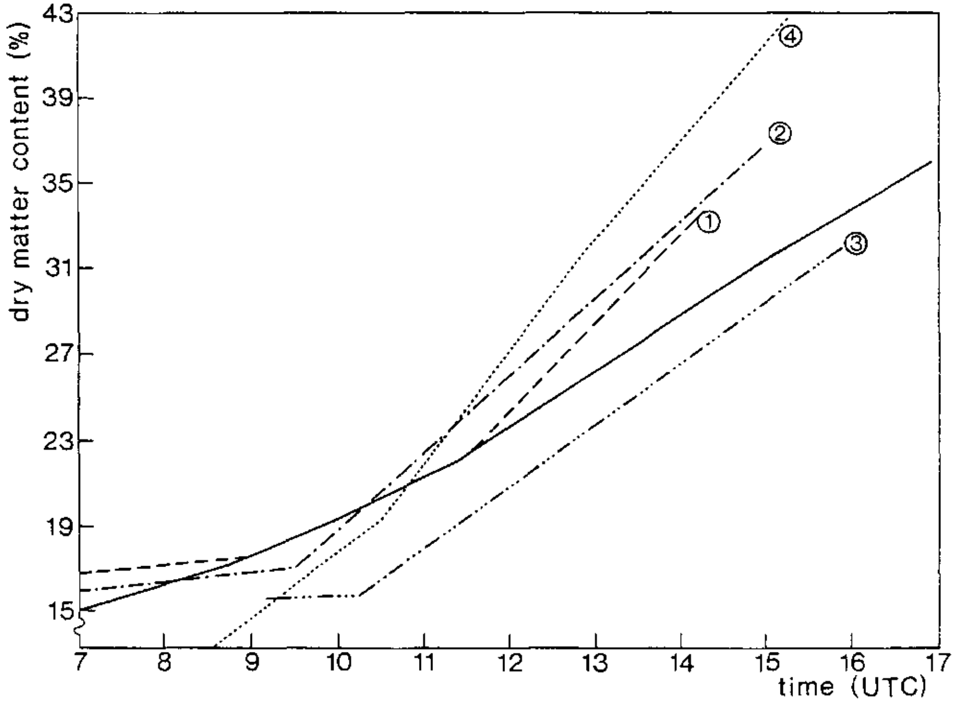

Figure 2: The course of the realised dry matter content of cut grass of four plots on 6 May 1988 at Duiven (The Netherlands). Also, the course of the diagnostic dry matter content (solid line) during the day is shown.

The dry matter content of the plot with less yield was distinctly higher than plot 3. The grass cover was very thin so that the drying process was very fast. Notice that plot 3 was cut late in the morning while plot 1 and 2 were cut early in the morning. The diagnostic line started also early in the morning. It is likely to assume that if plot 3 had a longer drying time, the dry matter content could have been higher, too. Just as on other days, on this day the diagnostic dry matter content was less than the realised ones.

In figure 3 again the realised dry matter content (measured in the field) exceeds the diagnostic ones (calculated by the model). The aim of this figure is to show the course of the prognostic dry matter content during the day. The prognostic dry matter content one day before the grass was cut agreed better than that calculated three days ahead.

On 27 June the forecast dew point temperature for 30 June was 14°C. The forecast maximum air temperature on that day was 19°C. The forecast dry matter content calculated by the model was 21.9% on 14.00 UTC if grass should be cut on

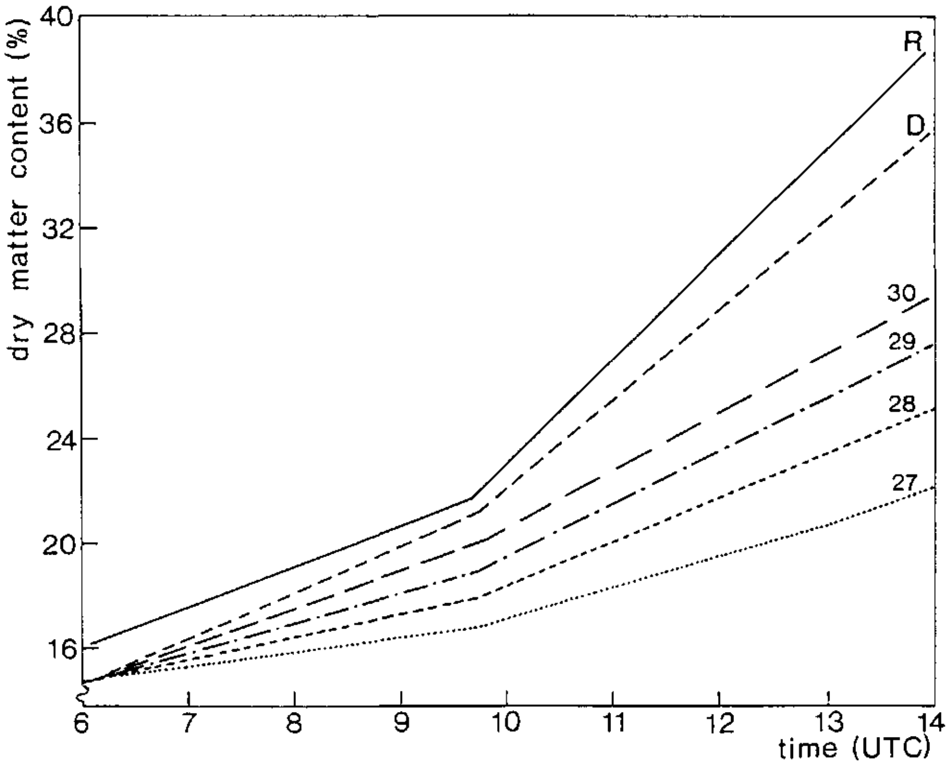

Figure 3: The course of the prognostic dry matter content of grass which will be cut on 30 June 1988 at Duiven (The Netherlands). Also the realised dry matter content (R) and the diagnostic dry matter content (D) are shown.

30 June 6.00 UTC. On 28 June the newly forecast dew point temperature for 30 June was 13°C, while the maximum air temperature was 20°C. The corresponding dry matter content for 30 June at 14.00 UTC was 25.1% when the grass would be cut at 6.00 UTC on 30 June. One day before cutting, the forecast dew point temperature was the same as was forecast on 27 June, namely 14°C. On 30 June the forecast maximum air temperature was 22°C, so that on 30 June 14.00 UTC the dry matter content was 27.5%. On 30 June early in the morning the forecast of the dew point temperature and the maximum air temperature were 15 and 23°C, respectively. The corresponding dry matter content increases to 29.3%. The real dew point temperature on 30 June 1988 varied between 12.2 and 15.0°C. At 8.00 UTC the air temperature was 20.4°C and the maximum air temperature reached 26.7°C between 13.00 and 14.00 UTC. At 14.00 UTC the diagnostic dry matter content was 35.4%, while the realised dry matter content was 38.4%. The calculations were based on the fact grass was cut at 6.00 UTC in the morning.

So, the prognostic dew point temperature was correct, but the air temperature became higher day by day. Thus, the dry matter content of cut grass became higher than forecast. When the dry matter content exceeds 35%, the grass is dry enough for ensiling without additives. When grass is ensiled below 35%, dry matter additives have to be used to reduce the number of bacterial spores. Additives common used in The Netherlands are molasses that contains sugar, organic acids such as formic acetic acid and salts.

Fortunately, in most instances the weather forecast doesnot deviate much from realised weather. In figure 4 the prognostic dry matter content three days ahead has been plotted versus the diagnostic dry matter content. The prognostic dry matter content is lower than the diagnostic ones. So, on most days the prognostic dry matter content is below the actual dry matter content in the field. Only in one dot the prognostic dry matter content exceeds the realised ones. The grass was cut one day before ensiling. The night between cutting and ensiling the precipitation was 1.0 mm, while the weather forecast was that the odds of precipitation were less than 10%. Consequently, the air temperature during the day of ensiling was below the forecasted ones. The dew point temperature was higher than forecast.

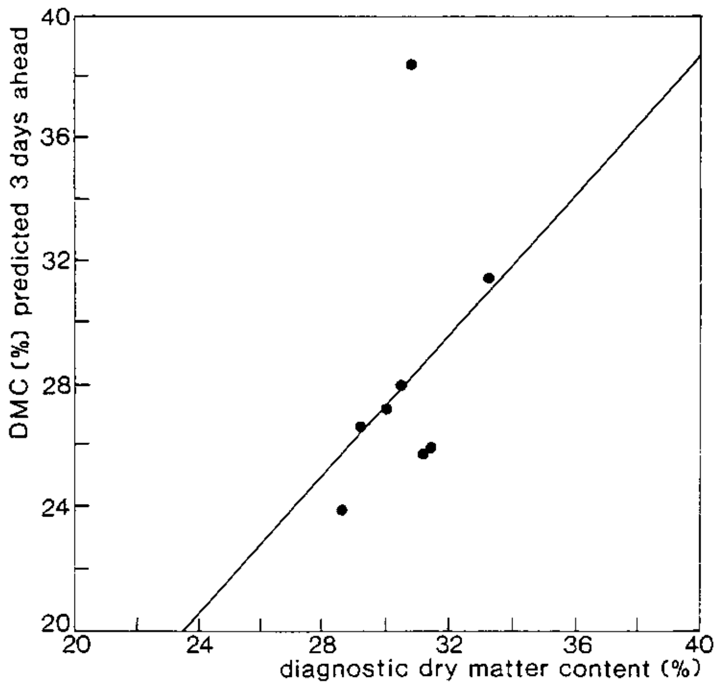

Figure 4: The result of the scatter diagram between the prognostic dry matter content three days ahead and the diagnostic dry matter content.

The realised dry matter content, the diagnostic dry matter content and the mean prognostic dry matter content are given in table 1. In one day different plots are examined. On average realised dry matter content is higher than the diagnostic ones and the diagnostic dry matter content is higher than the prognostic values.

Table 1. Values of the dry matter content of grass (%) at the end of the day on different plots. The given prognostic dry matter content is the mean value of the five forecast days (68% confidence intervals).

Date	Dry matter content		
1988	Realised	Diagnostic	Prognostic
May 6	33.0	28.6	24.9±1.8
May 6	36.8	31.2	26.9±2.1
May 6	31.7	31.4	27.2±2.2
May 6	45.9	31.4	27.2±2.2
June 3	24.1	30.4	27.5±1.5
June 3	37.2	33.3	30.6±1.8
June 3	35.6	30.0	26.6±1.4
June 3	39.9	29.2	26.1±1.2
June 24	31.2	30.8	34.0±3.7
June 30	54.1	43.5	31.9±3.3
June 30	56.1	42.5	30.4±3.3
June 30	52.3	35.4	26.0±3.2
June 30	38.4	35.4	26.0±3.2
September 21	29.1	34.1	51.3±1.3
September 21	40.7	33.6	50.7±1.3
September 21	33.4	29.3	47.0±1.4

4. Conclusions

The realised dry matter content is often higher than the diagnostic ones. On the other hand the diagnostic dry matter content is often higher than the prognostic ones. Because the model has only a few parameters, the realised dry matter content is sometimes different to the calculated ones. Of course, weather elements have to be forecast exactly to get the correct dry matter content.

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References

Agena, M.U., Bätjer, D., Wessels, G., 1968. Wieviel "Einfuhrtage" stehen im nordwestdeutschen Raum für die Bergung von Winterfutter zur Verfügung? Meteorologische Rundschau 21: 169-175.

Brück, I.G.M., Elderen, van E., 1969. Field drying of hay and wheat. Journal of Agricultural Engineering Research 14(2): 105-116.

Dyer, J.A., Brown, D.M., 1977. A climatic simulator for field drying hay. Agricultural Meteorology 18: 37-48.

Hill, J.D., 1976. Predicting the natural drying of hay. Agricultural Meteorology. 17: 195-204.

Hill, J.D., Ross, I.J., Barfield, B.J., 1977. The use of vapour deficit to predict drying time for Alfalfa hay. Transactions of the ASAE 20 (1): 372-374.

Rotz, C. A., Chen Y., 1985. Alfalfa drying model for the field environment. Transactions of the ASAE 28 (5): 1686-1691.

Thompson, N., 1981. Modelling the field drying of hay. Journal of Agricultural Science, Cambridge 97: 241-260.

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A Model for the Drying of Grass with Realtime Weather Data

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A model for the drying of grass is presented which uses weather elements measured by standard weather stations. The model is based on that of Brück and Van Elderen which is transformed into the present predictive model and uses the air temperature and dew point temperature, both at screen height, the wind speed at 10 m height, quantity of rain, the global radiation and the cloud cover. The decrease and increase of free and absorbed water in the grass is calculated. All weather elements are taken hourly, except the quantity of rain which is taken every 6 h. The drying process of the model is described and results are presented for two drying events. Favourable agreement was found between predicted and measured moisture contents of the grass in the field. The error in the calculated moisture content of grass at a stated time was at most 3% wb. Alternatively, the error in the time to reach a given moisture content was at most 2 h.

1. Introduction

Good conservation of grass can be achieved only if the weather is suitable. A drying model can calculate the moisture content of grass with time for given weather and yield conditions.

Several authors[1–4] have developed polynomial relationships which describe the course of the drying of grass by determining the accumulation of the saturation deficit of the air. The model of Neuschulz & Baganz[4] also takes into account the wind speed and the duration of the sunshine.

Some authors[5–7] have developed regression equations which are based on the initial, the final and the equilibrium moisture content. Other authors[8–10] have developed similiar regression equations without the equilibrium moisture content.

Physical models[11–13] are based on the Penman–Monteith equation.[14] The models of Thompson[12] and Smith *et al.*[13] use some weather parameters which are not available at standard weather stations. A predictive drying model must use weather elements measured by standard weather stations. This would enable such a model to have more universal application.

The model of Brück & Van Elderen[11] is the most suitable for transformation into a predictive model, because it is based on physical laws with hourly inputs of weather elements. The original model has been modified considerably in order to make it suitable for this use.

2. The drying process

After cutting, grass is placed in swaths, that is, homogeneous rows of grass with a constant thickness. The width of the swath depends on the machine used. In the Netherlands, the swaths are usually spread shortly after cutting, so the whole field is covered, more or less evenly, with grass. Because the grass is cut off from the roots there

Notation

E	mass flux of water vapour, $kg\,m^{-2}\,s^{-1}$
E_c	quantity of water condensed, $kg\,m^{-2}\,s^{-1}$
E_e	quantity of water evaporated, $kg\,m^{-2}\,s^{-1}$
E_t	quantity of water transpired, $kg\,m^{-2}\,s^{-1}$
E_v	term for the evaporation of free water, $J\,m^{-2}\,s^{-1}$
G	soil heat flux, $W\,m^{-2}$
L_v	latent heat of evaporation, $J\,kg^{-1}$
N	cloud cover in octas,
R_g	global radiation, $W\,m^{-2}$
R_n	net radiation, $W\,m^{-2}$
T	air temperature at 1·5 m, K
W_v	quantity of water per unit time, $kg\,m^{-2}\,s^{-1}$
X	numerator of Eqn (1), $J\,kg\,K^{-1}\,m^{-2}\,s^{-2}$
c_p	specific heat of air at constant pressure, $J\,kg^{-1}\,K^{-1}$
c_1	constant, $5{\cdot}31 \times 10^{-13}\,W\,m^{-2}\,K^{-6}$
c_2	constant, $60\,W\,m^{-2}$
c_3	constant, 0·12
d	zero plane displacement, m
e_a	actual vapour pressure, Pa
e_s	saturated vapour pressure, Pa
f_g	grass cover
f_w	ratio of free water to total water
k	von Karman's constant
q	total quantity of grass, $kg\,m^{-2}$
q_a	quantity of absorbed water, $kg\,m^{-2}$
q_d	quantity of dry matter, $kg\,m^{-2}$
q_f	quantity of free water, $kg\,m^{-2}$
q_r	quantity of rain on grass, $kg\,m^{-2}$
r_a	aerodynamic resistance of air, $s\,m^{-1}$
r_c	crop resistance, $s\,m^{-1}$
r_{cb}	crop resistance for absorbed water, $s\,m^{-1}$
r_{cr}	crop resistance for free water, $s\,m^{-1}$
r_{lu}	ratio from lower to upper layer
r_{ul}	ratio from upper to lower layer
s	slope of saturation humidity versus temperature curve, $Pa\,K^{-1}$
u_z	velocity of air at height z above earth's surface, $m\,s^{-1}$
z	height above earth's surface, m
z_0	roughness length, m
α	albedo, 0·23
Δ	difference between two succeeding hours
γ	psychrometric constant, $Pa\,K^{-1}$
ρ_a	density of air, $kg\,m^{-3}$
σ	Stefan-Boltzmann constant, $5{\cdot}67\,10^{-8}\,W\,m^{-4}\,K^{-4}$

Subscripts

l	lower layer
u	upper layer

is no supply of water from beneath, so the process of drying can start. In the Netherlands the net radiation supplies most of the energy for the evaporation of water.

The global radiation penetrates slightly into the depth of the swath, but the heating effect declines with depth. A flow of heat is generated from the upper few centimetres of the swath to the base. The consequence of this is that a layer of about 5 cm depth dries evenly. Beneath this layer no drying takes place. The dry upper layer grows during the drying process. After some time, the speed of drying decreases in the upper layer and the farmer then usually teds the grass.[11]

Tedding causes the grass to be mixed thoroughly. Again a near homogenous swath results witn a lower moisture content than immediately after mowing. Once more, two layers are formed. Just how far the drying process is promoted by tedding in practice is unknown. Some farmers ted a lot which produces high mechanical losses and increases labour costs. Others ted once or twice a day. The important point is to get an even product. However, if grass is to be chopped for ensiling, a strictly even product is not needed.

The water in the grass is more or less bound to dry matter. When grass is moistened on the outside by dew or rain, it is called free water, as is water in the stomatal cavities.[15] The driving force for evaporation is the difference in the water vapour pressure between the air just above the water surface and the free atmosphere.

Accordingly, if the water is strongly bound, the water vapour pressure just above the surface declines. The evaporation becomes smaller until it reaches zero at the critical relative air humidity. The water content obtained, called the equilibrium moisture content, is dependent on the kind of material. Shepherd[16] determined the critical air humidity for perennial ryegrass with an equilibrium moisture content in the temperature range of 10 to 30°C.

Besides the need for energy for evaporation, other resistances to drying exist: the water vapour has to be removed, but there are barriers to this. One barrier is the epidermis of the grass leaves. Some time after cutting, the stomata close.[17] As the plant dies, the cuticle lets through water vapour easily, but this takes some time. The resistance of the grass can be decreased by conditioning with machines which abrade the grass.

3. The model

3.1. *Model description*

Just after cutting the grass is almost even. The expected net radiation serves as the energy source by which the temperature of the cut grass is increased until it is the same as the air temperature at 1.5 m height. In practice, the outgoing longwave radiation is greater than that calculated, as a result of which there is less energy for evaporation. However, measurements show that the overestimation is within the small range expected.

The resistance to evaporation of water vapour is represented as a crop resistance. In this model there are two crop resistances: the crop resistance for free water and the crop resistance for absorbed water. Absorbed water has a much greater resistance than free water. When the moisture content declines, the bond forces increase and the crop resistance for absorbed water increases, too.

The resistance to evaporation of free water with respect to the moisture content is constant except in the case of high moisture contents, when the crop resistance decreases as the moisture content increases.

3.2. *Evaporation and condensation*

Grass dries through evaporation of free and absorbed water. On the other hand, condensation and rain increase the moisture content of the grass. Water evaporates and condenses, according to Monteith,[14] as given by:

$$L_v E = \frac{s(R_n - G) + \dfrac{\rho_a c_p (e_s - e_a)}{r_a}}{s + \gamma\left(1 + \dfrac{r_c}{r_a}\right)} \tag{1}$$

The soil heat flux, G, is assumed[18] to be on average one tenth of the net radiation, R_n. Standard weather stations usually do not measure the net radiation. Therefore, it has to be calculated using weather parameters which are measured. The net radiation can be calculated[19] using the equation:

$$R_n = \frac{(1-\alpha)R_g + c_1 T^6 - \sigma T^4 + c_2 N}{1 + c_3} \tag{2}$$

The aerodynamic resistance of the air, r_a, is calculated[15] using the equation:

$$r_a = \frac{\left(\ln \frac{(z-d)}{z_0}\right)^2}{k^2 u_z} \tag{3}$$

The zero plane displacement, $d = 0{\cdot}63\ h$ (h = height of cut grass) and the roughness length, $z_0 = 0{\cdot}13\ h$ (Ref. 15). The zero plane displacement is datum height in a crop above which normal turbulent exchange takes place. The height of the cut grass is on average 0·20 m.

The decrease of free water through evaporation can be calculated from Eqn (1) using the crop resistance for free water, r_{cr}, in place of r_c. If $L_v E$ is positive then any free water present evaporates.

The increase of free water through condensation is calculated by Eqn (1), in which the crop resistance, r_c, is zero. Negative values of $L_v E$ imply condensation.

3.3. *Free and absorbed water*

The crop resistance for free water plays a role after condensation (dew) or rain. On the other hand, the crop resistance for absorbed water becomes important during transpiration. Both resistances are dependent on the total quantity of grass and the moisture content of the grass in the upper layer.

Free water on the grass has resistance during transport between the particles of cut grass. Absorbed water within the grass has resistance as a result of transport through the stomata, the cuticle or the cracks and between the particles of the grass. Absorbed water has a long and sometimes difficult path. Therefore the resistance is large.

Values of the crop resistance were obtained from experiments in the field. The samples were taken at the pilot farm of the Institute of Agricultural Engineering (IMAG) at Duiven in the Netherlands (51° 57′ N and 6° 02′ E). The moisture content of the grass was determined hourly and the yield is known. The crop resistance, r_c, can be calculated from Eqn (1) using the experimental value for E. Tables 1 and 2 show some of the values obtained. In the model, intermediate values are obtained by interpolation.

As the amount of absorbed water declines during transpiration, the evaporation of free

Table 1
Values of the crop resistance of free water (s m^{-1}) dependent on the total quantity of grass (kg m^{-2}) and the moisture content of the grass in the upper layer (%).

Moisture content, %	*Total quantity of grass, kg m^{-2}*						
	1·00	1·25	1·50	1·75	2·00	2·25	2·50
60	480	420	360	300	230	170	110
70	270	240	200	170	130	100	65
80	130	110	95	80	60	45	30
90	40	35	30	25	20	15	10

Table 2
Values of the crop resistance of absorbed water ($s\,m^{-1}$) dependent on the total quantity of grass ($kg\,m^{-2}$) and the moisture content of the grass in the upper layer (%)

Moisture content, %	*Total quantity of grass, kg m⁻²* 1·00	1·25	1·50	1·75	2·00	2·25	2·50
20	12,400	10,800	9,240	7,650	6,070	4,480	2,890
30	5,110	4,460	3,800	3,150	2,500	1,820	1,190
40	2,480	2,160	1,850	1,530	1,210	900	580
50	1,610	1,400	1,200	990	790	580	370
60	880	760	650	540	430	320	200
70	440	380	330	270	210	160	100
80	190	170	140	120	95	70	45
90	60	50	45	35	30	20	15

water has to be taken into account. The amount of transpiration is calculated[11] by:

$$L_v E_t = f_g \frac{X - \left(s + \gamma\left(1 + \frac{r_{cr}}{r_a}\right) E_v\right)}{S + \gamma\left(1 + \frac{r_{cb}}{r_a}\right)} \tag{4}$$

The term for evaporation, E_v, takes into account the quantity of free water which is present and the evaporation of free water. If there is more free water present than water which evaporates in 1 h then: $E_v = f_w L_v E$, in which f_w is the ratio between the quantity of free water and the total quantity of water. In this case the crop resistance, r_c, in Eqn (1) is the crop resistance of free water, r_{cr}. If less free water is present than water which evaporates in 1 h the term of evaporation[11] is $E_v = 10^4 L_v W_v$, in which W_v is the quantity of water per unit time ($kg\,m^{-2}s^{-1}$).

3.4. *Moisture in the grass*

The water content of grass changes as a result of precipitation, condensation, evaporation and transpiration. In the model grass is divided into an upper layer, q_u and a lower layer, q_l. Both layers consist of dry matter, q_d, absorbed water, q_a, and free water, q_f. The line between the upper and lower layer descends at drying and rises at rewetting. The mass of the upper layer, q_u, is constant.[11]

$$q_u = q_{ud} + q_{ld} \tag{5}$$

Condensation, evaporation and transpiration take place only in the upper layer. Precipitation affects both upper and lower layers. In order to have a constant total mass of the upper layer, the boundary between the upper and lower layer rises or descends. At a low moisture content the upper layer is thicker than at a high moisture content.

Our experiments, carried out in 1988, 1989 and 1990, show that, on average, the moisture content of dry uncut grass is 79%. All the moisture is absorbed. At a higher moisture content the grass is more or less externally wet. Also in this case, free water is present. The maximum moisture content is 88%. Any added moisture simply runs off. Both the maximum quantity of absorbed water and that of free water are 3·75 times the quantity of dry matter.

When drying, the calculated evaporation is subtracted from the quantity of free water and the calculated transpiration is subtracted from the quantity of absorbed water. The amount of dry matter, absorbed water and free water transferred from the lower to the upper layer is given by the ratio,[11] r_{lu}, where q_l is the sum of the dry matter, absorbed water and free water in the lower layer.

$$r_{lu} = \frac{3600(E_e + E_t)}{q_l} \tag{6}$$

When grass becomes wet through condensation, the quantity of free water in the upper layer[11] increases with:

$$\Delta q_{uf} = 3600 E_c \tag{7}$$

A small part of free water is absorbed with the specific moisture flow of absorbed water of $0{\cdot}04\ \mathrm{kg\ h^{-1}\ kg^{-1}}$ dry matter,[20] until the maximum quantity of absorbed water is reached.

Precipitation which falls besides the swath, is lost into the soil, directly. During preciptation the quantities of absorbed and free water first increase in the upper layer. Water lost from the upper layer increases the absorbed and free water in the lower layer. The remaining water drains into the soil. If the maximum moisture content is not reached in both layers the increase of absorbed and free water[20] is:

$$\Delta q_a = 0{\cdot}04 q_r \quad (\text{if } q_d \geq q_r) \tag{8a}$$

$$\Delta q_f = 0{\cdot}96 q_r \quad (\text{if } q_d \geq q_r) \tag{8b}$$

$$\Delta q_a = 0{\cdot}04 q_d \quad (\text{if } q_d < q_r) \tag{8c}$$

$$\Delta q_f = 0{\cdot}96 a_d \quad (\text{if } q_d < q_r) \tag{8d}$$

The line between the upper and lower layer rises, so dry matter and water are transferred from the upper to the lower layer by the ratio:

$$r_{ul} = \frac{\Delta q_{ua} + \Delta q_{uf}}{q_u} \tag{9}$$

3.5. *Influence of machines used*

Immediately after cutting, 30 to 80% of the areas is covered with grass. So the decrease and increase of water is not at the top, because all the whole area is not all covered with grass.

At tedding, the upper layer and the lower layer completely mix and the whole cut area is covered with grass. Once more absorbed water, free water and dry matter is divided in the upper layer as well as in the lower layer. After tedding, the absorbed water, free water and dry matter can be calculated by:

$$\Delta q_{ua} = (q_{ua} + q_{la}) \frac{q_u}{q} - q_{ua} \tag{10a}$$

$$\Delta q_{uf} = (q_{uf} + q_{lf}) \frac{q_u}{q} - q_{uf} \tag{10b}$$

$$\Delta q_{ud} = (q_{ud} + q_{ld}) \frac{q_u}{q} - q_{ud} \tag{10c}$$

Windrowing the grass looks like tedding but after windrowing only 20 to 40% of the area is covered with grass, depending on the machine used.

4. Results

In the figures the universal time (UT) is used, because the model uses weather elements given in UT. In the Netherlands the local time is 2 h later than the universal time at summertime.

Figs 1 to *11* show the results of the model by means of a few examples. In the first example grass was cut on an afternoon in July after which two dry and sunny days followed. In the second example, grass was cut on an afternoon in May. In the evening the precipitation was 3·8 mm and the next day it was dry but cloudy.

Fig 1 shows the course of the weather elements for the first example. In the afternoon the air humidity was about 50%. The clouds were Cumulus, but sparse. In the afternoon the wind was predominant north westerly at about 4 m s^{-1}.

In the first example 25 t ha^{-1} of fresh grass with an initial moisture content of 79% was cut. *Fig. 2* shows the amount of absorbed water, free water and dry matter in the upper layer. Each hour the sum of these three elements is constant at 5·25 t ha^{-1}.

During the afternoon after cutting (which was immediately followed by tedding) and in the early evening there was no free water, because the fresh cut grass was dry. The absorbed water decreased rapidly as a result of transpiration. In the early evening transpiration is reduced. In fact, the decrease in the quantity of absorbed water was prevented by the transport of absorbed water from the lower layer to the upper layer. However, the transpiration wins easily. During this period the quantity of dry matter increased quickly at first thereafter slowly, because the upper layer became thicker.

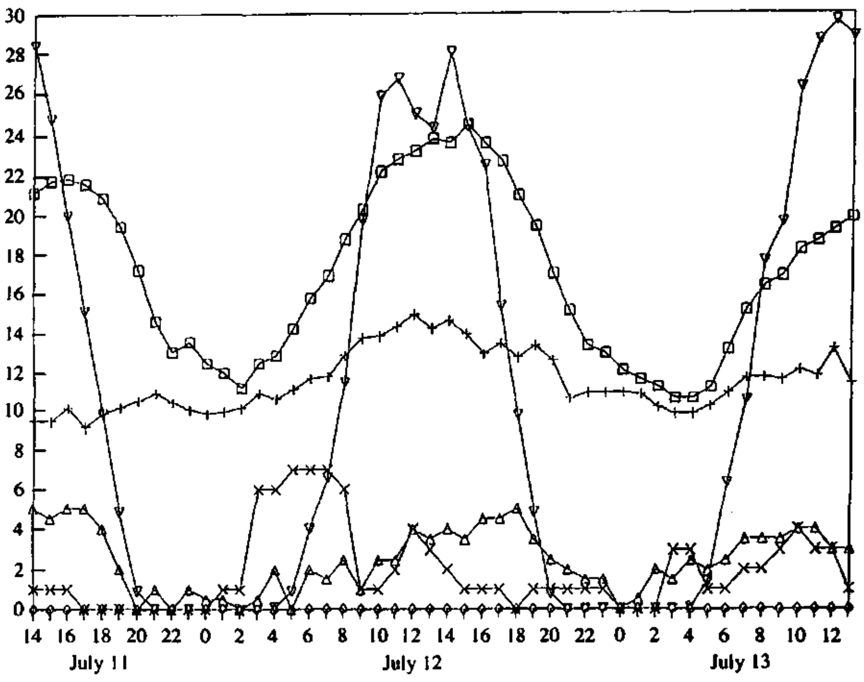

Fig. 1. Course of the weather elements (July 11–13, 1990). □, *air temperature in °C (at 1·5 m);* +, *dew point temperature °C (at 1·5 m);* ◇, *quantity of rain in mm* h^{-1}; △, *wind speed in m* s^{-1} *(at 10 m);* ×, *cloud cover in octas;* ▽, *global radiation in 10 J* cm^{-1}*)*

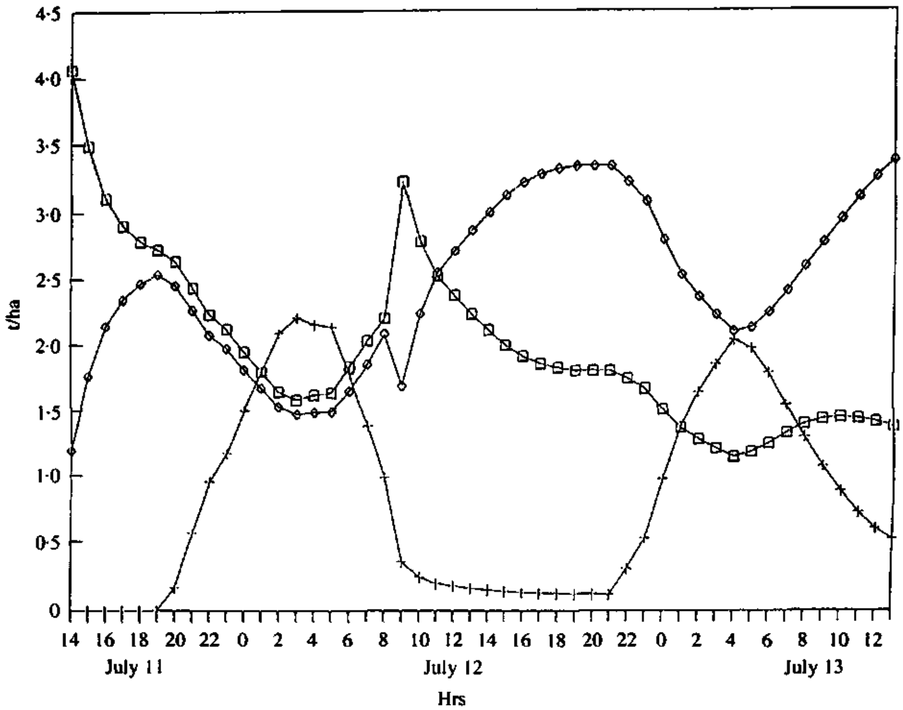

Fig. 2. The amount of absorbed water, free water and dry matter in the upper layer (July 11–13, 1990). □, absorbed water; +, free water; ◇, dry matter

Later in the evening and during the night both the quantity of absorbed water and the quantity of dry matter decreased, because the upper layer became thinner. Although free water was transported to the lower layer, the increase through condensation was greater with the consequence that the quantity of free water in the upper layer also increased.

Next morning free water decreased through evaporation. The quantity of dry matter increased, because the upper layer became thicker. The amount of absorbed water decreased through transpiration, but increased as the upper layer grew in thickness. The last process prevailed, through which the amount of absorbed water increased.

At 1100 hrs the grass was tedded for the second and last time, by which means absorbed water was transported from the lower layer to the upper layer. The upper layer became thinner and the quantity of dry matter in the upper layer decreased for a while. The amount of absorbed water decreased and the quantity of dry matter increased. Only 125 kg ha^{-1} of free water is present. All free water in the upper layer evaporated but, because the upper layer became thicker, free water from the lower layer was transported to the upper layer. This process did not take place in the afternoon, at cutting, because free water was also absent in the lower layer.

During the second evening and the day after the redistribution of free water, absorbed water and dry matter were similiar to that of the first evening and the next day. On the last day the grass was not tedded.

Fig. 3 shows the amount of absorbed water, free water and dry matter in the lower layer. From cutting and until 1900 hrs in the evening, the quantity of absorbed water and dry matter decreased, because the lower layer became thinner. As in the upper layer, the lower layer had no free water.

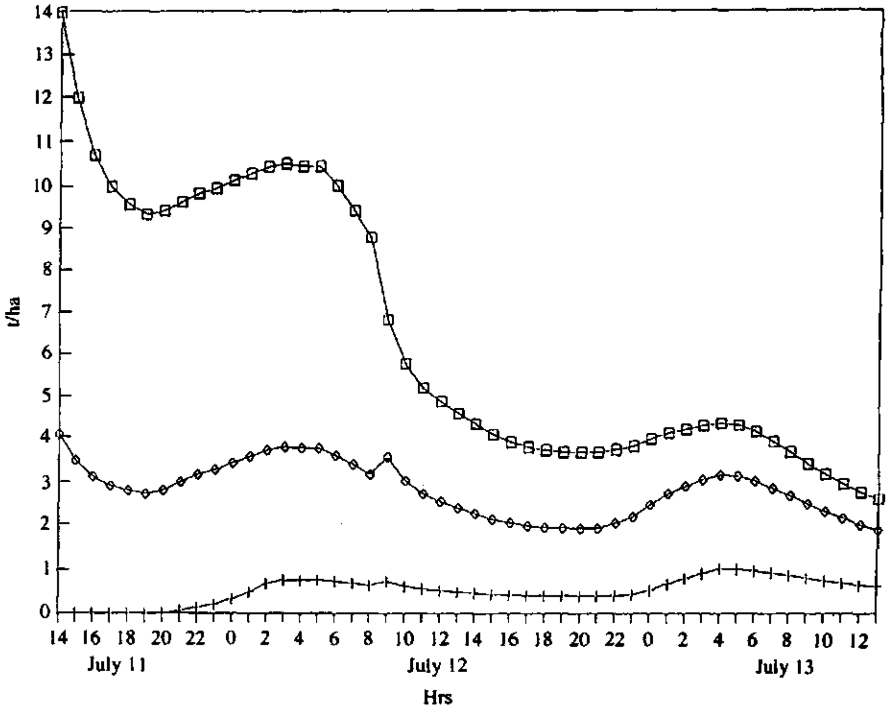

Fig. 3. The amount of absorbed water, free water and dry matter in the lower layer (July 11–13, 1990). □, absorbed water; +, free water; ◇, dry matter

Later in the evening and during the night absorbed water, free water and dry matter from the upper layer were transported to the lower layer and because of this the lower layer became thicker.

A change in the amount of the lower layer free water, absorbed water and dry matter became smaller, or all three components became greater in the case when free water was present. Tedding is an exception. At 1100 hrs on the first morning free water and dry matter were transported from the upper layer to the lower layer by tedding. On the other hand, absorbed water was transported from the lower layer to the upper layer. In general, the direction of the transport due to tedding is dependent on the situation.

Fig. 4 shows the increase and decrease of the amount of water. At night the transpiration was zero. One hour after tedding the transpiration was high. The high level of condensation in the first night at 0100 hrs was the result of a temporary increase in wind speed and air temperature.

Fig. 5 shows the moisture content of the upper layer, the lower layer and the total layer. The upper layer had a daily changing moisture content. Tedding caused the moisture content in all layers to become the same. In the daytime the moisture content of the lower layer is constant. During the night the lower layer became thicker, because a part of the dry matter and water in the upper layer was transported to the lower layer. Through this, the moisture content of the lower layer decreased.

The second example shows the influence of precipitation. The weather elements are shown in *Fig. 6*. In the afternoon the air humidity was about 70%. A lot of clouds were present, mainly stratocumulus.

In this case 25 t ha^{-1} of fresh grass with an initial moisture content of 80·3% was cut.

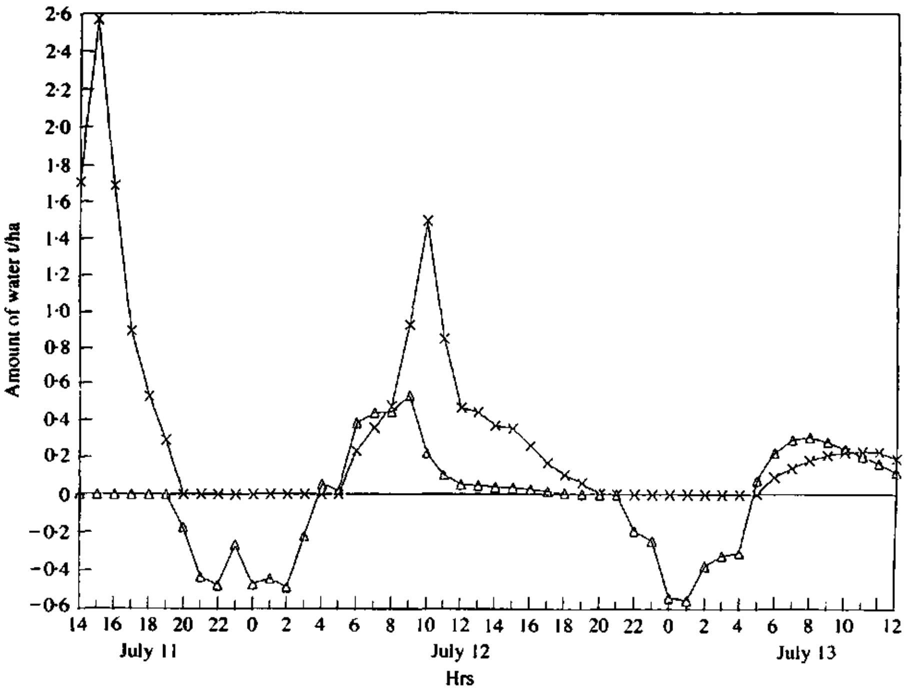

Fig. 4. Increase and decrease of the amount of water (July 11–13, 1990). △, evaporation and condensation; ×, transpiration

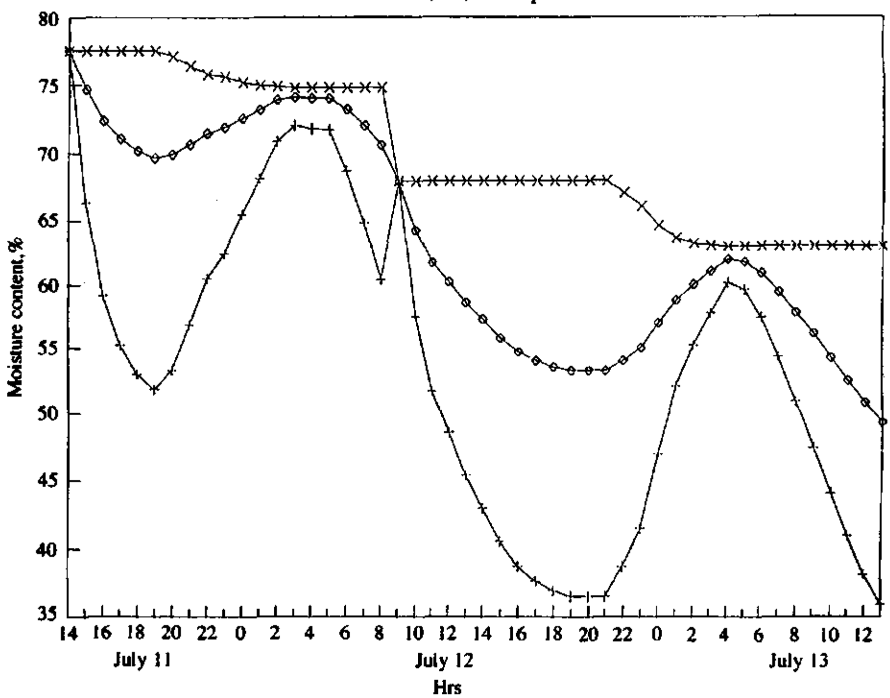

Fig. 5. Moisture content of the upper layer, the lower layer and the total layer (July 11–13, 1990). +, upper layer; ×, lower layer; ◇, total layer

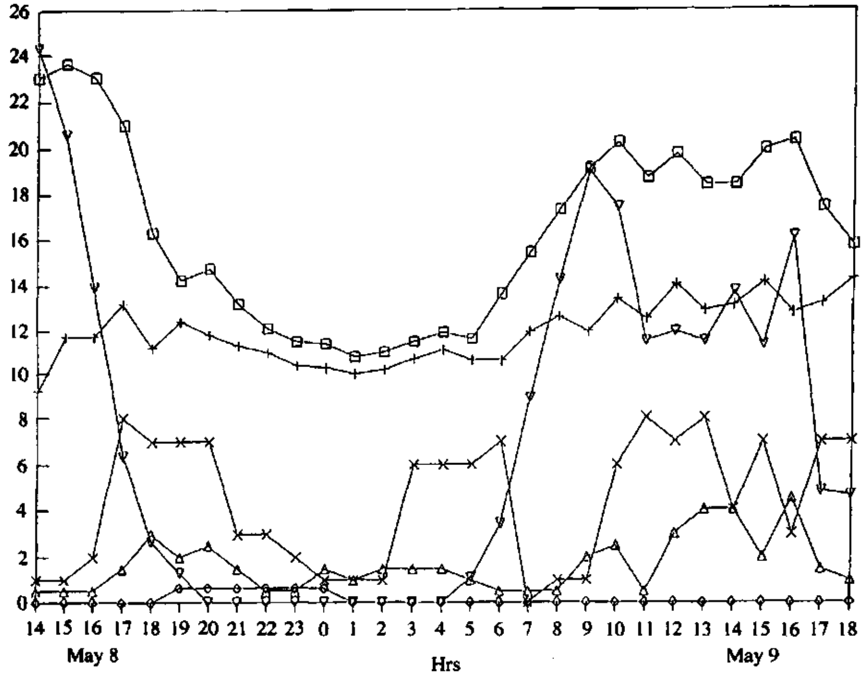

Fig. 6. Course of the weather elements (May 8–9, 1990). □, air temperature in °C (at 1·5 m); +, dew point temperature °C (at 1·5 m); ◇, quantity of rain in mm h⁻¹; △, wind speed in m s⁻¹ (at 10 m); ×, cloud cover in octas; ▽, global radiation in 10 J cm⁻²)

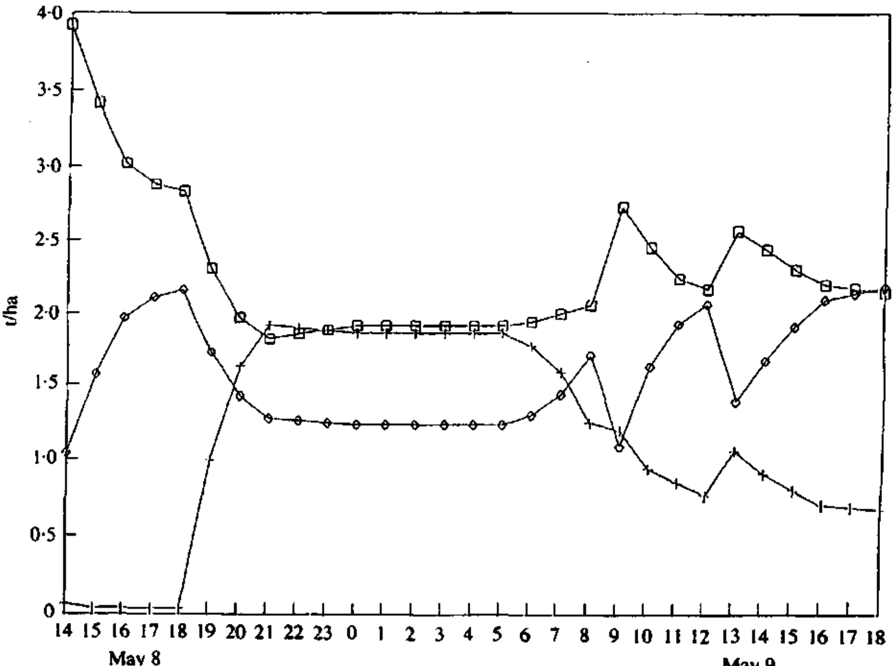

Fig. 7. The amount of absorbed water, free water and dry matter in the upper layer (May 8–9, 1990). □, absorbed water; +, free water; ◇, dry matter

Fig 7 shows the amount of absorbed water, free water and dry matter in the upper layer. During the early first hours free water was present, because at cutting the grass was wet externally. A precipitation of 3·8 mm caused a rapid increase of free water until the level of maximum capacity of free water was reached. The superfluous water was transported to the lower layer and the soil. The absorbed water increased during precipitation, because the maximum capacity for absorption of water was not reached. The next day, the grass was tedded twice, namely at 0900 hrs and at 1300 hrs. In *Fig. 7*, downward peaks in the amount of dry matter indicated tedding.

Fig. 8 shows the amount of absorbed water, free water and dry matter in the lower layer. Precipitation caused an initial rapid increase of free water in the evening. At 2300 hrs both the upper layer and the lower layer reached maximum capacity for free water. Water was absorbed only. The superfluous water was transported into the soil. In *Fig. 8* upward peaks in the amount of dry matter indicate tedding at 0900 and 1300 hrs.

Fig. 9 shows the amount of the increased quantity of water during rain. Only a small part is absorbed water and the greater part is free water. Until midnight, the quantity of free water increased every hour, because the upper layer became thinner. From midnight the upper layer was saturated with free water. The lower layer can contain more free water than the upper layer, because the lower layer is thicker. At 2200 hrs the lower layer again became thicker, through which both free water and absorbed water increased. At 2300 hrs only a part of the free water could adhere to the lower layer, but at midnight the maximum capacity for free water was reached. On the other hand during the whole night, absorbed water increased both in the upper layer and in the lower layer. The rate of increase of water in the upper layer decreased slowly with time, because the upper layer became thinner. On the other hand the rate of increase of absorbed water in the lower layer increased slowly with time, because the lower layer became thicker.

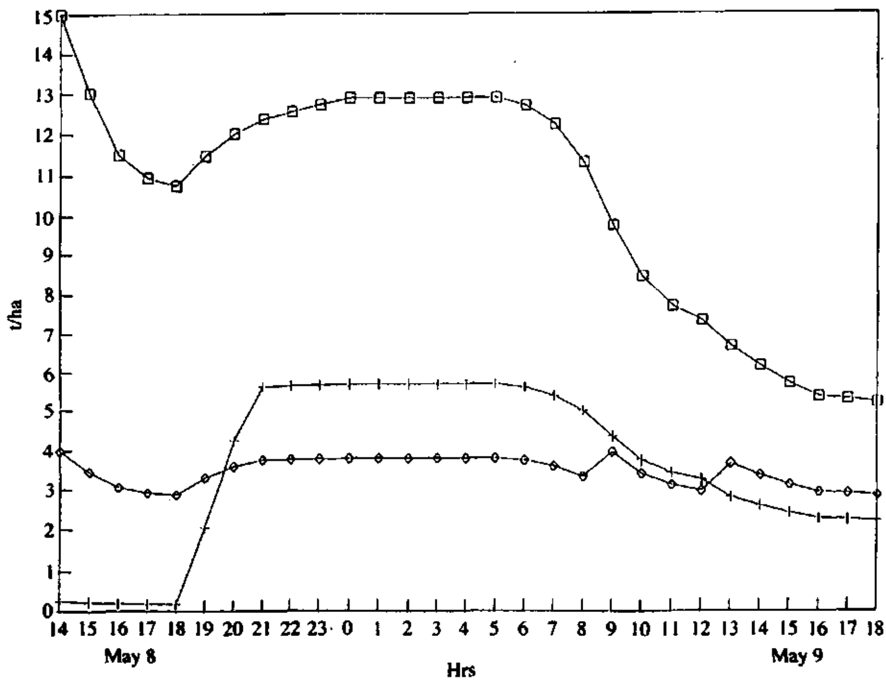

Fig. 8. The amount of absorbed water, free water and dry matter in the lower layer (May 8–9, 1990).
□, absorbed water; +, free water; ◇, dry matter

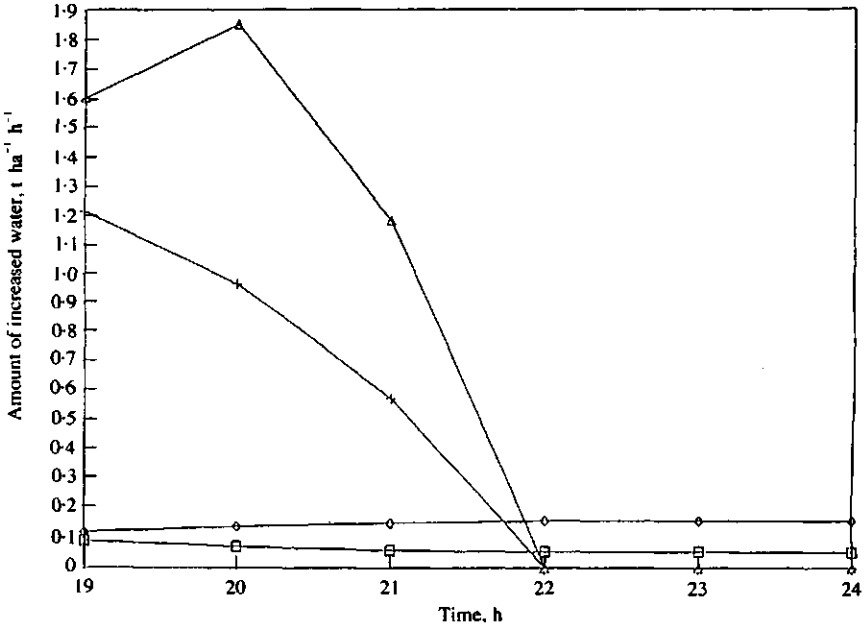

Fig. 9. The amount of increased quantity of water during rain (May 8–9, 1990). □, *increased absorbed water in the upper layer;* +, *increased free water in the upper layer;* ◇, *increased absorbed water in the lower layer;* △, *increased free water in the lower layer*

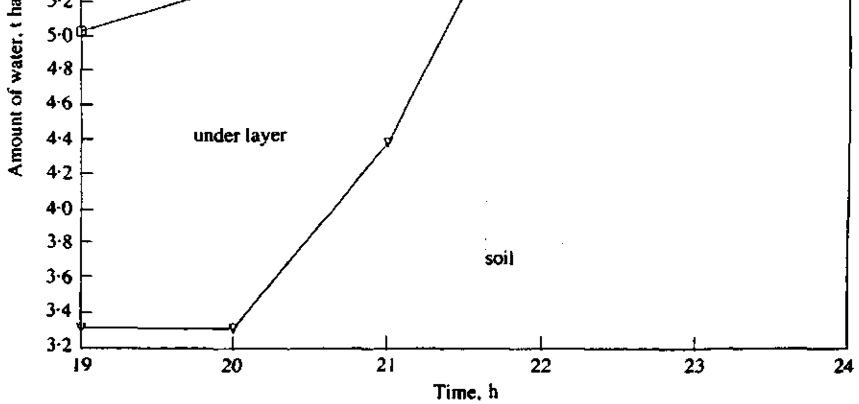

Fig. 10. Transport of water through the layers during rain (May 8–9, 1990). +, *transport of water into the upper alyer;* □, *transport of water into the lower layer;* ▽, *water lost into the soil*

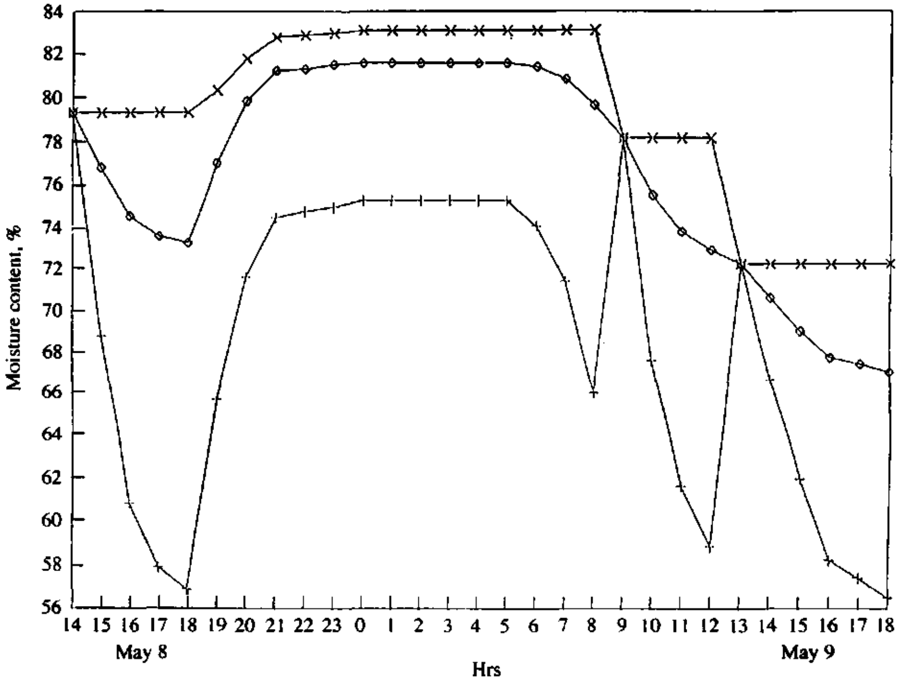

Fig. 11. Moisture content of the upper layer, the lower layer and the total layer (May 8–9, 1990). +, upper layer; ×, lower layer; ◇, total layer

Fig. 10 shows the transport of water through the layers during rain. Each hour 6·3 t ha^{-1} of water falls upon the upper layer. For the first few hours, 3·3 t water ha^{-1} was lost into the soil. After saturation this quantity became greater, namely 6·1 t water ha^{-1} h^{-1}. The other water was taken up by the upper layer and the lower layer. Every hour the upper layer took up less water than it did the hour before. Also after saturation with free water the lower layer can take up to 150 kg water ha^{-1} h^{-1}, while the upper layer can take only 50 kg ha^{-1} h^{-1}.

Fig. 11 shows the moisture content in the upper layer, the lower layer and the total layer, similar to that in *Fig. 5*.

5. Discussion

The two examples given show the results of the model. In *Figs. 12* and *13* the results of the model are compared with the moisture content of the grass in the field in two different years. In *Fig. 12*, 14 t ha^{-1} of fresh grass was cut in May 1989. It was sunny with a maximum temperature of about 22°C. The dew point temperature at midday was about 6°C. In contrast, *Fig. 13* shows 24 t ha^{-1} of fresh grass was cut in June 1990. It was cloudy but dry weather. The maximum temperature and dew point temperature were about 15 and 7°C.

The 95% confidence intervals of the moisture content of the grass in the field are given with vertical bars. The error in the calculated moisture content of grass at a stated time is at most 3% wb or alternatively, the error in the time a stated moisture content is reached is at most 2 h.

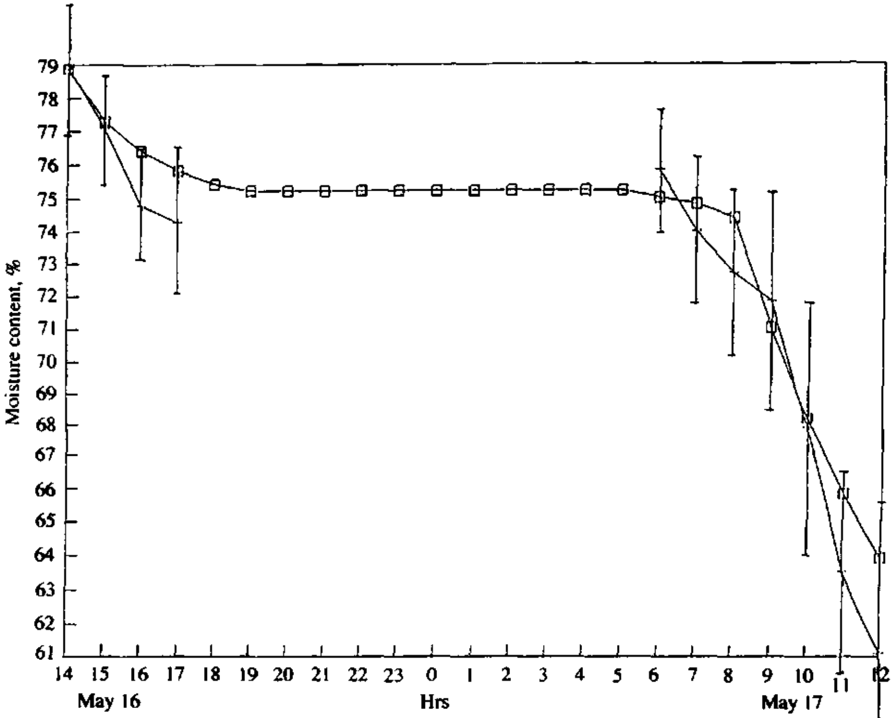

Fig. 12. Moisture content of cut grass. The model compared with experiments in the field. Vertical bars show spread of standard deviation (May 16–17, 1989). □, model; +, field

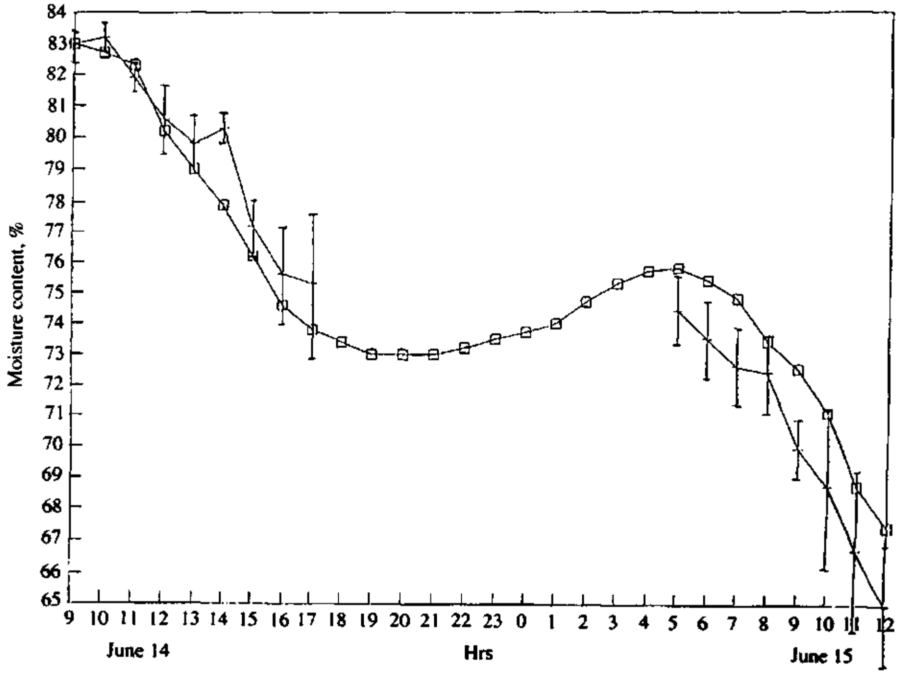

Fig. 13. Moisture content of cut grass. The model compared with experiments in the field. Vertical bars show spread of standard deviation (June 14–15, 1990). □, model; +, field

6. Conclusions

The input of this model requires only weather elements that are usually forecast by meteorologists. Because the model uses hourly imputs, the time the moisture content of grass is low enough for ensiling can be determined. It is possible to make a prediction of the moisture content of the grass a few days ahead. The results of the model agree favourably with measured moisture contents of the grass in the field.

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References

[1] **Agena, M. U.: Bätjer, D.; Wessel, G. Wieviel.** "Einfuhrtage" stehen im nordwestdeutschen Raum für die Bergung von Winterfutter zur Verfügung? (How many "carting days" are available in the northwestern region of Germany to bring in the winter fodder?) Meteorologische Rundschau 1968, **21**(6): 169–175

[2] **Spatz, G.; van Eimern, J.; Lawrynowicz R.** Der Trocknungsverlauf von Heu im Freiland. (Variation of drying rate of hay in the field) Bayerisches Landwirtschaftliches Jahrbuch 1970, **47**: 446–464.

[3] **Olfe, H. C.** Untersuchungen über die Korrespondenz der meteorologischen Daten mit den thermodynamischen Trocknungsmöglichkeiten von Halmfutter. (Investigations of the correlation of the meteorological data with thermodynamic drying capacity of stalky forage) KTBL-Berichte über Landtechnik 1971, **141**: 138 p

[4] **Neuschulz, A.; Baganz, K.** Berechnung über den Trocknungsverlauf beim Welken von Futterpflanzen. (Calculation on the drying rate of fodder plants) Deutsche Agrartechnik 1972, **22**(12): 569–571.

[5] **Hill, J. D.** Predicting the natural drying of hay. Agricultural Meteorology 1976, **17**: 195–204

[6] **Boyce, D. S.; Parke, D.; Dumont A. G.** Effects of conservation methods on hay value: a simulation model study. Forage conservation in the 80's. British Grassland Society, Occasional Symposium 11, Brighton 1979: 442–449.

[7] **Pitt, R. E.** Forage drying in relation to pan evaporation. Transactions of the ASAE 1984, **27**: 1933–1944.

[8] **Hayhoe, H. N.; Jackson, L. P.** Weather effects on hay drying rates. Canadian Journal of Plant Science 1974, **54**: 479–484

[9] **Dyer, J. A.; Brown, D. M.** A climatic simulator for field drying hay. Agricultural Meteorology 1977, **18**: 37–48

[10] **Gupta, M. L.; MacMillan, R. H.; McMahon, T. A.; Bennett, D. W.** A simulation model to predict the drying time for pasture hay. Grass and Forage Science 1989, **44**: 1–10

[11] **Brück, I. G. M.; van Elderen, E.** Field drying of hay and wheat. Journal of Agricultural Engineering Research 1969, **14** (2): 105–116

[12] **Thompson, N.** Modelling the field drying of hay. Journal of Agricultural Science, Cambridge 1981, **97**: 241–260

[13] **Smith, E. A.; Duncan, E. J.; McGechan, M. B.; Haughey, D. P.** A model for the field drying of grass in windrows. Journal of Agricultural Engineering Research 1988, **41**: 251–274

[14] **Monteith, J. L.** Evaporation and environment. Proceedings Symposium of the Society for Experimental Biology 1965, **19**: 205–234

[15] **Monteith, J. L.; Unsworth, M. H.** Principles of environmental physics. London: Edward Arnold 1990: 291 p.

[16] **Shepherd, W.** Moisture relations of hay species. Australian Journal of Agricultural Research 1958, **9**: 437–445

[17] **Clark, B. J.; Prioul, J.-L.; Couderc, H.** The physiological response to cutting in Italian ryegrass. Journal of the British Grassland Society 1977, **32:** 1–5

[18] **de Bruin, H. A. R.; Holtstag, A. A. M.** A simple parameterization of the surface fluxes of sensible and latent heat during daytime compared with the Penman-Monteith concept. Journal of Applied Meteorology 1982, **21:** 1610–1621

[19] **Holtstag, A. A. M.; van Ulden, A. P.** A simple scheme for daytime estimates of the surface fluxes from routine weather data. Journal of Climate and Applied Meteorology 1983, **22** (4): 517–529

[20] **van Elderen, E.; de Feijter, J.; van Hoven, S. P. J. H.** Moisture in a grass sward. Journal of Agricultural Engineering Research 1972, **17:** 209–218

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Determination of the Quality of Forecast Moisture Content of Cut Grass using Forecast Weather Elements

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Abstract

The moisture content of cut grass is forecast by a grass drying model using forecast standard weather elements as input. The standard weather elements used in the model are the air temperature, dew point temperature, wind speed, amount of precipitation, global radiation and cloud cover. In May, during four years 1989 to 1992 inclusive, a five-day weather forecast is made every day. The forecasts were compared with realised weather that occurred during May, over these four years. Every successive day, starting with the following day, the moisture content of grass, cut at 08.00 h, is forecast over the course of the day. On dry days, the model teds the grass once a day. Forecasting the moisture content one day ahead (the following day) gives a more reliable prediction than more days ahead. The quality of the forecast of the moisture content of grass depends heavily on the quality of the forecast of precipitation, air temperature and global radiation. Errors in the forecast of dew point temperature and wind speed play a more minor role.

1. Introduction

Forage conservation is a weather dependent operation. Up to now the shortcomings of weather forecasts have been a major handicap to planning the timing of cutting grass. Adverse weather during the field period of ensiling of grass causes substantial losses in the palatability and yield. A successful drying process reduces the moisture content of cut grass to 70% at most. Only then can good conservation of grass be achieved.

A previous paper[1] determined the response of the drying of grass to the weather elements. The grass surface temperature was greatly affected by global radiation. The temperature within the grass swath approached the standard air temperature.

Another paper[2] describes a model which calculates the course of the moisture content of cut grass with realtime weather data. This model shows a good fit with measured moisture contents. The weather elements used are: air temperature and dew point temperature, both at screen height, wind speed at 10 m height, amount of precipitation, global radiation and cloud cover. All weather elements are taken hourly, except precipitation which is taken every 6 h. During drying the moisture content of grass can be calculated using the formula of Penman-Monteith[3]. The net radiation can be calculated using global radiation, air temperature (at 1.5 m height) and cloud cover[4].

The present paper compares the moisture content of the grass calculated by the drying model using forecast weather elements against moisture contents calculated by the grass drying model using realised weather data. The forecast weather elements are standard weather elements which are forecast hourly up to five days ahead. The forecasts were made in May, during the four years 1989 to 1992 inclusive, because much grass is ensiled in this month. In May, grass grows quickly (130 kg ha^{-1} d^{-1} dry matter), because the leaves are young and are wellsupplied with water and nutrients. The temperature and global radiation are also favourable for growth[5]. A series of weather forecasts, made at different times ahead, are used, so that appropriate data can be fed into the grass drying model. This gives a series of forecasts of the moisture content of grass. The further ahead that the weather is forecast, than the less reliable will these forecasts be.

2. Model input

In the grass drying model, several factors influence the moisture content of cut grass. Forecast weather as well as the time and place are important. In this paper, the moisture content of cut grass is determined during one day hourly from 08.00 h till 20.00 h (local time) at Deelen (52°04'N, 5°53'E). Besides weather parameters, crop parameters play a role. To start the drying process, the initial moisture content of grass is put into the model. The moisture content of grass at mowing time varied from about 78% to 88% and depended on the time of mowing, the grass species used, the stage of maturity and the nitrogen and water application[1]. In this paper the initial moisture content is set at 83.4%. This was the mean value for grass cut at 08.00 h in the morning[1]. Immediately after cutting, 30% to 80% of the area is covered with grass, depending on the cutting machine used. After tedding, the whole cut area is supposed to be covered with grass. Grass is tedded only when the weather is dry. Table 1 shows the values of the crop parameters used in this paper.

The moisture content of cut grass can be forecast hourly up to five days ahead. Grass can be cut on the current day, the next day or later with a maximum of five days ahead. A similar calculation is also possible when grass is already cut e.g. on the previous day or earlier. In this case realised weather elements are used with the

Table 1. Values of the crop parameters used in this paper.

Amount of dry matter (kg ha^{-1})	3320
Initial moisture content (%)	83.4
Part covered by grass on cutting	0.31
Cutting time (local time h)	7
Tedding time (local time h)	10

possibility of also using forecast weather elements. Every successive day, starting with the next day, the moisture content of grass is forecast during one day. With a five-day weather forecast, five forecasts of the grass moisture contents are made.

Table 2 shows an example of the six forecasts made on six successive days, namely May 4 up to May 9 inclusive. In the forecasts of the grass moisture content, made on May 4, grass may be cut the next day (May 5), the day following the next day (May 6), and so on (May 7, May 8, May 9). In the same way in the forecasts of the grass moisture content, made on May 5, grass may be cut the next day (May 6), the day following the next day (May 7), and so on (May 8, May 9, May 10). For the realised days May 6, May 7 and May 8, forecasts of the grass moisture contents are made in the same way. In this example, on May 4 to May 8 inclusive, forecasts of the moisture content of grass which is cut at May 9, are made (namely 5, 4, 3, 2 and 1 day(s) ahead). Also, the moisture content of grass which is cut on May 9 is calculated using realised weather.

The grass moisture contents calculated with forecast weather are compared with those calculated with realised weather and the differences are examined. The weather elements responsible for the deviations in the moisture contents are identified and discussed.

Table 2. An example of weather forecasts.

Number of days ahead	Weather forecast made on given date					
Past	May 4	May 5	May 6	May 7	May 8	May 9
1	May 5	May 6	May 7	May 8	May 9	May 10
2	May 6	May 7	May 8	May 9	May 10	May 11
3	May 7	May 8	May 9	May 10	May 11	May 12
4	May 8	May 9	May 10	May 11	May 12	May 13
5	May 9	May 10	May 11	May 12	May 13	May 14

3. Results and discussion

The hourly moisture contents calculated using forecast weather elements are subtracted from the corresponding moisture contents calculated using realised weather elements. The daily mean deviations in moisture contents are calculated and taken to be positive when the grasss is wetter than forecast and negative when the grass is dryer than forecast. Table 3a shows an example of moisture contents using forecast and realised weather respectively for grass cut on May 9, 1990. Table 3b shows the difference between moisture content for realised and forecast weather for grass cut on May 9, 1990. The daily mean deviations in the grass moisture content in this example are 5 out of 620 data. Table 3c shows the forecast weather elements and realised weather elements for May 9, 1990.

The data are put in a two-way table with the drying days and the time lag between the forecast drying days and the realised drying day. A drying day is a day on which grass is cut and dries during that day. Here time lag means the difference between forecast values and realised values which refer to the same day. The

Table 3a. Moisture contents (%) calculated from forecast weather and realised weather for grass cut on May 9, 1990.

Time on May 9 h	Weather forecast for May 9 made on given date					Realised
	May 4 (d_5)	May 5 (d_4)	May 6 (d_3)	May 7 (d_2)	May 8 (d_1)	May 9 (d_0)
8	83.5	83.0	82.9	83.2	83.2	83.3
9	83.4	82.5	82.3	82.9	82.9	83.1
10	83.3	81.8	81.5	82.4	82.4	82.7
11	83.0	81.2	80.9	79.8	79.4	79.9
12	82.6	80.5	80.2	77.3	76.4	78.0
13	82.2	79.8	79.4	75.1	73.6	76.9
14	81.8	79.1	78.6	73.2	71.0	75.9
15	81.5	78.5	77.9	71.1	72.1	75.3
16	81.2	77.8	77.2	68.8	70.2	74.7
17	80.9	77.4	76.7	67.0	69.8	73.4
18	80.6	77.0	76.3	65.9	68.5	72.1
19	80.4	76.8	76.0	65.3	69.8	71.6
20	80.3	76.7	75.9	65.1	71.0	71.3

Table 3b. Difference between moisture content (%) based on realised and forecast weather respectively for grass cut on May 9, 1990.

Time on May 9	Difference in moisture contents *				
	$d_0 - d_5$	$d_0 - d_4$	$d_0 - d_3$	$d_0 - d_2$	$d_0 - d_1$
8	-0.2	0.3	0.4	0.1	0.1
9	-0.4	0.6	0.8	0.2	0.2
10	-0.6	0.9	1.2	0.3	0.3
11	-3.1	-1.3	-1.0	0.1	0.5
12	-4.6	-2.5	-2.2	0.7	1.6
13	-5.3	-2.9	-2.5	1.8	3.3
14	-5.9	-3.2	-2.7	2.7	4.9
15	-6.2	-3.2	-2.6	4.2	3.2
16	-6.5	-3.1	-2.5	5.9	4.5
17	-7.5	-4.0	-3.3	6.4	3.6
18	-8.5	-4.9	-4.2	6.2	3.6
19	-8.8	-5.2	-4.4	6.3	1.8
20	-9.0	-5.4	-4.6	6.2	0.3
Mean	-5.1	-2.6	-2.1	3.2	2.1

* If positive, the grass is wetter than calculated from forecast weather.

Friedman two-way analysis of variance by ranks[6] was used to test the dependence of the error of forecasting the moisture content of grass on the time lag of the weather forecast. This test reveals significant differences in relation to the time lag. Next, a t-test was used to test differences between pairs of time lags. Table 4, based on analysis of variance and t-tests for differences between pairs of time lag, mainly shows that forecasting the moisture content of grass one day ahead (day 1) provides a more reliable prediction than more days ahead. The quality of the forecast decreases with increasing time lag. The deviations with sign show that, on average, cut grass may be equally dryer or wetter than forecast ones.

A deviation in forecasting the moisture content of cut grass is caused by inexact forecasting of one of more weather elements that influence the drying of grass. The effect of an error in forecasting one weather element has to be considered in relation to all other weather elements that influence drying of grass. For example, an error in the forecast of global radiation can influence air temperature. Precipitation can decrease air temperature.

Tabel 3c. Standard weather elements which are forecast for May 9, 1990 and realised values on May 9, 1990. The values relate to the time from 8 to 20 h, inclusive. T_x = maximum air temperature; T_d = dew point temperature; RRR = precipitation; u = mean wind speed; R_g = total global radiation.

Weather elements	Weather forecast for May 9 made on given date					Realised weather
	May 4 (d_5)	May 5 (d_4)	May 6 (d_3)	May 7 (d_2)	May 8 (d_1)	May 9 (d_0)
T_x (°C)	17.8	17.6	18.1	18.6	22.6	20.7
T_d (°C)	8.1	7.3	7.5	6.9	10.7	12.5
RRR (mm)	2.2	0	0	0	1.0	0
u (m s^{-1})	4.5	3.8	3.8	4.3	3.2	6.3
R_g (J cm^{-2})	1670	1948	1938	2337	2226	1646

Precipitation has by far the largest influence on the moisture content of cut grass compared with other weather elements. On dry days the mean moisture content of grass at 20.00 h is 67.1 ± 5.9%. On days with precipitation the mean moisture content of grass at 20.00 h is high. Fig. 1 shows the influence of the amount of precipitation during daytime on the moisture content of cut grass. If the amount of precipitation is less than 2 mm some drying occurs on newly cut grass owing to the other weather elements. If the amount of precipitation is more than 3 mm the moisture content of grass increases. The other weather elements cannot compensate for the precipitation. This figure also shows that precipitation does not greatly increase the moisture content of newly cut grass, because the moisture content is already high. Further precipitation does not have much additional effect, because the moisture content is already near to the maximum[2]. The spread in moisture content arising from a fixed quantity of precipitation is caused by the effect of other weather elements.

Table 4. Mean absolute deviation in forecasting the moisture content of cut grass with respect to the time lag of the five-day weather forecast (n = 620). The Least Significant Difference is 0.44.

	Days ahead				
	5	4	3	2	1
Deviation	2.36	2.99	2.74	2.16	1.69

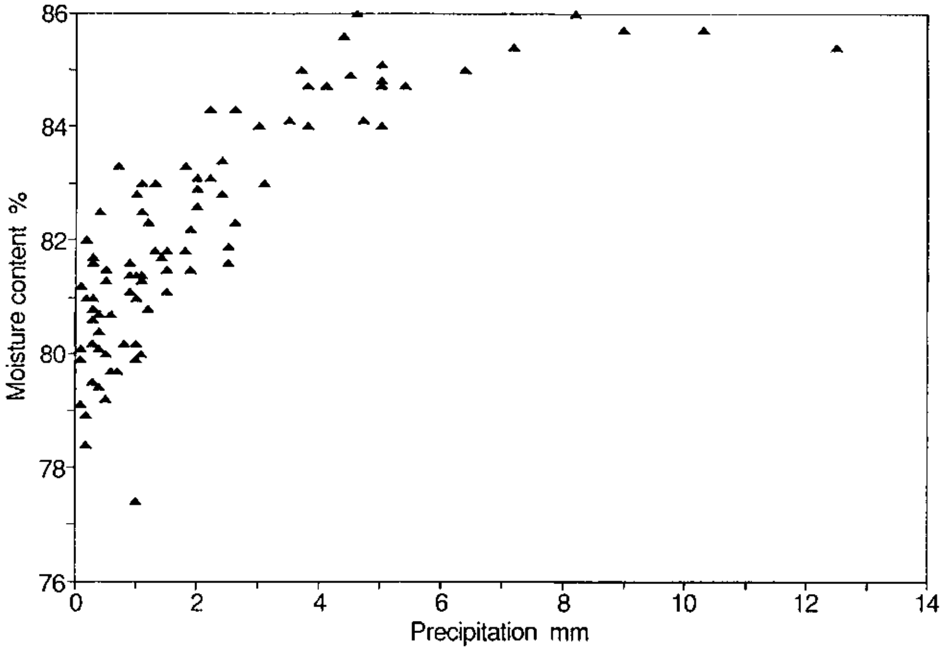

Fig 1. The influence of the amount of precipitation between 08.00 h and 20.00 h on the moisture content of cut grass at 20.00 h. Grass is assumed cut at 08.00 h with a moisture content of 83.4% (n = 92).

Thus, it is important to know whether precipitation occurs. Table 5 shows the relation between weather forecast and realised weather with respect to precipitation. The number of days on which the forecast and realised weather are in agreement, are indicated. If dry weather is forecast the probability is 0.97 (448/461) that realised weather is dry. However if precipitation is forecast the probability is only 0.46 (74/159) that realised weather contains precipitation. In 70 out of 74 forecasts with precipitation the amount of precipitation is more than that forecast (0.95).

A forecast with precipitation, results in more precipitation than that forecast or it remains dry. If realised weather was dry at the time when precipitation was forecast the farmer would have had more options available (e.g. to cut, to ted). It is a rare occurrence that precipitation is forecast and it remains dry (0.14 = 85/620). In most instances, the precipitation forecast (dry or not dry) is correct (0.84= (448+74)/620).

Table 5. Relation between the weather forecast and realised weather with respect to precipitation, expressed in number of days (n = 620).

		Realised		
		Dry	Wet	Total
Forecast	Dry	448	13	461
	Wet	85	74	159
	Total	533	87	620

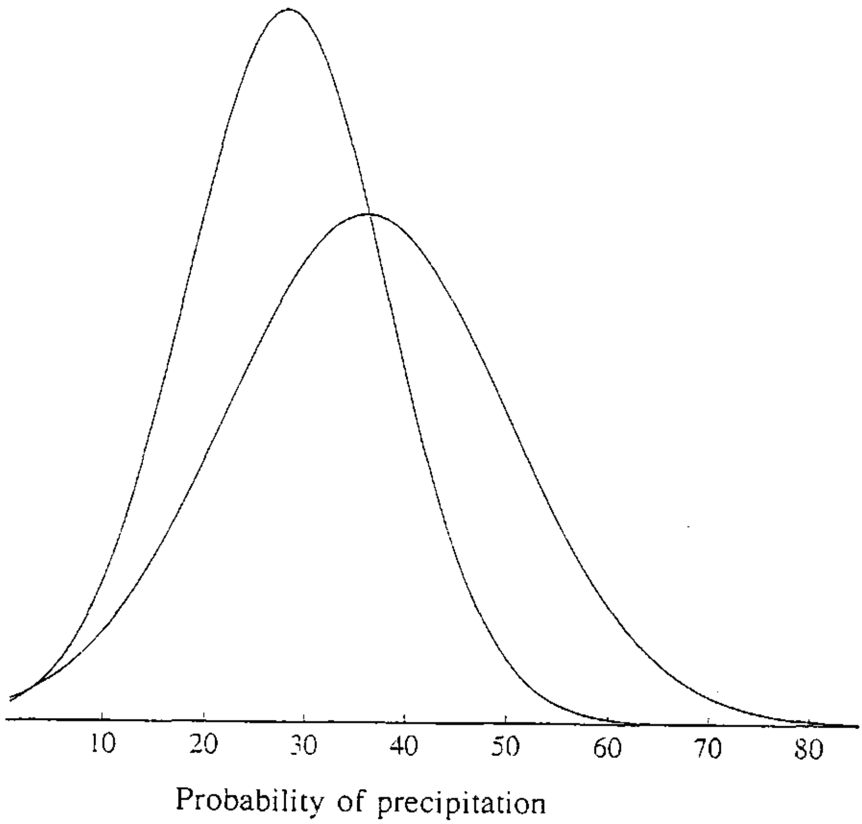

Fig 2. Two curves with a normal distribution of the probability of precipitation for May in the Netherlands. In the left-hand curve precipitation is forecast, but it remains dry. In the right-hand curve as well as forecast weather and realised weather contains precipitation (≥ 0.3 mm).

If precipitation is forecast the probability of precipitation is also important. In Fig. 2 two curves with a normal distribution show the probability of precipitation for May; so the area under the curve represents unity. In the left-hand curve precipitation is forecast, but it remains dry. Here the probability of precipitation is 28±10%. In the right-hand curve as well as forecast weather and realised weather contains precipitation (≥ 0.3 mm). In this curve the probability of precipitation is 36±14%. If the probability of precipitation is less than 13% (left tail of the right-hand curve) realised weather is dry (95% confidence). If the probability of precipitation is more than 45% (right tail of the left-hand curve) precipitation occurs (95% confidence). It is the choice of the farmer to take his decision in relation to the probability of precipitation.

On dry days the daily mean deviations are grouped (as in the example of Table 3b). In Table 6 data are included only, if the absolute difference between the forecast moisture content and realised moisture content is less than four. If the absolute deviation is more than four, the number of observations are too small for a useful discussion. Within a group the daily mean deviations of the weather elements are calculated in the same way as the calculations of the moisture content in Tables 3a and 3b. So Table 6 shows the daily mean deviations in moisture content of cut grass and the corresponding deviations in weather elements on dry days. The realised moisture content of grass is as likely to be dryer as wetter than forecast. On average, dew point temperature and wind speed do not have an effect on the

Table 6. Daily mean deviations of the moisture content of grass (mc) on dry days in relation to the deviations in the weather elements (68% confidence intervals).

Moisture content % w.b.	Number of observations	Air temperature °C	Dew point temperature °C	Wind speed m s $^{-1}$	Global radiation J cm^{-2} h^{-1}
-4<mc≤-3	13	3.7±2.2	-0.5±1.3	-1.9±5.0	2±25
-3<mc≤-2	27	3.6±1.8	-0.2±1.8	-0.7±2.6	-3±25
-2<mc≤-1	67	1.9±1.5	-0.6±1.8	0.0±2.3	-4±30
-1<mc≤0	82	1.3±1.4	-0.1±2.7	0.2±2.3	-4±26
0<mc≤1	76	0.2±1.5	-0.1±2.3	0.3±2.6	-20±30
1<mc≤2	50	-0.3±1.2	0.5±2.1	1.3±2.9	-38±44
2<mc≤3	31	-1.2±1.8	0.8±2.0	0.5±3.2	-48±34
3<mc≤4	16	-1.3±1.5	0.0±1.8	2.8±3.1	-57±48

deviations in moisture content of cut grass. If the hourly values of the standard air temperature are averaged between 2 and 6 °C more than the forecast ones, the daily mean moisture content of cut grass decreases more than 3%. If the hourly global radiation, averaged over the day, is between 10 and 100 J cm^{-2} h^{-1} less than the forecast value the daily mean moisture content of cut grass increases more than 3%. Both weather elements are considered under Dutch weather circumstances.

The deviation of a weather element has to be related to the value of the weather element concerned. Table 7 shows some dry days with a moisture content of about 67% at 20.00 h in relation to standard weather elements. In general, low air humidity is related with low moisture content of grass at 20.00 h. This is in agreement with Atzema[1] and Thompson[7] that a high wind speed reduces the speed of drying. Two examples are given. First, out of four days with about the same air humidity the total global radiation is greatest by far on May 27, 1989. However on that day the moisture content of the grass is not the lowest, because of a high mean wind speed. Secondly, on May 17, 1992 and May 19, 1991 the moisture content of the grass at 20.00 h is almost the same in spite of a high air humidity and a low total global radiation on May 19, 1991. On these days the wind speed is quite different.

So far, only the daily mean deviations in moisture content have been discussed. Naturally, the course of the moisture content of cut grass during the drying day is dependent on the courses of the weather elements. During the drying day, the time courses of the moisture contents which are forecast on different days can follow a different path. They can diverge more and more; the difference between the forecast moisture contents can stay constant during (a part of) the day; also the forecast moisture contents can come close to each other at the end of the day.

Table 7. Some dry days with a moisture content of grass (mc) of about 67% at 20.00 h in relation to standard weather elements. T_x = maximum air temperature; T_d = dew point temperature; rh = relative air humidity; u = wind speed; R_g = global radiation

Date	T_x °C	T_d mean °C	rh 17.00 h (%)	u mean m s^{-1}	R_g total J cm^{-2}	mc 20.00 h (%)
May 1, 1989	17.8	2.1	35	4.6	2334	66.7
May 8, 1989	19.0	6.0	43	3.7	2457	67.1
May 22, 1990	18.8	6.1	44	4.3	2652	67.1
May 27, 1989	19.2	5.9	42	6.0	3007	67.4
May 17, 1992	18.4	6.4	45	4.4	2674	68.3
May 19, 1991	14.8	6.3	57	1.5	1671	68.4

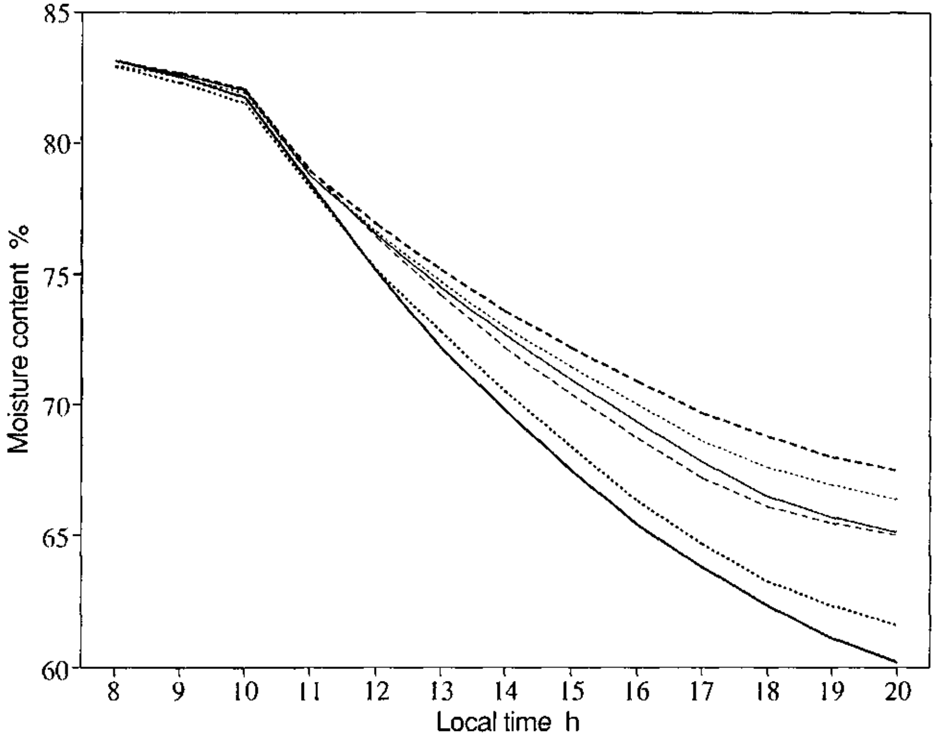

Fig 3a. The course of the forecast and realised moisture content (%) of grass which is assumed cut at 08.00 h, for May 20, 1992.

----- forecast on May 15 (5 days ahead) —— forecast on May 18 (2 days ahead)
········ forecast on May 16 (4 days ahead) ········ forecast on May 19 (1 day ahead)
----- forecast on May 17 (3 days ahead) —— realised

Two examples are given. In Fig. 3a realised moisture content of cut grass is lower than the forecast ones. Fig. 3c shows that the deviations in forecast global radiation are small. However the forecast air temperature between 2 and 5 days ahead was far to low (Fig. 3b). In Fig. 4a the realised moisture content of cut grass remains higher than the forecast ones. Fig. 4c shows that the realised global radiation is rather lower than the forecast ones. Because the difference between the realised and the forecast air temperature on day 1 and 2 (Fig. 4b) is small the difference between the realised and forecast moisture content on day 1 and 2 is at most 2%.

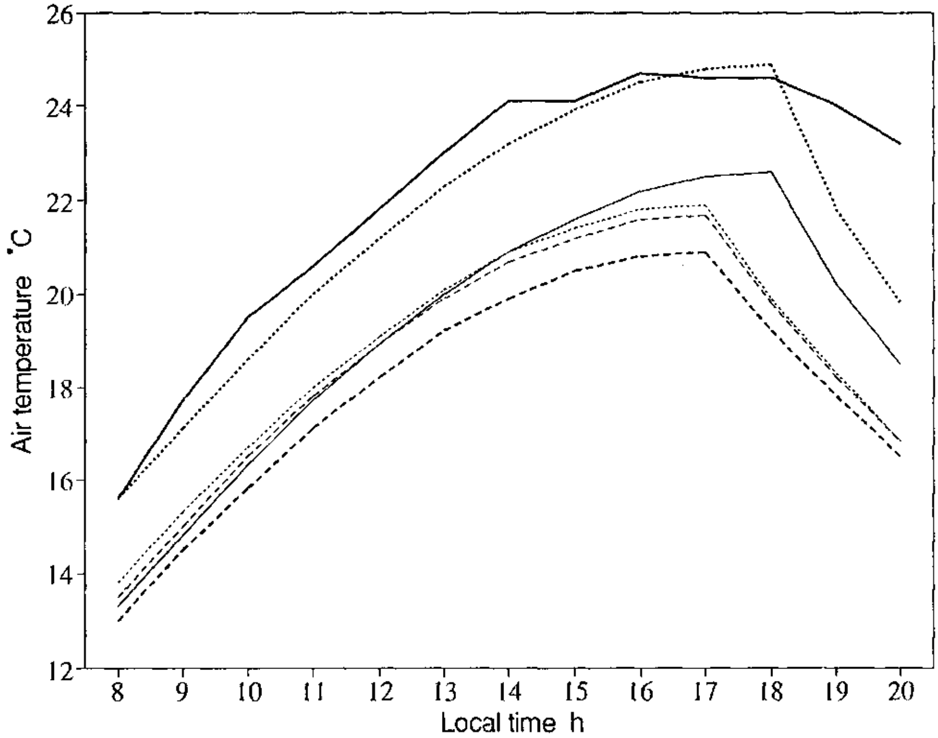

Fig 3b. The course of the forecast and realised standard air temperature (°C) for May 20, 1992.

----- *forecast on May 15 (5 days ahead)* —— *forecast on May 18 (2 days ahead)*
.... *forecast on May 16 (4 days ahead)* .... *forecast on May 19 (1 day ahead)*
----- *forecast on May 17 (3 days ahead)* —— *realised*

4. Conclusions

Forecasting the moisture content of cut grass one day ahead (the next day) is better than more days ahead. The realised moisture content of grass is as likely to be dryer as wetter than forecast. Precipitation has by far the greatest influence on the moisture content of cut grass compared with other weather elements. If the amount of precipitation is less than 2 mm, some drying occurs on newly cut grass

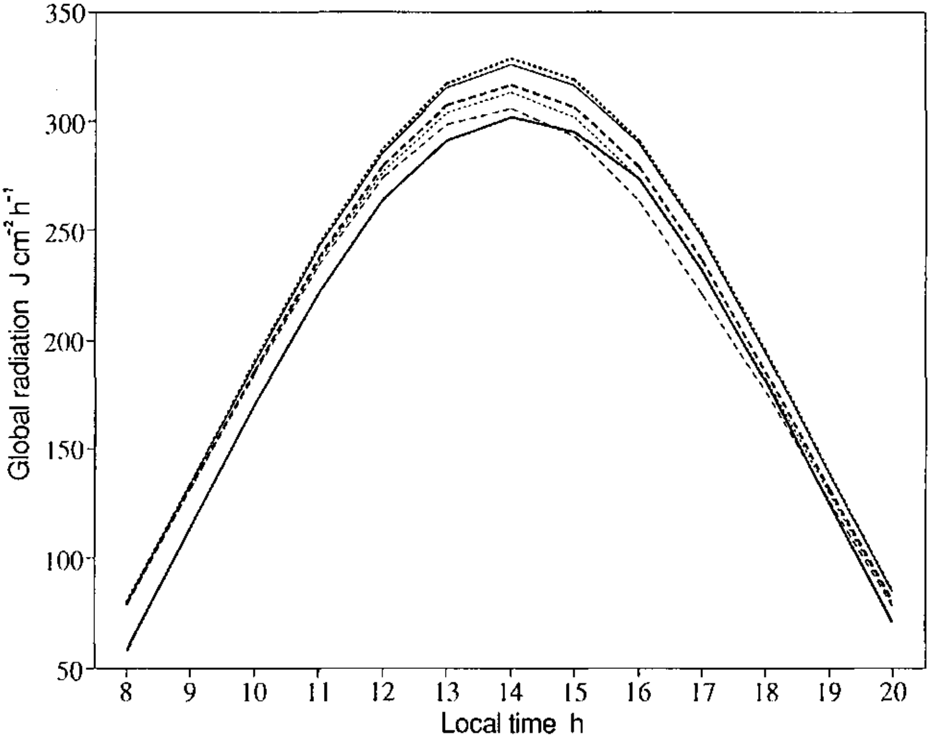

Fig 3c. The course of the forecast and realised global radiation (J cm^{-2} h^{-1}) for May 20, 1992.

----- forecast on May 15 (5 days ahead) —— forecast on May 18 (2 days ahead)
········ forecast on May 16 (4 days ahead) ········ forecast on May 19 (1 day ahead)
----- forecast on May 17 (3 days ahead) —— realised

owing to the other weather elements. When the precipitation amount is more than 3 mm the moisture content of grass increases. If precipitation is forecast, the probability of precipitation is important, too. On dry days, errors in the forecast moisture content are mainly caused by errors in the forecast air temperature and global radiation. Errors in the forecast dew point temperature and wind speed play a more minor role. A high wind speed reduces the speed of grass drying. During the drying day, the deviation between the forecast and realised moisture content of cut grass can change hourly.

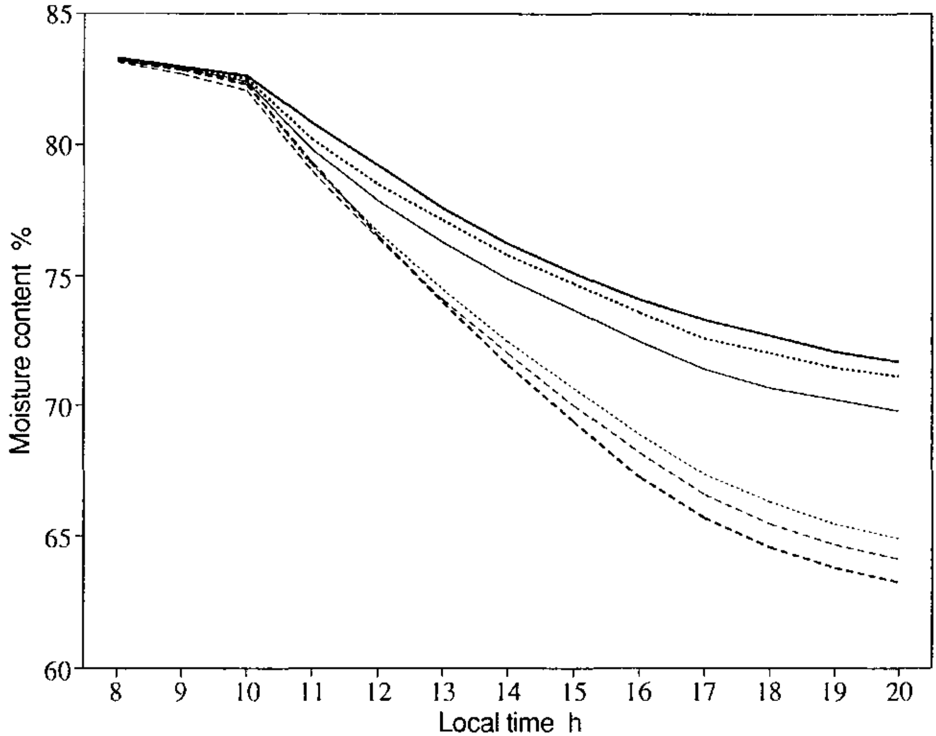

Fig 4a. The course of the forecast and realised moisture content (%) of grass which is assumed cut at 08.00 h. for May 28, 1990.

----- forecast on May 23 (5 days ahead) —— forecast on May 26 (2 days ahead)
.... forecast on May 24 (4 days ahead) .... forecast on May 27 (1 day ahead)
----- forecast on May 25 (3 days ahead) —— realised

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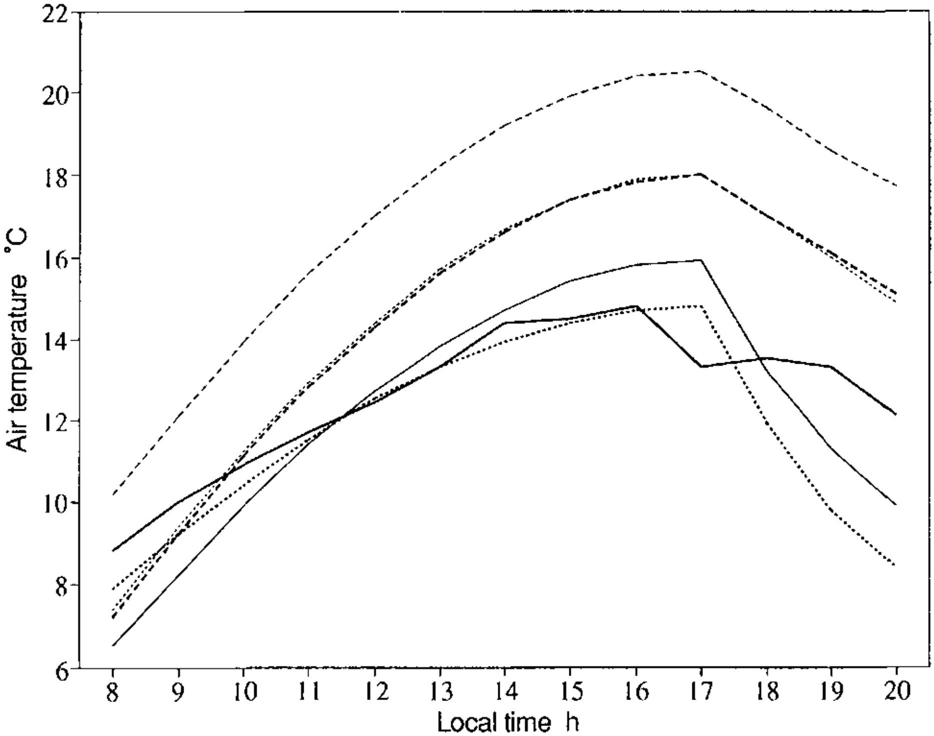

Fig 4b. The course of the forecast and realised standard air temperature (°C) for May 28, 1990.

----- *forecast on May 23 (5 days ahead)* —— *forecast on May 26 (2 days ahead)*
.... *forecast on May 24 (4 days ahead)* .... *forecast on May 27 (1 day ahead)*
----- *forecast on May 25 (3 days ahead)* —— *realised*

References

[1] Atzema, A.J. The effect of the weather on the drying rate of cut diploid and tetraploid perennial ryegrass (Lolium perenne, L.) and diploid hybrid ryegrass (Lolium perenne x L. multiflorum). Grass and Forage Science 1993, 48: 362-368

[2] Atzema, A.J. A Model for the drying of grass with realtime weather data. Journal of Agricultural Engineering Research 1992, 53: 231-247

[3] Monteith, J.L. Evaporation and environment. Proceedings, Symposium of the Society for Experimental Biology 1965, 19: 205-234

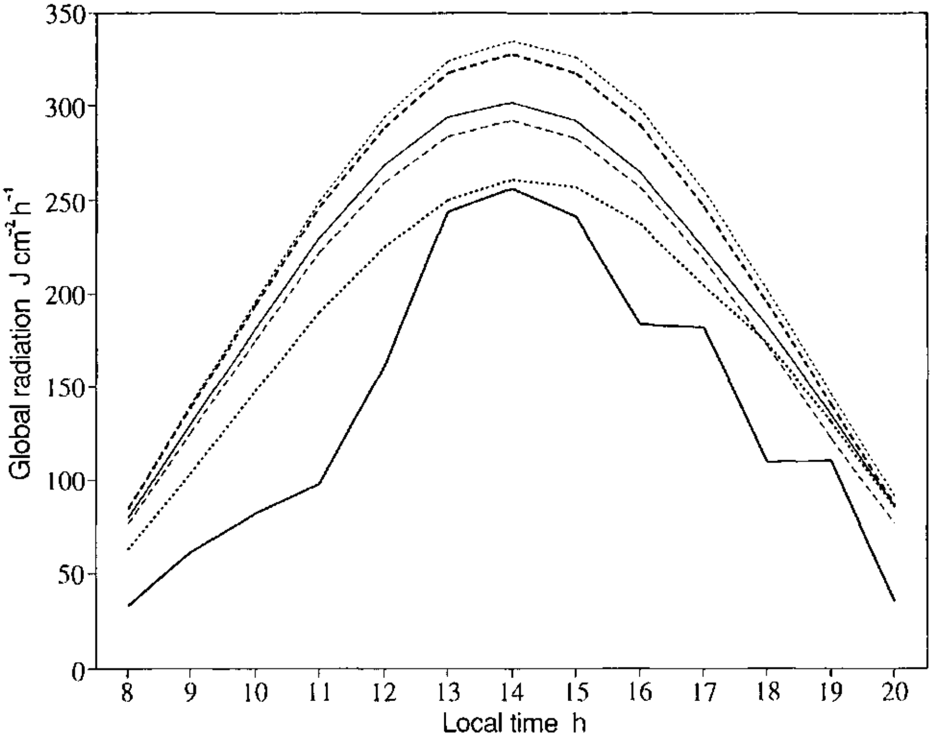

Fig 4c. The course of the forecast and realised global radiation (J cm-2 h-1) for May 28, 1990.

----- *forecast on May 23 (5 days ahead)* —— *forecast on May 26 (2 days ahead)*
.... *forecast on May 24 (4 days ahead)* .... *forecast on May 27 (1 day ahead)*
----- *forecast on May 25 (3 days ahead)* —— *realised*

[4] Holtslag, A.A.M.; van Ulden A.P. A simple scheme for daytime estimates of the surface fluxes from routine weather data. Journal of Climate and Applied Meteorology 1983, 22: 517-529

[5] Behaeghe, T.J. De seizoenvariatie in de grasgroei (The seasonal variation in the growing of grass) Gent: Rijksuniversiteit 1979: 272 p.

[6] Siegel, S.; Castellan N.J. Nonparametric statistics. Singapore: McGraw-Hill Book Company 1988: 399 p.

[7] Thompson, N. Modelling the field drying of hay. Journal of Agricultural Science, Cambridge 1981, 97: 241-260

Part 2

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Moisture content of cereals at harvesting time by comparing microclimate values and standard weather data

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Abstract

The relationship between standard weather data and the microclimate of wheat and barley during harvesting time has been determined. The moisture content of wheat and barley together with the weather elements have been measured at 3 different experimental sites in the Netherlands in the harvesting seasons of 1990 and 1991. The difference in the dew point temperature in the screen and in the field is small. However, the differences between air temperature in the screen and those at different heights in wheat as well as in barley are considerable. In daytime the surface temperature of barley is higher than that of wheat under the same weather conditions as a result of a higher absorbtion coefficient. Both for wheat and barley, the maximum difference between the calculated moisture content is 0.5 %, using the air temperature at 1.5 m height from the nearest standard weather station and the surface temperature of the ears. Barley has a greater daily cycle in the moisture content of the grains than wheat as a result of a high equilibrium moisture content during the night and a low one in daytime.

Keywords: moisture content, temperature, wheat, barley, harvesting time

Introduction

The weather has a great influence on the moisture content of the grains of cereals during harvesting time. The prediction of the moisture content of the grains of cereals through the input of standard weather elements into a model has been described by Atzema (1993). In literature little is known about the relationship between standard weather data and the microclimate of cereals. Van Eimern (1964) described the relationship between temperatures at different heights within immature cereals (barley and wheat) and screen temperature. In mature wheat differences between surface temperature of the ear at 1.2 m and air temperature at 1.2 m are described. Beinhauer (1975) shows the relationship between the mean values of air temperature within immature wheat crop and screen temperature. Both Van Eimern and Beinhauer, showed in daytime the measured temperatures in the stands of wheat and barley are higher than the screen temperatures.

The difference in temperatures of the ears in wheat and in barley can be great. The reflection coefficient for wheat and barley is 26 and 23, respectively (Monteith, 1990). The transmission of radiation in barley is 50 % (Monteith, 1969). The ears of barley bent downward which provides the surface of the crop is more closed. Also the leaves of barley are more horizontal than that of wheat (Ross, 1975). Therefore the transmission of radiation in wheat is more than 50 %. So the absorbtion coefficient is less than 24 for wheat and 27 for barley. This is the reason in daytime the temperature of the ears of barley is higher than that of wheat under the same weather conditions.

The aim of the present research program is to forecast the moisture content of the grains of cereals at harvesting time by a weather-driven model. This paper only describes the response of the moisture content of wheat and barley to the weather elements. The moisture content is influenced by the temperature of the grains, which has to be estimated from the air temperature at 1.5 m height as measured at standard weather stations. Only then the moisture content of cereals can be calculated by a model using the input of realtime weather data. The model uses six meteorological elements, namely air temperature, dew point temperature, both at screen height, wind speed at 10 m height, amount of rain, global radiation and cloud cover. All weather elements are taken hourly, except the quantity of rain which is taken every 6 hours (Atzema, 1993).

In practice farmers are only interested in the moisture content of cereals at threshing. During harvesting, the straw moisture content influences the moisture content of the grains. Usually the grains are ripe earlier than the straw and the lower part of the straw is wetter than the upper part of the straw. Also (green) weeds can increase the moisture content of the grains at harvesting, because moisture is pressed out of the weeds and moisten the grains (Van Kampen, 1969). Therefore the differences of the moisture content of the grains are also compared before and after threshing.

Material and methods

During the harvesting season of 1990 and 1991 the moisture content of mature barley and wheat (from stadia DC 91) together with weather elements have been measured at 3 different experimental sites in the Netherlands: in the South-East (Kessel), in the South-West (Haamstede) and in the North-East (Weiwerd). The meteorological data of the experimental sites are compared with those of the nearest standard weather stations (Volkel, Vlissingen and Eelde, respectively). Table 1 shows the locations of the experimental sites and the standard weather stations.

Table 2 shows the periods of time the experiments were carried out. In the Netherlands the harvesting time of cereals always start in the South-East, continuing in the South-West (some days till one week later) and finishes in the North-East (on average 3 weeks later than in the South-East). During the harvesting time of wheat in 1990, it was very hot. This is the reason why the differences in the harvesting time between the different regions were very small. In 1991 on the other hand the harvesting time started late as a consequence of cold weather during the growing season.

The size of the experimental sites were at least 1 ha and those in Weiwerd were

Table 1. The locations of the experimental sites and the standard weather stations.

Type of site	Site	Geographic position	
Experimental site	Kessel	51°18'N	6°04'E
	Haamstede	51°42'N	3°45'E
	Weiwerd	53°19'N	6°56'E
Standard weather station	Volkel	51°39'N	5°42'E
	Vlissingen	51°27'N	3°36'E
	Eelde	53°08'N	6°35'E

Table 2. The periods of time the experiments were carried out.

Year	Site	Crop	Time
1990	Kessel	barley	11-13 July
	Haamstede	barley	26-30 July
	Kessel	wheat	24 July-2 August
	Haamstede	wheat	1-4 August
	Weiwerd	wheat	4-12 August
1991	Weiwerd	barley	28-30 July
	Weiwerd	wheat	21-23 August

situated in an area with a lot of cereals. The measurements were performed each hour from dawn till dusk. A sample of ears was taken in the field at random. After threshing by hand with the help of sandpaper, the moisture content of the grains was determined (six-fold samples) by a cereal moisture content meter (type Protimeter Digital Grainmaster). In this machine the grains were ground before measuring. The air temperature and dew point temperature were measured with an Assmann psychrometer. The surface temperature of the ears has been determined by a infrared radiation thermometer (type CHINO Portable Radiation Thermometer Comet 8000). The global radiation has been measured by a pyranometer (type Kipp CM5).

To compare the moisture content of the grains before and after threshing, a sample of ears in the field just before combining and a sample of grains just after combining were taken.

At drying the moisture content of the grains of cereals can be calculated using the formula of Penman-Monteith (Monteith, 1965):

$$L_v E = \frac{s\,R_n + \dfrac{\rho_a c_p (e_s - e_a)}{r_a}}{s + \gamma\left(1 + \dfrac{r_c}{r_a}\right)} \qquad (1)$$

The net radiation can be calculated (Holtslag & Van Ulden, 1983) by:

$$R_n = \frac{aR_g + c_1 T^6 - \sigma T^4 + c_2 N}{1 + c_3} \qquad (2)$$

The height of the crop is set at 0.8 m and the wind speed (10 m height) is taken 2 m s^{-1}. Therefore r_a is 62 s m^{-1} and at a moisture content of 16 % r_c is 21875 s m^{-1} (Atzema, 1993).

The equilibrium moisture content M_e is calculated by the Henderson equation (Henderson, 1952). The modified version of the Henderson equation is (Anon., 1982):

$$M_e = \left[\frac{\ln\left(1-\frac{e_a}{e_s}\right)}{-c_4\,(T+c_5)}\right]^{\frac{1}{c_6}} \qquad (3)$$

Results and discussion

Both in wheat as well as in barley there is no significant difference in the dew point temperature (1.5 m height) between the experimental plot and the nearest weather station. The difference in the dew point temperature in the screen and in the field is 0.7 ± 1.7 °C (n = 260) and 0.1 ± 1.4 °C (n = 114) for wheat and barley, respectively. However, the differences in the air temperatures are considerable.

Figure 1 shows the mean hourly temperatures in wheat of 3 successive days within the same air mass (Haamstede; 1 until 3 August 1990): the air temperature at 1.5 m height at the nearest standard weather station, the surface temperature of the ears, the air temperature at the height of the ears (1.0 m height) and above the canopy (1.5 m height). The surface temperature has the largest daily cycle. The maximum air temperature is reached late in the afternoon, since this temperature is dependent on the heat flux from the underlying surface. At daytime, the air temperature above the canopy (1.5 m height) is greater than that in the screen above short grass. The air is heated from the surface of the crop and the distance above the wheat is small compared to that above grass. Also the air temperature in the neighbourhood of the ears (1.0 m height) is higher than that above the canopy (1.5 m height).

Figure 2 shows the mean hourly temperatures in barley of 4 successive days within the same air mass (Haamstede; 26 until 29 July 1990): the air temperature at 1.5 m height at the nearest standard weather station, the surface temperature of the ears, the air temperature at the height of the ears (0.7 m height) and above the canopy (1.5 m height). In barley the difference between the surface temperature and the other temperatures is greater than that in wheat. Barley absorbs more heat than wheat under the same weather conditions.

In Table 3 and 4 the theoretical maximum differences in moisture content has been calculated for wheat and barley, respectively, when using the air temperature from the nearest standard weather station and the surface temperature of the grains, at daytime. The input of the weather elements are the mean values of the experiments in 1990 and 1991 (for wheat 18 days and for barley 10 days) under dry weather conditions only. The mean dew point temperature is 14 °C and the sky is cloudless. The yield of the wheat and barley is estimated at 7000 and 5500 kg ha^{-1}, respectively. So at a moisture content of 16 % only 1120 and 880 kg ha^{-1} water is present for wheat

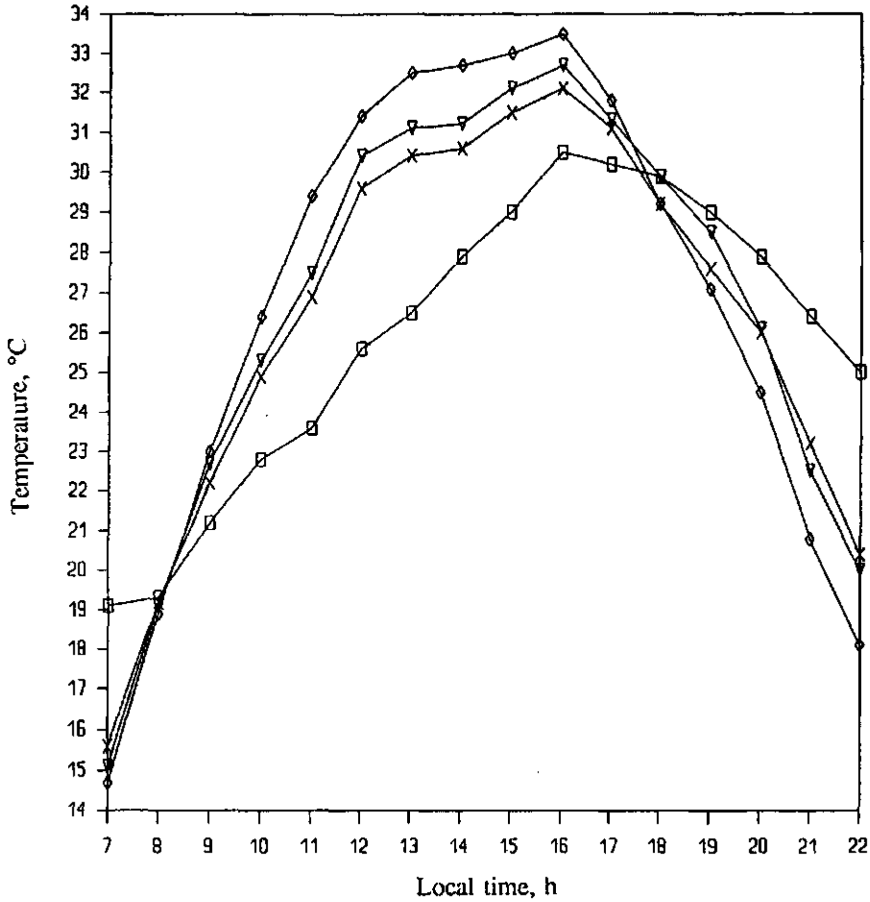

Fig. 1. Mean hourly temperatures in wheat at Haamstede and the corresponding screen temperature at Vlissingen of 3 successive days (1–3 August 1990). ◇ surface temperature of the ears; ▽ air temperature in wheat at 1.0 m height; × air temperature in wheat at 1.5 m height; □ screen temperature at Vlissingen.

and barley, respectively. Despite in these experiments the maximum difference in temperature is 7 °C, the maximum difference in grain moisture content is only 0.5 %, both for wheat and barley. Because under the same weather conditions barley absorbs more heat than wheat, the difference in moisture content of barley appears early in the day.

To have a constant crop resistance, every hour the moisture content was reset at 16 %. So the differences in moisture content can not be added. In reality the differences between the calculated moisture content and the moisture content in the field is smaller. Firstly, the temperature of the grains is lower than the surface temperature of the grains. Secondly, a higher temperature decreases the moisture content of the cereals with the consequence the crop resistance increases considerable.

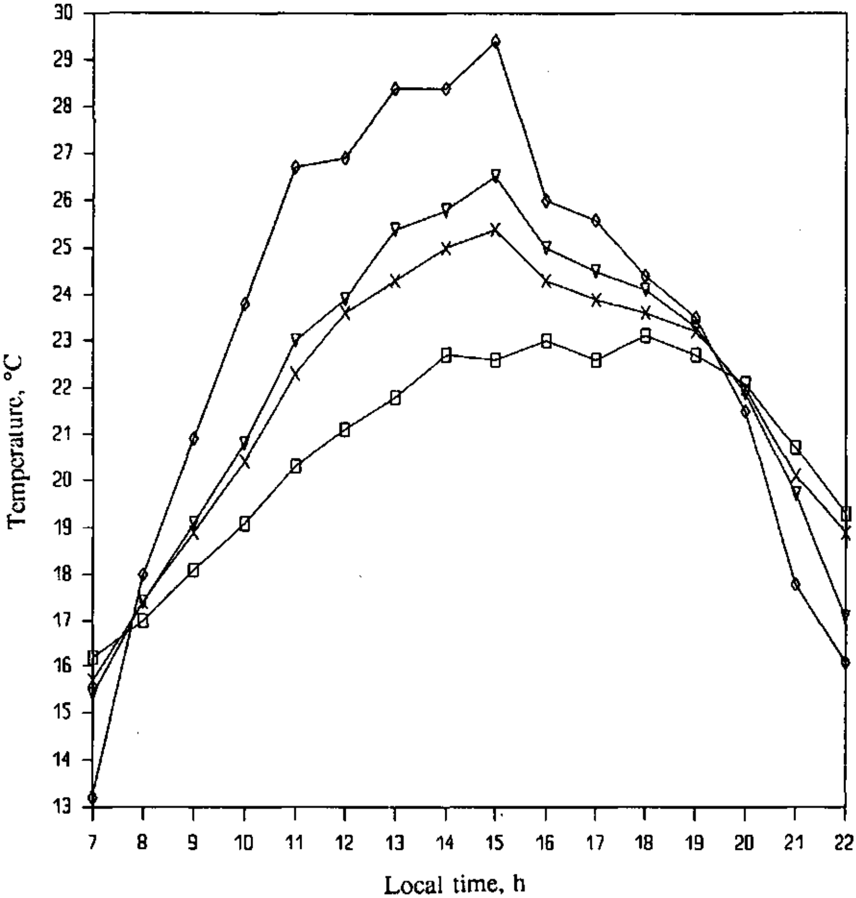

Fig. 2. Mean hourly temperatures in barley at Haamstede and the corresponding screen temperature at Vlissingen of 4 successive days (26–29 July 1990). ◇ surface temperature of the ears; ▽ air temperature in barley at 0.7 m height; × air temperature in barley at 1.5 m height; □ screen temperature at Vlissingen.

Figure 3 shows the course of the average moisture content of wheat (18 days) and barley (10 days) during the day. Compared to wheat, in the morning the moisture content of barley decreases rapidly and in the evening the moisture content of barley increases rapidly. These results agree with those of Van Kampen (1969).

The minimum quantity of absorbed water of the grains depend on the temperature and the dew point temperature of the surrounding air. This moisture content is the equilibrium moisture content. Water left in the grains is bound too strongly. Figure 4 shows the calculated equilibrium moisture content of wheat and barley with varying air temperature. The dew point temperature is set at 14 °C. From Tables 3 and 4 it can be seen that during the wheat experiments the average air temperature was higher than that during the barley experiments. With an equal dew point temperature

Table 3. Percentage difference in moisture content (Δ) in wheat calculated using the air temperature from the nearest weather station ($T_{a,st}$) or the surface temperature of the ears (T_s). Every hour (local time) the temperatures and the global radiation (R_g) are the mean values during 18 experimental days under dry weather conditions.

Time (h)	$T_{a,st}$ (°C)	T_s (°C)	R_g ($J\ cm^{-2}h^{-1}$)	Δ (%)
8	16.2	18.5	57	0.05
9	18.9	22.4	81	0.11
10	21.2	26.2	156	0.23
11	22.5	28.5	179	0.31
12	23.4	30.0	202	0.38
13	24.2	30.5	252	0.42
14	24.6	31.4	258	0.49
15	25.5	30.5	235	0.34
16	26.0	29.8	221	0.24
17	25.5	28.2	181	0.16
18	24.3	26.8	141	0.11
19	23.6	25.5	96	0.07
20	22.4	23.0	55	0.02

Table 4. Percentage difference in moisture content (Δ) in barley calculated using the air temperature from the nearest weather station ($T_{a,st}$) or the surface temperature of the ears (T_s). Every hour (local time) the temperatures and the global radiation (R_g) are the mean values during 10 experimental days under dry weather conditions.

Time (h)	$T_{a,st}$ (°C)	T_s (°C)	R_g ($J\ cm^{-2}h^{-1}$)	Δ (%)
8	17.0	20.3	48	0.11
9	18.4	22.9	99	0.16
10	19.9	25.7	156	0.29
11	21.2	27.3	187	0.39
12	21.5	27.8	219	0.42
13	22.2	28.1	269	0.45
14	22.6	29.3	267	0.51
15	22.9	30.0	248	0.54
16	23.1	28.8	241	0.40
17	23.0	27.8	197	0.29
18	23.1	27.1	152	0.24
19	22.8	25.7	117	0.15
20	21.9	24.1	70	0.09
21	20.4	21.5	33	0.03

(14 °C), an air temperature of 26 °C sets the equilibrium moisture content of wheat at 11.8 % and an air temperature of 23 °C sets the equilibrium moisture content of barley at 12.4 %. Since most of the time the air temperature is lower than given above, the moisture contents of wheat and barley have higher values.

In Fig. 4 the equilibrium moisture content of wheat is equal to that of barley if the air temperature and dew point temperature is 17 °C and 14 °C, respectively. If the air

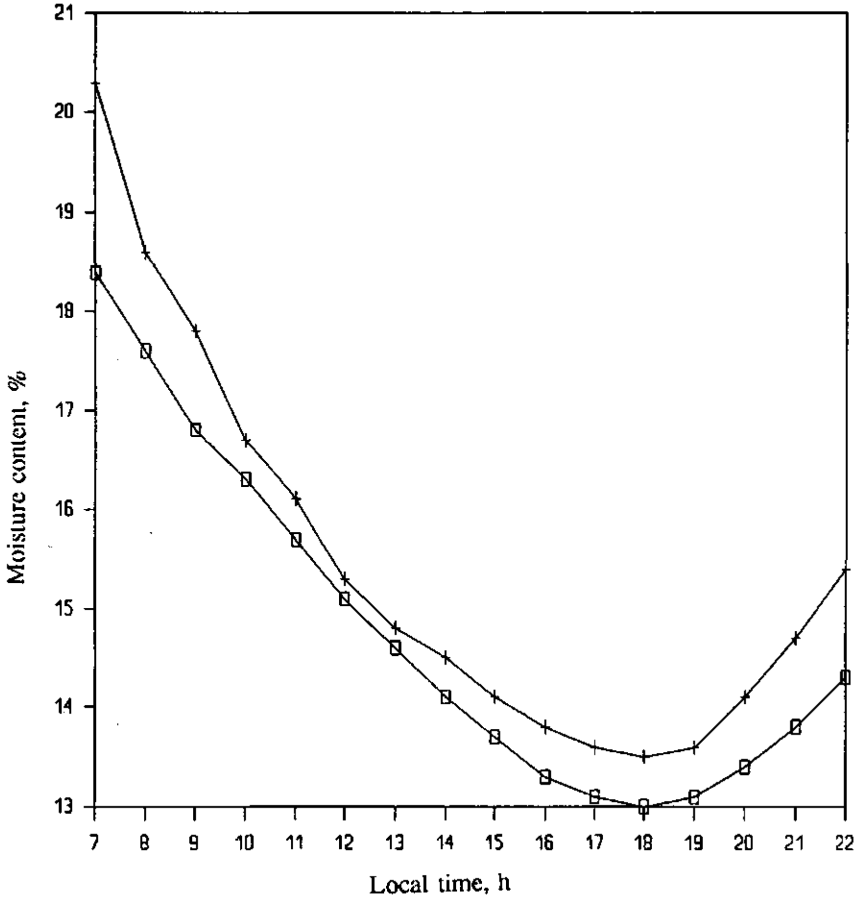

Fig. 3. Course of the average moisture content during the day. □ wheat; + barley.

temperature decreases (and the dew point temperature remains 14 °C) the equilibrium moisture content of barley is higher than that of wheat. Usually in the night, when the relative humidity is high, the moisture content of barley is higher than that of wheat under the same weather conditions. The line marked with * in Fig. 5, calculated with equation 3, represents an equal equilibrium moisture content of wheat and barley. The mark * represents the example of Fig. 4. In low temperatures with a high humidity the equilibrium moisture content of barley is higher than that of wheat. In a high temperature or a low humidity the equilibrium moisture content of barley is lower than that of wheat.

At combining the grains come into close contact with the straw. In many cases moisture is transferred from straw to grains. If the moisture content (m.c.) of wheat is less than 17.2 %, the straw is ripe and no green weeds are present, the differences between the moisture content before and after threshing is small (Van Kampen,

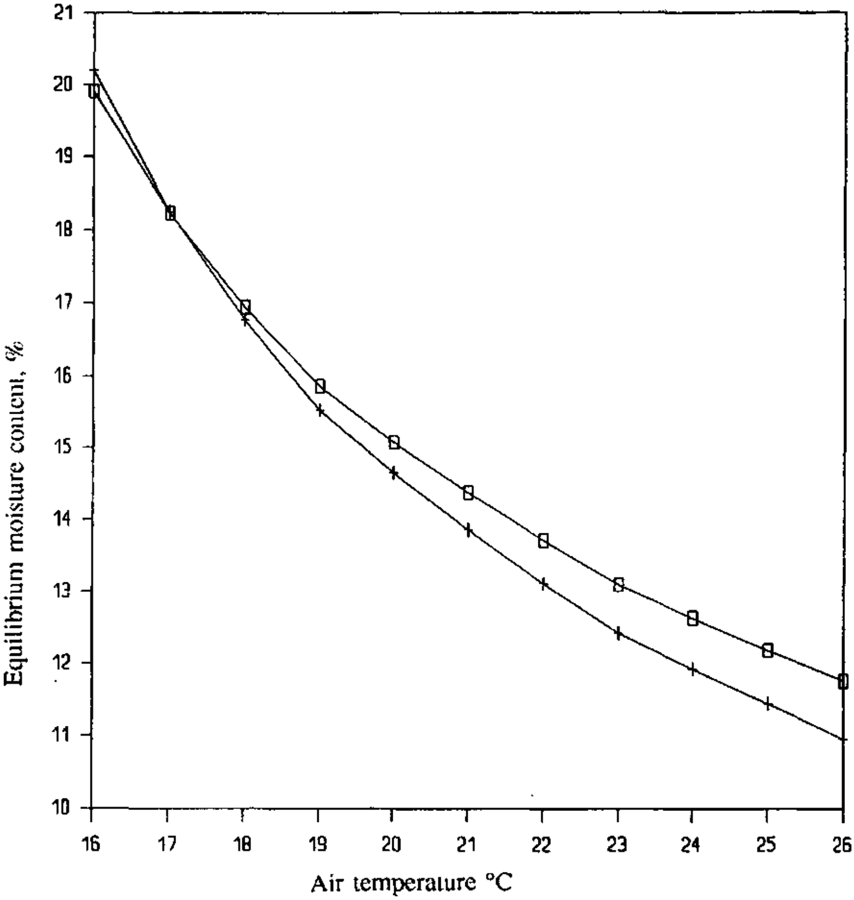

Fig. 4. Equilibrium moisture content versus the air temperature. Dew point temperature is 14 °C. □ wheat; + barley.

1969). In our measurements in wheat the mean moisture content before and after threshing was 15.0 % and 15.2 %, respectively (n = 21; m.c. < 17.2; 8 different days).

Quite different were the results of our measurements in barley. The mean moisture content of barley before and after threshing was 13.1 % and 14.7 %, respectively (n = 11; 4 different days). Despite a low moisture content the rise in moisture content is 1.6 %. The outside of the straw of barley is more smooth than that of wheat.

Conclusions

Both in wheat and in barley no significant difference is present in the dew point temperature (1.5 m height) between the experimental plot and the nearest weather sta-

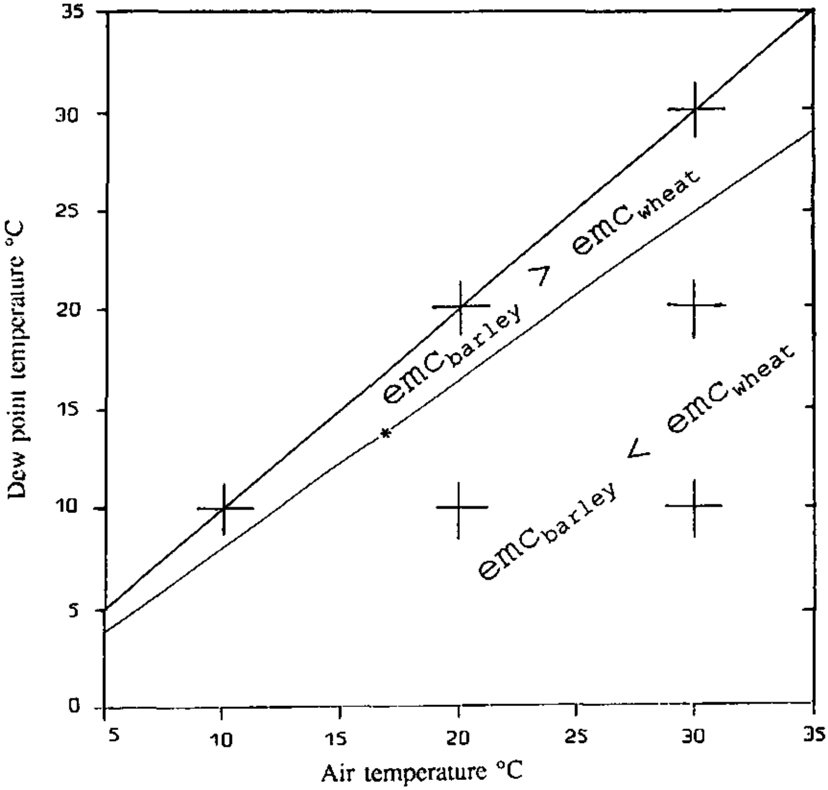

Fig. 5. Equilibrium moisture content (emc) of wheat and barley in relation to dew point temperature and air temperature. The grid (—|—) is also given.

tion. However the air temperature above wheat and barley is higher than that in the screen. Both for wheat and barley, in daytime the maximum difference between the calculated moisture content is 0.5 %, using the air temperature at 1.5 m height from the nearest standard weather station and the surface temperature of the ears. Because under the same weather conditions barley absorbs more heat than wheat, the difference in moisture content of barley appears early on the day. Barley has a greater daily cycle in the moisture content of the grains than wheat. In low temperatures with a high humidity the equilibrium moisture content of barley is higher than that of wheat. In a high temperature or in a low humidity the equilibrium moisture content of barley is lower than that of wheat. In wheat the differences between the moisture content before and after threshing is small if the moisture content of wheat is low, the straw is ripe and no green weeds are present.

Acknowledgements

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References

Anonymous, 1982. Moisture relationships of grains. Agricultural Engineers Yearbook, ASAE D245.4: 314-318.

Atzema, A.J., 1993. A model for the prediction of the moisture content of cereals at harvesting time with Realtime Weather Data. *Journal of Agricultural Engineering Research* 54: 245-256.

Beinhauer, R., 1975. The dependence and estimation of differences of temperature of a wheat stand from screen values). (In German). *Agricultural Meteorology* 15: 87-95.

Henderson, S.M., 1952. A basic concept of equilibrium moisture. *Agricultural Engineering* 33: 29-32.

Holtslag, A.A.M. & A.P. van Ulden, 1983. A simple scheme for daytime estimates of the surface fluxes from routine weather data. *Journal of Climate and Applied Meteorology* 22: 517-529.

Monteith, J.L., 1965. Evaporation and environment. Proceedings, Symposium of the Society for Experimental Biology 19: 205-234.

Monteith, J.L., 1969. Light interception and radiative exchange in crop stands. In: J.D. Eastin, F.A. Haskins, C.Y. Sullivan & C.H.M. van Bavel (Eds), Physiological aspects of crop yield, p. 89-115. American Society of Agronomy and Crop Science Society of America Madison, Wisconsin.

Monteith, J.L. & M.H. Unsworth, 1990. Principles of environmental physics. Edward Arnold, London, 291 pp.

Ross, J., 1975. Radiative transfer in plant communities. In: J.L. Monteith (Ed.), Vegetation and the atmosphere. Vol.1: Principles, p. 13-55. Academic Press, London.

Van Eimern, J., 1964. Investigations on the climate of agricultural plant covers. (In German). *Berichte des Deutschen Wetterdienstes* 96: 103 pp.

Van Kampen, J.H., 1969. Optimizing harvesting operations on a large scale grain farm. PhD Thesis, Wageningen Agricultural University, 176 pp.

Notation

E	mass flux of water vapour	kg m^{-2} s^{-1}
L_v	latent heat of evaporation	J kg^{-1}
M_e	equilibrium moisture content	% wb
N	cloud cover in octas	
R_g	global radiation	W m^{-2}
R_n	net radiation	W m^{-2}
T	temperature	K
a	fraction absorbed global radiation (0.67)	
c_p	specific heat of air at constant pressure (1010)	J kg^{-1} K^{-1}
c_1	constant $(5.31 \cdot 10^{-13})$	W m^{-2} K^{-6}
c_2	constant (60)	W m^{-2}
c_3	heating coefficient [0.32 (barley); 0.12 (wheat)]	
c_4	constant [0.229 (barley); 1.23 (wheat)]	
c_5	constant [195 (barley); 64 (wheat)]	
c_6	constant [2.01 (barley); 2.56 (wheat)]	

e_a	actual vapour pressure	Pa
e_s	saturated vapour pressure	Pa
r_a	aerodynamic resistance of air	$s\ m^{-1}$
r_c	crop resistance	$s\ m^{-1}$
s	slope of saturation humidity vs temperature curve	$Pa\ K^{-1}$
γ	psychrometric constant	$Pa\ K^{-1}$
ρ_a	density of air	$kg\ m^{-3}$
σ	Stefan-Boltzmann constant ($5.67 \cdot 10^{-8}$)	$W\ m^{-4}\ K^{-4}$

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A Model for the Prediction of the Moisture Content of Cereals at Harvesting Time with Realtime Weather Data

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A model which predicts the course of the moisture content of wheat and barley at harvesting time is presented. The input of the weather elements can be measured by standard weather stations. The model uses the air temperature and the dew point temperature, both at screen height, the wind speed at 10 m height, amount of rain, the global radiation and the cloud cover. All weather elements are taken hourly, except the quantity of rain which is taken every 6 h. The process of drying and rewetting is described. Different weather conditions are shown. The course of the moisture content of wheat and barley calculated by the model is compared with measurements made in field experiments. Favourable agreement was found between model and experiment.

1. Introduction

When harvesting cereals, weather has a great influence on the moisture content of the grain. It is important to harvest the grain with the right moisture content. When the moisture content of wheat or barley is far above 16% the product is unsuitable for storage, without mould formation. A moisture content far below 16% means a loss of profit, because less moisture is sold. For planning purposes, it is essential to know the moisture content of the grain beforehand. For this, a model which calculates the moisture content of cereals and a weather forecast is needed.

Several models[1–4] use regression equations which are based on the initial, final and equilibrium moisture content. Only the constant in the equations is different in the models. The regression equation of Van Kampen[5] takes the daily radiation into account but does not contain the equilibrium moisture content. Hesselbach[6] used a polynomial relationship with 12 parameters (weather and crop). Philips and O'Callaghan[7] use four types of data (crop, weather, economic and machine). The common feature is that all these models are empirical.

Van Elderen and Van Hoven[8] produced a physical model based on the Penman–Monteith equation. The advantage of modelling the physical processes is that the effect on the drying rate of a wide range of weather conditions is correctly modelled.

The aim of the present model is that it can be used with the help of hourly forecasts of weather elements. The model of Van Elderen and Van Hoven[8] is the most suitable to be transformed into a prognostic model, because it is based on physical processes with hourly input of weather elements. The original model has been modified considerably in order to make it suitable for prognostic use.

In the empirical models[1–7] the calculation of dew was weak. Voigt[1] and Crampin and Dalton[3] use correction factors. Van Kampen[5] uses the length of the night. The calculated condensation with the Penman–Monteith equation was in all cases too high, because the field was only partially covered with cereals. So not all the calculated condensation water can be deposited on the cereals. Therefore, during the night a new empirical relationship needs to be used.

Notation

E	mass flux of water vapour, $kg\,m^{-2}\,s^{-1}$	c_6	constant [2·01 (barley); 2·56 (wheat)]
L_v	latent heat of evaporation, $J\,kg^{-1}$	c_7	constant
M_e	equilibrium moisture content, % wb	d	zero plane displacement, m
M_i	moisture content at time i, % wb	e_a	actual vapour pressure, Pa
M_{i+1}	moisture content at time $i+1$, % wb	e_s	saturated vapour pressure, Pa
N	cloud cover in octas	k	von Karman's constant
R_g	global radiation, $W\,m^{-2}$	r_a	aerodynamic resistance of air, $s\,m^{-1}$
R_n	net radiation, $W\,m^{-2}$	r_c	crop resistance, $s\,m^{-1}$
T	air temperature at 1·5 m, K	s	slope of saturation humidity vs temperature curve, $Pa\,K^{-1}$
a	fraction absorbed global radiation (0·67)	u_z	velocity of air at height z above earth's surface, $m\,s^{-1}$
c_p	specific heat of air at constant pressure, $J\,kg^{-1}\,K^{-1}$	z	height above earth's surface, m
c_1	constant $(5{\cdot}31\times10^{-13})$, $W\,m^{-2}\,K^{-6}$	z_0	roughness length, m
c_2	constant (60), $W\,m^{-2}$	γ	psychrometric constant, $Pa\,K^{-1}$
c_3	heating coefficient	ρ_a	density of air, $kg\,m^{-3}$
c_4	constant [0·229 (barley); 1·23 (wheat)]	σ	Stefan-Boltzmann constant $(5{\cdot}67\times10^{-8})$, $W\,m^{-4}\,K^{-4}$
c_5	constant [195 (barley); 64 (wheat)]		

2. Cereals

The moisture content of cereals is determined when the grains are mature (Feekes 11·3 or higher). To run the model at the start the moisture content of a dry crop has to be put into the model, so the moisture content has to be determined in the afternoon or in the early evening in dry weather. The moisture content of the same kind of cereals at the same time is not always equal. There can be differences in the moisture content at harvesting time depending on the cultivar, plant nutrients, diseases or plant protection sprays. Because plots can be treated differently, it is possible the same kind of cereals on a particular plot can be harvested earlier than those on another plot. In the model the yield of wheat and barley is assumed to be 6000 kg d.m./ha and 4500 kg d.m./ha, respectively.

3. The model

3.1. *Meteorological basis*

When drying, cereals lose free and absorbed water. Dew and rain rewet the cereals. At drying, the formula of Penman–Monteith[9] is used:

$$L_vE = \frac{sR_n + \dfrac{\rho_a c_p(e_s - e_a)}{r_a}}{s + \gamma\left(1 + \dfrac{r_c}{r_a}\right)} \tag{1}$$

Standard weather stations usually do not measure the net radiation. Therefore, it has to be calculated using weather parameters which are measured. The net radiation can be calculated[10] using the equation:

$$R_n = \frac{aR_g + c_1 T^6 - \sigma T^4 + c_2 N}{1 + c_3} \tag{2}$$

The heating coefficient for wheat and barley[10] is 0·12 and 0·32, respectively. Only a part of the global radiation is absorbed by the grain. The remaining part is absorbed by the soil or is reflected.[11]

The aerodynamic resistance of the air, r_a, can be calculated[12] using the equation:

$$r_a = \frac{\left(\ln \frac{(z-d)}{z_0}\right)^2}{k^2 u_z} \tag{3}$$

The zero plane displacement, $d = 0{\cdot}63h$ (h = height of the cereals) and the roughness length, $z_0 = 0{\cdot}13h$.[12] The zero plane displacement is datum height in a crop above which normal turbulent exchange takes place. The height of the cereals is 0·80 m on average (present experiments).

3.2. *Equilibrium moisture content*

The minimum quantity of absorbed water of the grains depends on the temperature and the dew point temperature of the surrounding air. This moisture content is the equilibrium moisture content. Water left in the grains is absorbed too strongly. The equilibrium moisture content, M_e, is calculated by the Henderson equation.[13] The modified version of the Henderson equation is:[14]

$$M_e = \left[\frac{\ln\left(1 - \frac{e_a}{e_s}\right)}{-c_4(T + c_5)}\right]^{1/c_6} \tag{4}$$

Fig. 1 shows the equilibrium moisture content of barley and wheat in relation to the air

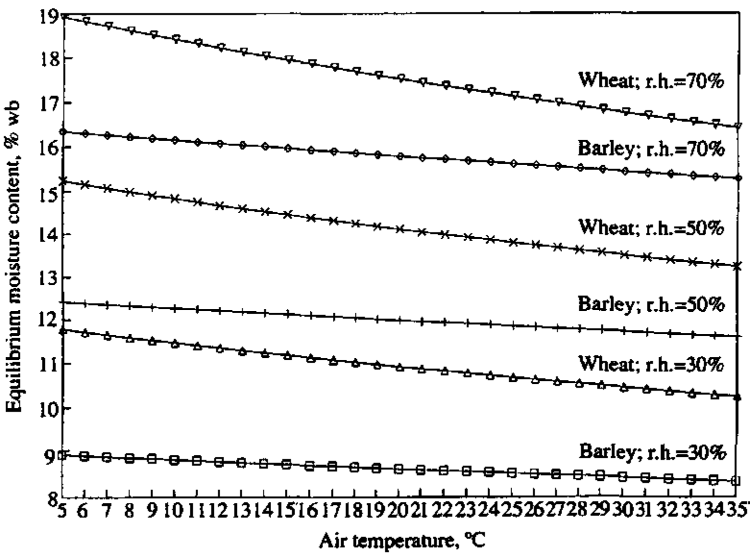

Fig. 1. Equilibrium moisture content of barley and wheat in relation to the air temperature and the relative air humidity (r.h.)

Table 1

Values of the crop resistance of absorbed water ($s\,m^{-1}$) dependent on the moisture content of the cereals (% wet basis)

Moisture content, %	*Crop resistance $s\,m^{-1}$*
12	51 500
14	30 250
16	21 875
18	16 625
20	9 300
22	6 750
24	4 525
26	3 050
28	2 250

temperature and the relative air humidity. Because the weather is changing continuously, the time is too short to reach the equilibrium moisture content. Within the same weather conditions the equilibrium moisture content of wheat is higher than that of barley.

3.3. *Free and absorbed water*

The moisture of the grain can be divided into free water and absorbed water. Dew and rain provide the grain with free water. Diffusion of free water from the reservoir provides absorbed water within the grain. The absorbed water decreases by transpiration, while free water evaporates.

The crop resistance for absorbed water depends on the moisture content. Values of the crop resistance were obtained from experiments in the field. The moisture contents of barley and wheat together with weather elements were determined hourly during the harvesting periods in 1989, 1990 and 1991 at the experimental site in Weiwerd which is situated in the north-east of the Netherlands (53°19'N 6°56'E). The crop resistance, r_c, can be calculated from Eqn (1) using the experimental value for E. Table 1 shows some of the values of the crop resistances of absorbed water. For use in the model, intermediate values are obtained by interpolation. The crop resistance for free water is zero. So the transpiration as well as the evaporation is calculated by Eqn (1). At the start of the calculation the grain consists of dry matter and absorbed water.

3.4. *Rewetting*

In the model, dew is formed when the net radiation is negative. The increase in the moisture content can be calculated[15] using the equation:

$$M_{i+1} = M_i + c_7(M_e - M_i) \tag{5}$$

The constant, c_7, changes with the temperature and is, for barley and wheat respectively:

$$c_7 = 10^6 e^{-(4426/T+273)} \tag{6a}$$

$$c_7 = 7{\cdot}2 \times 10^6 e^{-(5094/T+273)} \tag{6b}$$

The quantity of water which diffuses from the reservoir to the grain is 0·05 and 0·06 times the quantity of water of the reservoir for barley and wheat,[16] respectively.

When it rains, 25% of the water wets the grain, while the remaining water wets the straw or falls on the soil.[16] The maximum moisture content of the grains is 34%.[4] This value conforms to field experiments in 1989, 1990 and 1991.

4. Results and discussion

The results of the model are shown on the basis of three examples in three different years. The course of the moisture content in dry weather of wheat and barley is shown. Wheat and barley are also shown in the same weather conditions. The third example shows the drying and rewetting of wheat in a period of rain. In the figures the universal time (UT) is used, because the model uses weather elements given in UT. In the Netherlands the local time is 2 h later than the universal time at summertime.

4.1. *Wheat*

Fig. 2 shows the course of the moisture content of wheat. The values of the experiments in the field are obtained by taking samples (in sixfold) in the tank of the combine at harvesting. The results of the model agree favourably with the experimental values.

Fig. 3 shows the weather on the 22nd and 23rd of August 1991. It was dry and rather sunny. The clouds on the first day were mainly cirrus and altocumulus, so the global radiation was only slightly diminished by the clouds. It was warm, particularly the first day, with a relative humidity of about 45%.

Fig. 4 shows the course of the absorbed water and free water of wheat. *Fig. 5* shows the action of the transpiration, evaporation, dew and diffusion of water from the reservoir to the grain. At 0200 hrs (UT) the temperature of the air rose for a while. The forming of dew almost stopped. Some hours later the humidity of the air became high. Again dew was formed. At 0900 hrs (UT) the transpiration was higher than the diffusion, so the maximum amount of absorbed water that night was reached at about 0800 hrs (UT). The maximum amount of free water was reached at 0600 hrs (UT). After this time the evaporation exceeded the formation of dew.

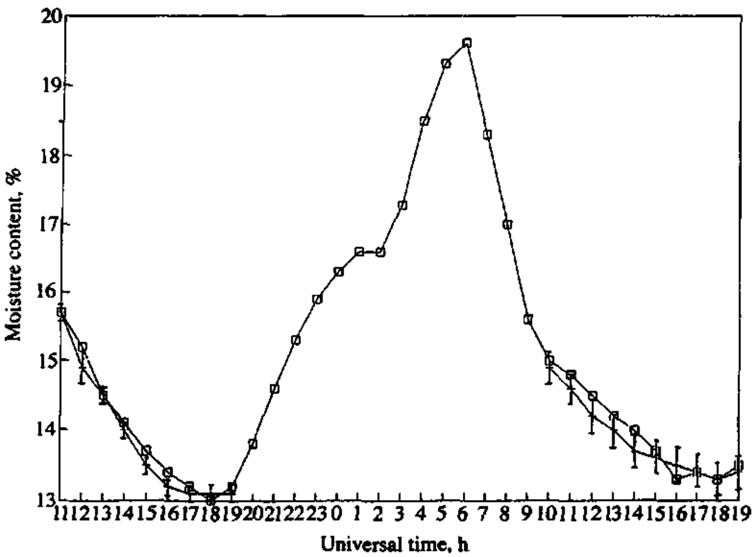

Fig. 2. Course of the moisture content of wheat. The model compared with the experiments in the field. Vertical bars show spread of standard deviation (22–23 August, 1991). —⊟—, model; —┼—, field

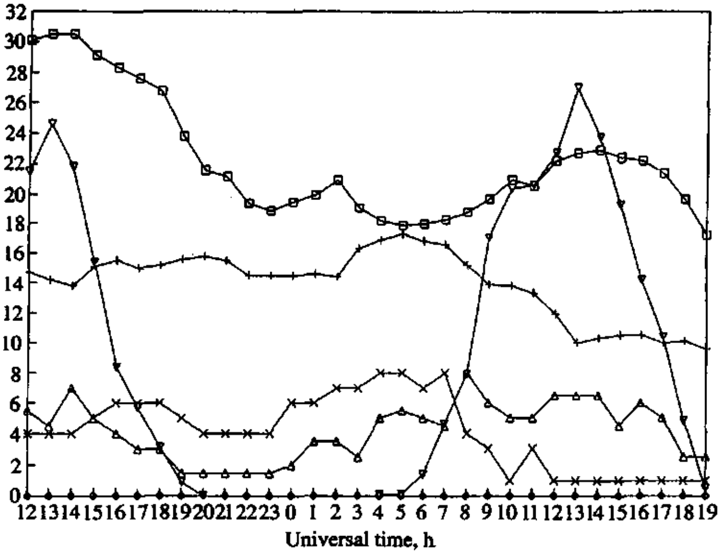

Fig. 3. Course of the weather elements (22–23 August 1991). —⊟—, *air temperature in °C (at 1·5 m);* —+—, *dew point temperature °C (at 1·5 m);* —◇—, *quantity of rain in mm h^{-1};* —△—, *wind speed in m s^{-1} (at 10 m);* —×—, *cloud cover in octas;* —▽—, *global radiation in 10 J cm^{-2})*

4.2. *Barley*

Fig. 6 shows the course of the moisture content of barley. The samples in the field are taken in the same way as those of wheat. Again the results of the model agree favourably with the experimental values.

During the night the relative humidity of the air was high and the wind speed was low which were good conditions for dew. During the day, there were sunny periods. The clouds were mainly stratocumulus and cumulus. The relative humidity during the day was about 50% (*Fig. 7*).

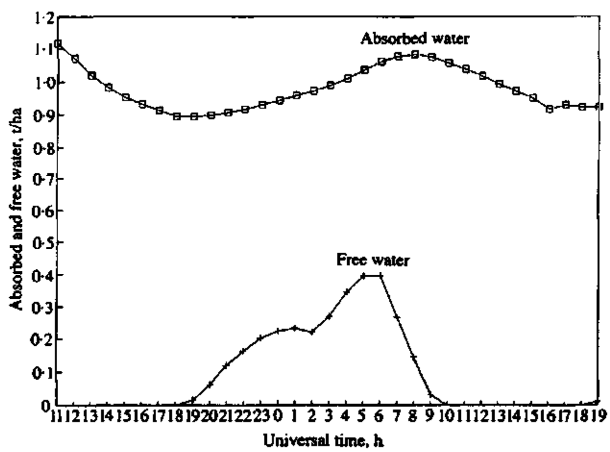

Fig. 4. The course of absorbed and free water (22–23 August, 1991)

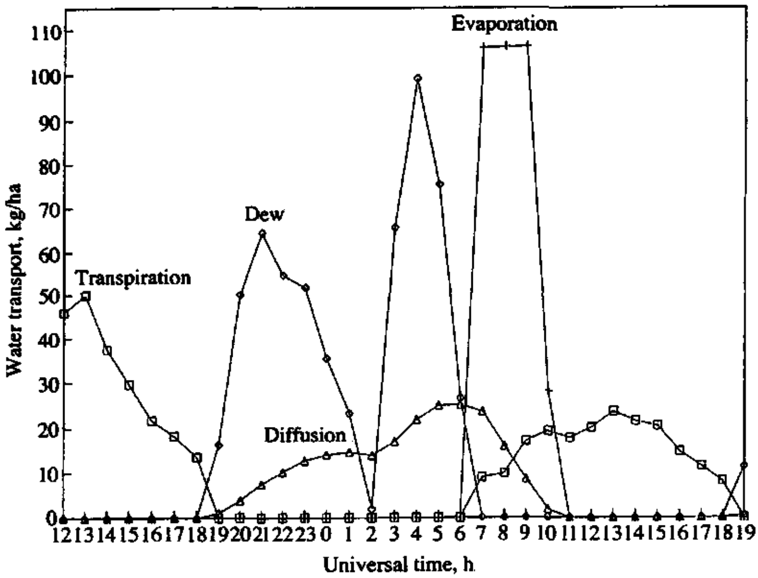

Fig. 5. The action of the transpiration, evaporation dew and diffusion of water from the reservoir to the grain (22–23 August, 1991)

Fig. 8 shows the course of the absorbed water and free water of barley. *Fig. 9* shows the action of the transpiration, evaporation, dew and diffusion of water from the reservoir to the grain. The maximum amount of absorbed water and of free water is reached at 0600 hrs (UT). After this time the transpiration exceeds the diffusion and the evaporation exceeds the formation of dew.

Under the same weather conditions in the evening barley moistens earlier and faster than wheat. During the daytime barley will become dry rapidly (*Fig. 10*). The grain of barley is exposed more to the air than the grain of wheat. These results agree with those of Van Kampen.[5]

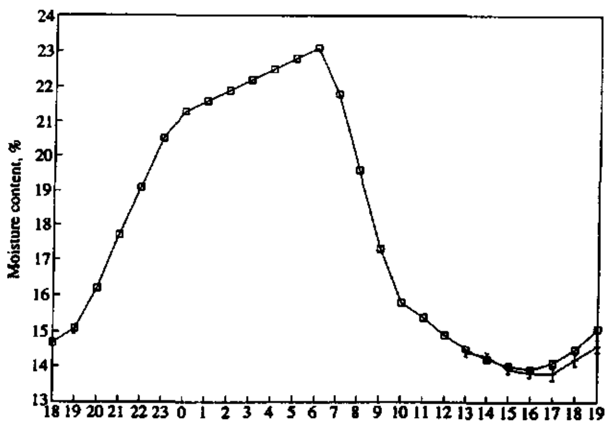

Fig. 6. Course of the moisture content of barley. The model compared with the experiments in the field. Vertical bars show spread of standard deviation (22–23 August, 1989) —⊟—, model; —+—, field

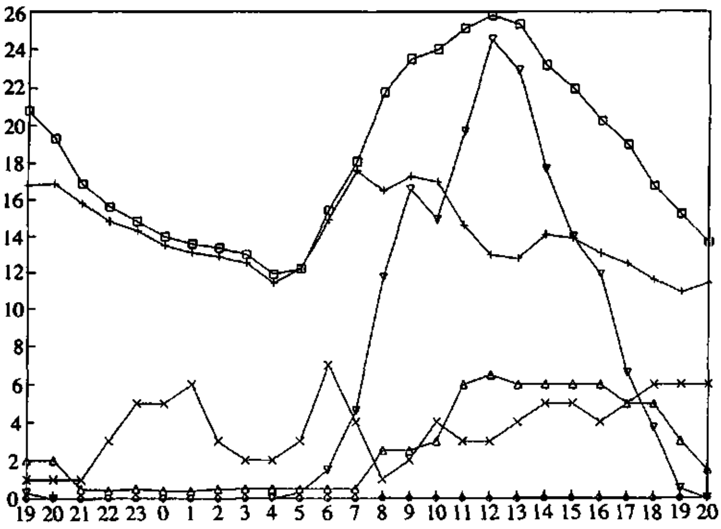

Fig. 7. Source of the weather elements (22–23 August, 1989). —⊟—, *air temperature in °C (at 1·5 m);* —+—, *dew point temperature °C (at 1·5 m);* —◇—, *quality of rain in mm* h^{-1}; —△—, *wind speed in m* s^{-1} *(at 10 m);* —×—, *cloud cover in octas;* —▽—, *global radiation in 10 J* cm^{-2}*)*

4.3. *A period of rain*

Fig. 11 shows the weather during a period of rain. This period can be divided into two parts: August 5–7 and August 8–10. In the first period there were showers, cumulus clouds and sunny periods in between. The relative humidity during daytime was 60% on average. The total precipitation in the first period was 6·8 kg m^{-2}. In the second period the air temperature was a little bit higher. The relative humidity was 65%. Most of the time it was cloudy, mainly stratocumulus. The total precipitation in this period was only 0·5 kg m^{-2}. The precipitation is calculated every 6 h. At the hourly calculation it is assumed each hour takes an equal quantity of the total at the sixth hour.

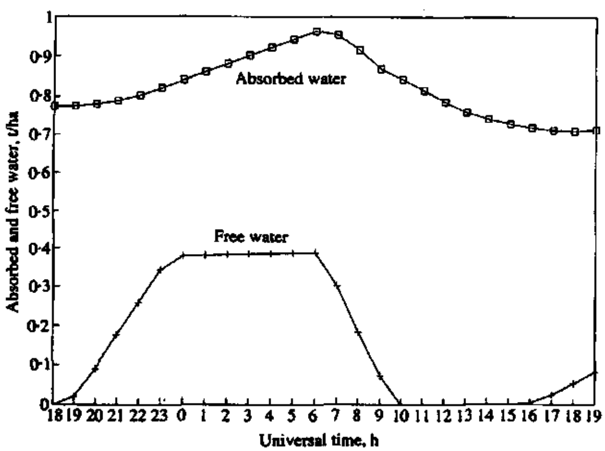

Fig. 8. The course of absorbed and free water (22–23 August, 1989)

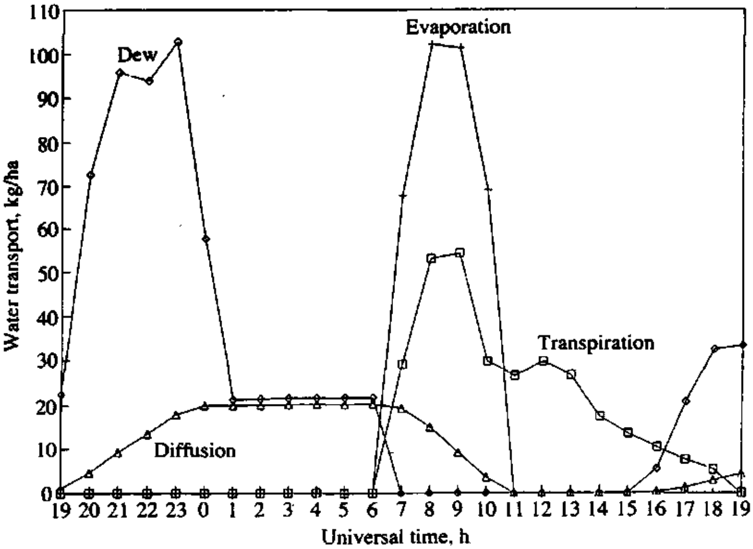

Fig. 9. The action of the transpiration, evaporation, dew and diffusion of water from the reservoir to the grain (22–23 August, 1989)

The course of the moisture content of wheat during rain is shown in *Fig. 12*. Differences between the model and the field experiments can be the result of the input of the rain once per 6 h. In reality, within the six hours, one or more hours may be dry. Although in some hours the differences between the model and the field experiments is large, later on, the model expresses reality. In a weather forecast, it can be difficult to predict the exact time of the precipitation. During a period of rain, cereals are not harvested. It is only important to predict the real moisture content after the period of rain. When it is raining, the differences in the moisture content of cereals within a plot can be considerable at the same moment. So the spread in the average moisture content in one plot can be large. In

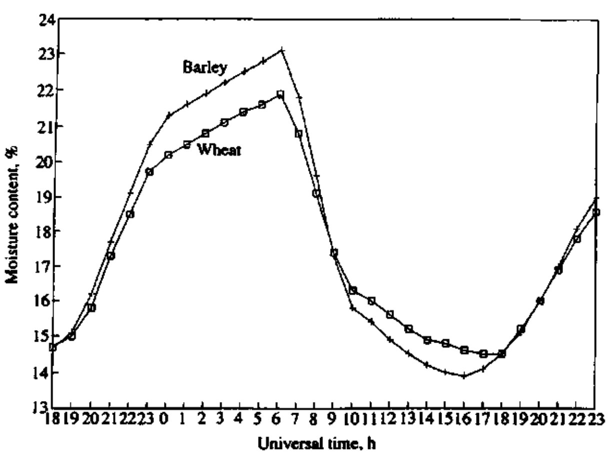

Fig. 10. Model results of the moisture content of wheat and barley in the same weather conditions (22–23 August, 1989)

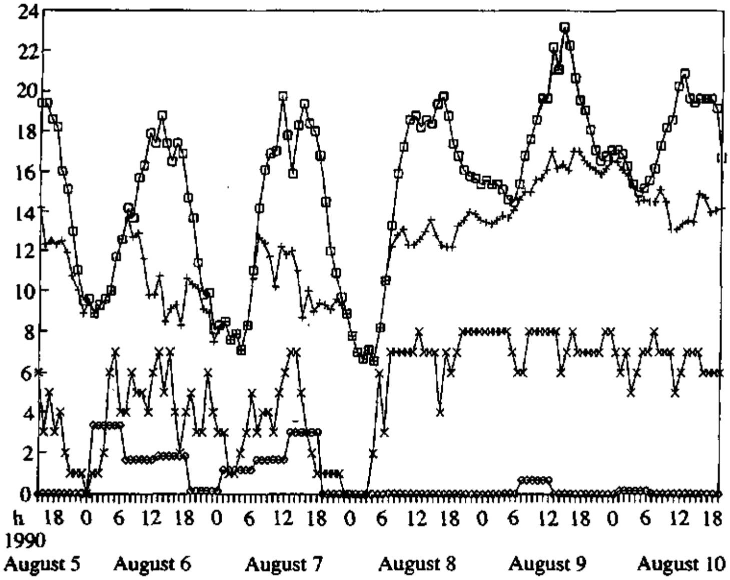

Fig. 11. Course of the weather elements during a period of rain (5–10 August, 1990). —⊟—, air temperature in °C (at 1·5 m); —+—, dew point temperature °C (at 1·5 m); —◇—, quantity of rain in mm h^{-1}; —✕—, cloud cover in octas

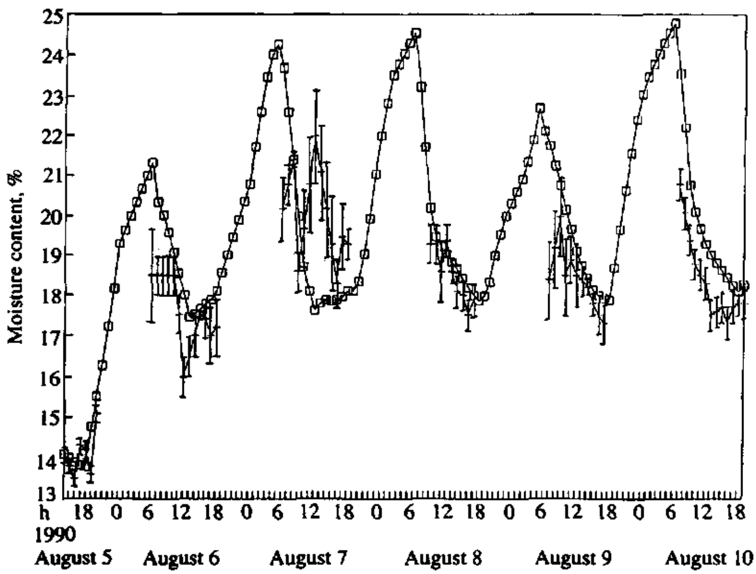

Fig. 12. Course of the moisture content of wheat during a period of rain. The model compared with experiments in the field. Vertical bars show spread of standard deviation (5–10 August, 1990). —⊟—, model; —+—, field

the first period (August 5–7) the moisture content of the wheat increased because of rain. In the second period (August 8–10) the moisture content did not decrease much because the humidity of the air was high and it was cloudy.

5. Conclusions

During harvesting time the moisture content of wheat as well as barley can be calculated a few days ahead. The model requires only weather elements that are usually forecast by meteorologists. The hourly input of the weather elements provides information from which the course of the moisture content can be determined. The change of the moisture content of barley is faster than that of wheat in response to the weather. The results of the model agree favourably well with values obtained by experiments in the field.

Acknowledgements

Thanks are due to the private weather information company Meteo Consult, Wageningen, which provides the computer facilities. The author also acknowledges B. Abma, C. A. Hoek and M. P. C. Zeelen, of the Department of Meteorology, who assisted in producing the present model. I express my gratitude to L. D. Atzema who give me the facilities to do the field experiments during the cereal harvesting at the cereal farm in Weiwerd. Credit is also to my colleagues J. Birnie and A. D. Welgraven who supplied the instruments for the field experiments.

References

[1] **Voigt, V.** Der Kornfeuchtigkeitsverlauf auf dem Halm stehenden Getreides unter dem Einfluß der Witterung und Folgerungen für den Mähdrusch (The development of kernel moisture content of standing grain due to the influence of weather and the consequences for combine-harvesting). Ph.D. Thesis, Hohenheim, 1955, 60 pp

[2] **Boyce, D. S.** Grain moisture and temperature changes with position and time during through drying. Journal of Agricultural Engineering Research 1965, **10**(4): 333–341

[3] **Crampin, D. J.; Dalton, G. E.** The determination of the moisture content of standing grain from weather records. Journal of Agricultural Engineering Research 1971, **16**(1): 88–91

[4] **Smith, E. A.; Bailey, P. H.; Ingram, G. W.** Prediction of the field moisture content of mature barley and wheat by commonly used drying equations. Journal of Agricultural Engineering Research 1981, **26**: 171–178

[5] **van Kampen, J. H.** Optimizing harvesting operations on a large scale grain farm. Ph.D. Thesis, Wageningen 1969, 176 pp

[6] **Hesselbach,** J. Zur Ermittlung arbeitswirtschaftlichter Daten hochmechanisierter Ernteverfahren (Research on economic data at the intensive grain harvest). KTL-Berichte über Landtechnik 1968, **122**: 262 pp

[7] **Philips, P. R.; O'Callaghan, J. R.** Cereal harvesting—a mathematical model. Journal of Agricultural Engineering Research 1974, **19**: 415–433

[8] **van Elderen, E.; van Hoven, S. P. J. H.** Moisture content of wheat in the harvesting period. Journal of Agricultural Engineering Research 1973, **18**: 71–93

[9] **Monteith, J. L.** Evaporation and environment. Proceedings Symposium of the Society for Experimental Biology 1965, **19**: 205–234

[10] **Holtslag, A. A. M.; van Ulden A. P.** A simple scheme for daytime estimates of the surface fluxes from routine weather data. Journal of Climate and Applied Meteorology 1983, **22**(4): 517–529

[11] **van Elderen, E.; van Hoven, S. P. J. H.; Kroeze, G. H.** Short wave radiation in a wheat crop during the harvest-period. Journal of Agricultural Engineering Research 1972, **17**: 94–98

[12] **Monteith, J. L.; Unsworth, M. H.** Principles of environmental physics. 1990: 291 pp

[13] **Henderson, S. M.** A basic concept of equilibrium moisture. Agricultural Engineering 1952, **33**: 29–32

[14] **Agricultural Engineers Yearbook.** Moisture relationships of grains. ASAE D245.4, 1982: 314–318

[15] **O'Callaghan, J. R.; Menzies, D. J.; Bailey, P. H.** Digital simulation of agricultural drier performance. Journal of Agricultural Engineering Research 1971, **16**(3): 223–244

[16] **Brück, I. G. M.; van Elderen E.** Field drying of hay and wheat. Journal of Agricultural Engineering Research 1969, **14**(2): 105–116.

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Determination of the Quality of Forecast Moisture Content of Cereals at Harvesting Time using Forecast Weather Elements

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Abstract

The moisture content of wheat and barley is forecast during the harvesting period. Each hour the forecast model uses standard weather elements of air temperature, dew point temperature, wind speed, amount of precipitation, global radiation and cloud cover. Over a period of four years 1989 to 1992 inclusive, a five-day weather forecast is made every day during one month during the harvesting period. The forecasts were compared with the realised weather elements in this period. Forecasting the moisture content of wheat and barley up to four days ahead gives a better prediction of moisture content than with a longer forecasting period. On average, barley has a greater deviation in the forecast moisture content than wheat. High moisture contents of the grains can be caused by low air temperature, low global radiation, high dew point temperature, high wind speed, and precipitation.

1. Introduction

For planning purposes it is important to forecast the moisture content of cereals. When the moisture content of wheat or barley is far above 16% the product is unsuitable for storage, because of the risk of mould formation. Usually at night the moisture content of ripe grains is high e.g. 22%. During daytime the moisture content decreases. Some hours before sunset the minimum moisture content is reached, e.g. 16% at 18 h (local time). In the evening, cereals rewet as a result of factors such as dew. A rough indication of the amount of dew formed during the night is provided by the difference between the dew point temperature at noon and the minimum temperature at night[1]. In the morning this water has to evaporate. The period of time this process takes depends on the weather.

In a previous paper the relationship between standard weather data and the microclimate of wheat and barley during harvesting time is determined[2]. Both for wheat and barley, the maximum difference between the calculated moisture content was 0.5%, using air temperature at 1.5 m height from the nearest standard weather station and surface temperature of the ears.

Next, another paper describes a model which calculates the diurnal course of the moisture content of wheat and barley with realtime weather data[3]. This model has been shown to give a good fit with measured moisture contents. The weather elements used are air temperature and dew point temperature, both at screen height, wind speed at 10 m height, amount of precipitation, global radiation and cloud cover. All weather elements are taken hourly, except precipitation which is taken every 6 h. During drying the moisture content of the grains can be calculated using the formula of Penman-Monteith[4]. The net radiation can be calculated using global radiation, air temperature (1.5 m) and cloud cover[5]. The equilibrium moisture content M_e is calculated a the modified version of the Henderson equation[6,7].

The present paper tests the forecast of the moisture content of cereals by the model[3] using forecast weather elements against the moisture content of cereals calculated by the model[3] using realised weather data. Every day a five-day forecast of the moisture content of cereals has been made during a period of four years 1989 to 1992, inclusive. The second part of July and the first part of August (total one month a year) is chosen, because the crop is harvested during this period, depending on the weather in the previous months. The forecast and realised weather elements used, come from the standard weather station Eelde (53°08'N 6°35'E), in the North-East of the Netherlands which is an important cereal growning area.

2. Model input

Several possible factors can be considered for forecasting the moisture content of cereals. The forecast weather as well as the time and place are important. In this paper the standard weather station Eelde (53°08'N, 6°35'E) is used. Besides the weather parameters, crop parameters play a role. To start the model calculation the initial moisture content must be known. This can be determined by measuring the moisture content in the afternoon or in the early evening in dry weather. Then the model calculates the moisture content for the next and next but one day using forecast weather elements. However, when it is not possible to measure the moisture content, this variable has to be estimated. In this paper, the initial moisture content is assumed to be equal to the equilibrium moisture content, but with a maximum value of 20%. It takes time to approach the equilibrium moisture content, but on most occasions by 21.00 h the minimum moisture content has been reached and it has begun to rise again. At that time the equilibrium moisture content may approach the moisture content of the grains[2].

Table 1. Symbols for the realised and forecast moisture content of cereals (r and f, respectively) for August 9. The subscripts 0, 1, 2, 3, 4 and 5 indicate the successive realised and forecast day; r_0 is the starting day.

Date	Number of days ahead					
	5	4	3	2	1	0
August 4	r_0	r_0	r_0	r_0	r_0	r_0
August 5	f_1	r_1	r_1	r_1	r_1	r_1
August 6	f_2	f_1	r_2	r_2	r_2	r_2
August 7	f_3	f_2	f_1	r_3	r_3	r_3
August 8	f_4	f_3	f_2	f_1	r_4	r_4
August 9	f_5	f_4	f_3	f_2	f_1	r_5

Table 1 shows an example of six successive calculations of the moisture content of cereals forecast for August 9. The model starts at 21.00 h on day r_0. The first run contains five forecast days (f_1, f_2, f_3, f_4 and f_5) and a part of the starting day (r_0). The minimum moisture content on day f_5 in this run is compared with day r_5 in the run with realised weather elements only. In the second run the first full day (r_1) the moisture contents are equal by comparing the run with four days forecast weather with the run with real weather for those days. The minimum moisture content on day f_4 in this run is also compared with day r_5 in the run with realised weather elements only, and so on. On the day being considered (in the example: August 9) the moisture content calculated with the forecast weather elements is subtracted from the corresponding moisture content calculated with realised weather elements (= r_5).

A difference in the moisture content between a run with forecast weather and that with realised weather only, can be caused on one day or more than one day. Therefore, the difference in moisture content needs to be examined day by day. In the run with five forecast days the minimum moisture content on day f_1 is compared with day r_1 in the run with realised weather elements only; the minimum moisture content on day f_1 in the run with four days forecast weather is compared with day r_2 in the run with realised weather elements only, and so on. Again the moisture content calculated with the forecast weather elements (=f_1) is subtracted from the corresponding moisture content calculated with realised weather elements. In this way, the weather elements responsible for the deviations in the moisture contents can be examined.

3. Results and discussion

In the present paper a positive (negative) deviation in the moisture content means the grains are wetter (dryer) than forecast. The data are put in a two-way table containing the days the moisture content of the grains are examined and the time lag between the forecast days and the realised day. Here time lag means the difference between forecast values and realised values which refer to the same day. The Friedman two-way analysis of variance by ranks[8] is used to test the dependence of the error of forecasting the moisture content of the grains on the time lag of the forecast. This test reveals significant differences in relation to the time lag. Next a t-test is used to test differences between pairs of time lags. Table 2, based on analysis of variance and t-tests for differences between pairs of time lags, mainly shows that forecasting the moisture content of wheat and barley up to four days ahead is significantly better than with a longer forecasting period. The quality of the forecast decreases with increasing time lag. Barley has a greater deviation in the moisture content than wheat.

A deviation in forecasting the moisture content of grains is caused by inexact forecasting of one or more weather elements. Precipitation wets the grains, but at the same time other weather elements can dry the grains. Thus, it is possible the grains dry while precipitation occurs. Figure 1 shows the deviation of the moisture content of the grains is caused not only by precipitation. Both the total number of observations and those with precipitation only look like a normal distribution. The maximum increase in moisture content of wheat (barley) with a yield of 6000 (4500) dry matter ha^{-1} is 1.25 (1.4), 2.5 (2.8) and 5.0 (5.6) % when the amount of precipitation is 0.5, 1.0 and 2.0 mm, respectively. If the moisture content of the grains is high, the crop resistance is low[3]. Hence, in most cases the high moisture content of the grains do not increase if the amount of precipitation is high.

Several weather elements contribute to causing a deviation in the moisture content of wheat and barley. The effect of an error in forecasting one weather element has considered in relation to the whole range of weather elements that influence moisture content of cereals. For example, an error in forecasting global radiation

Table 2. Mean absolute deviation in forecasting the moisture content (%) of wheat and barley in dependence of the time lag of the five-day weather forecast (n = 620). The Least Significant Difference for wheat and barley is 0.21 and 0.23, respectively.

Deviation	Days ahead				
	5	4	3	2	1
Wheat	2.01	1.87	1.53	1.26	0.81
Barley	2.08	1.90	1.61	1.36	0.91

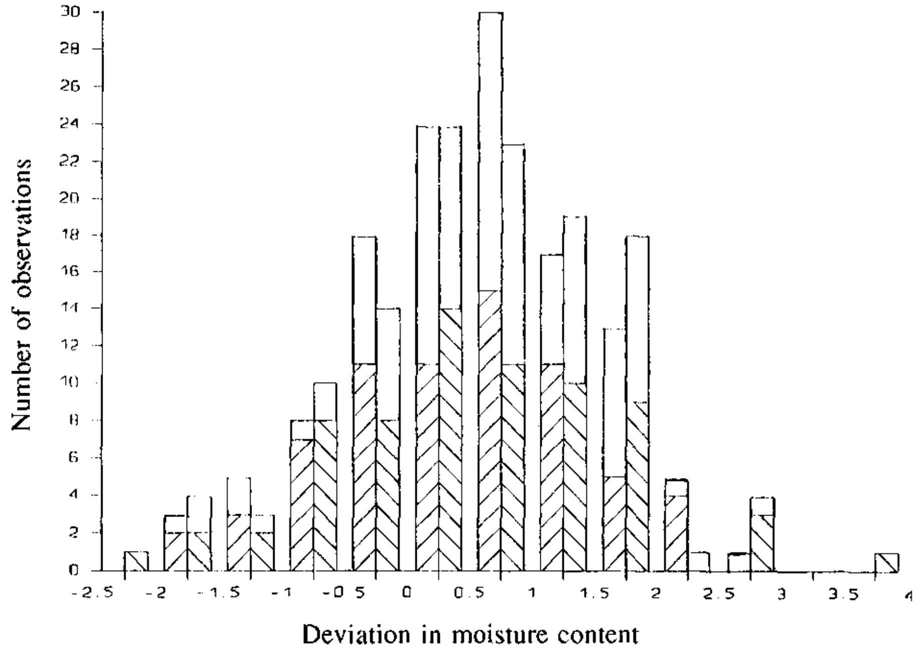

Fig 1: The deviation of the moisture content (%) of wheat (left) and barley (right) in groups of 0.5%. Shaded areas represent observations with precipitation only.

can influence air temperature. Precipitation can decrease air temperature.

Figures 2-6 show an example of the course of the moisture contents of barley and the weather elements concerned. The thick line represents the realised values. So, in the run with one forecast day the moisture content on the preceding days are equal to those on the days with realised weather. First, the difference in moisture content is examined day by day by comparing the first forecast day f_1 with the corresponding realised day, only. In this example forecast air temperature is too high on all days. Four days ahead forecast dew point temperature is too low compared with realised values (f_1 versus r_2). Four, 2 and 1 days ahead forecast global radiation is too high (f_1 versus r_2, r_4 and r_5, respectively). Two and 1 days ahead forecast wind speed is too high (f_1 versus r_4 and r_5, respectively). In all instances, the first forecast day was dry, but in fact there was 1 mm precipitation. So, 5, 4, and 3 days ahead forecast moisture content is too low in the daytime. Striking is the slight increase in moisture content the night of July 18-19 (fig. 2). In this night the formation of dew is opposed by the dry air in this night (fig. 3). At daytime, 2 and 1 days ahead wind speed and precipitation increase the moisture content, while air temperature, dew point temperature and global radiation decrease the moisture content.

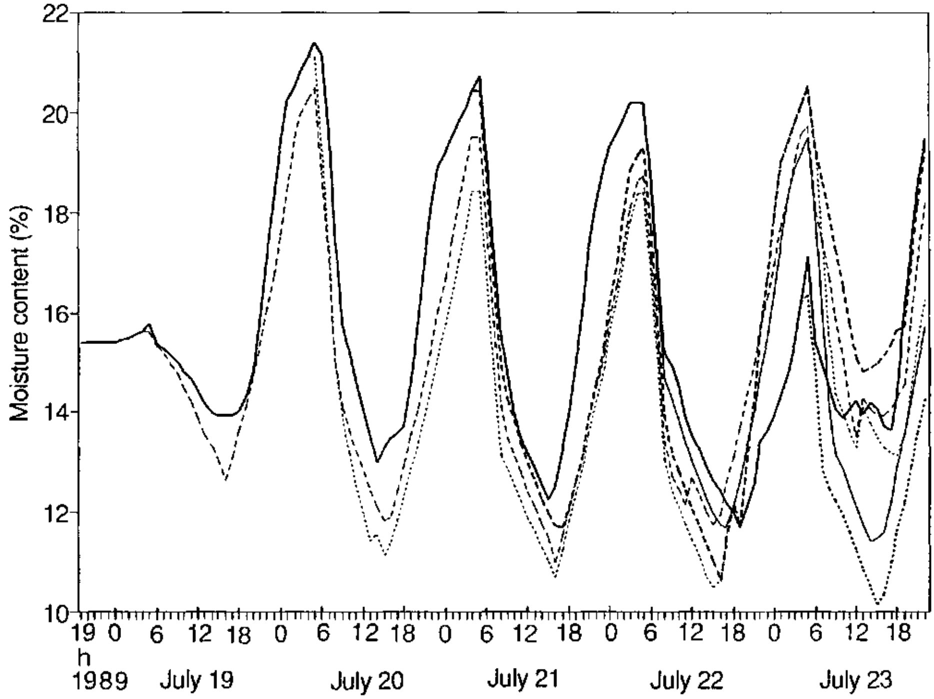

Fig 2: The course of the forecast and realised moisture content (%) of barley for July 23, 1989.

----- forecast on July 18 (5 days ahead) —— forecast on July 21 (2 days ahead)
.... forecast on July 19 (4 days ahead) .... forecast on July 22 (1 day ahead)
----- forecast on July 20 (3 days ahead) —— realised

When considering not only the first forecast day, but also the following days, there are more instances when the weather elements can counteract one another. In the example 5, 4 and 3 days ahead precipitation is forecast on day 0 (1.8, 1.7 and 4.2 mm, respectively) with the overall result that the forecast moisture content on day 0 increases while on the preceding days the moisture content was lower than the realised value. The moisture content on day 0 forecast 3 days ahead was too high compared with the realised value as a result of a larger forecast amount of precipitation than on the other days. Also in this example the amount of precipitation does not give a quantitative increase of the moisture content.

Data used (number = 620) reveal low air temperature, low global radiation, high dew point temperature, high wind speed and precipitation can cause a high moisture content of the grains. In most instances a combination of the weather elements is responsible for the deviation in the moisture content. Thompson[9] and Atzema[10] also noted the adverse effect on the drying rate of cut grass in the field from an increas-

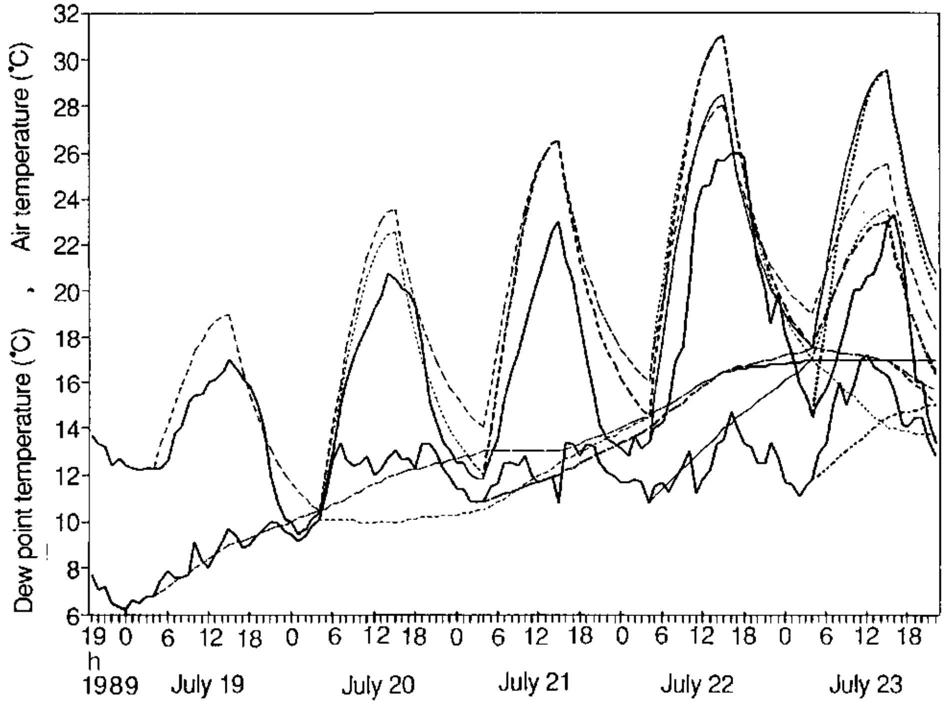

Fig 3: The course of the forecast and realised air temperature (°C) (above) and dew point temperature (°C) (bottom) for July 23, 1989.

----- forecast on July 18 (5 days ahead) —— forecast on July 21 (2 days ahead)
.... forecast on July 19 (4 days ahead) .... forecast on July 22 (1 day ahead)
----- forecast on July 20 (3 days ahead) —— realised

ing wind speed. The moisture content of cereals is low (about 16%) compared with cut grass destined for ensiling (about 60%). This means that for cereals also dew point temperature and wind speed are important. In grass the role of wind speed is more important if the moisture content of grass has decreased to a low level[10].

4. Conclusions

The quality of forecasting the moisture content of wheat and barley decreases with increasing time lag. Up to four days ahead the forecast of the moisture content is significantly better than with a longer forecasting period. Barley shows a greater deviation of the moisture content than wheat. The deviation of the forecast moisture content of the grains is caused not only by precipitation, but other weather elements also play a role. The amount of precipitation does not give quantitative increase of

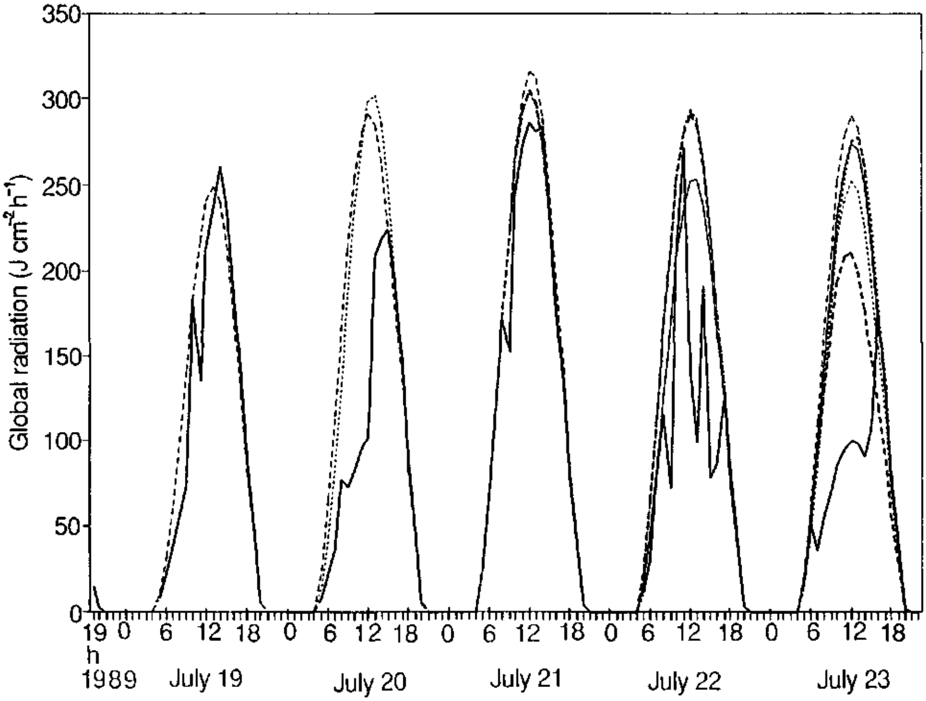

Fig 4: The course of the forecast and realised global radiation (J cm^{-2} h^{-1}) for July 23, 1989.

----- forecast on July 18 (5 days ahead) —— forecast on July 21 (2 days ahead)
········ forecast on July 19 (4 days ahead) ········ forecast on July 22 (1 day ahead)
----- forecast on July 20 (3 days ahead) —— realised

the moisture content. A high moisture content of the grains can be caused by low air temperature, low global radiation, high dew point temperature, high wind speed and precipitation. The low moisture content of cereals compared with cut grass destined for ensiling denotes that dew point temperature and wind speed are also important. The quality of forecasting the moisture content of cereals depends heavily on the quality of the forecast of the weather elements.

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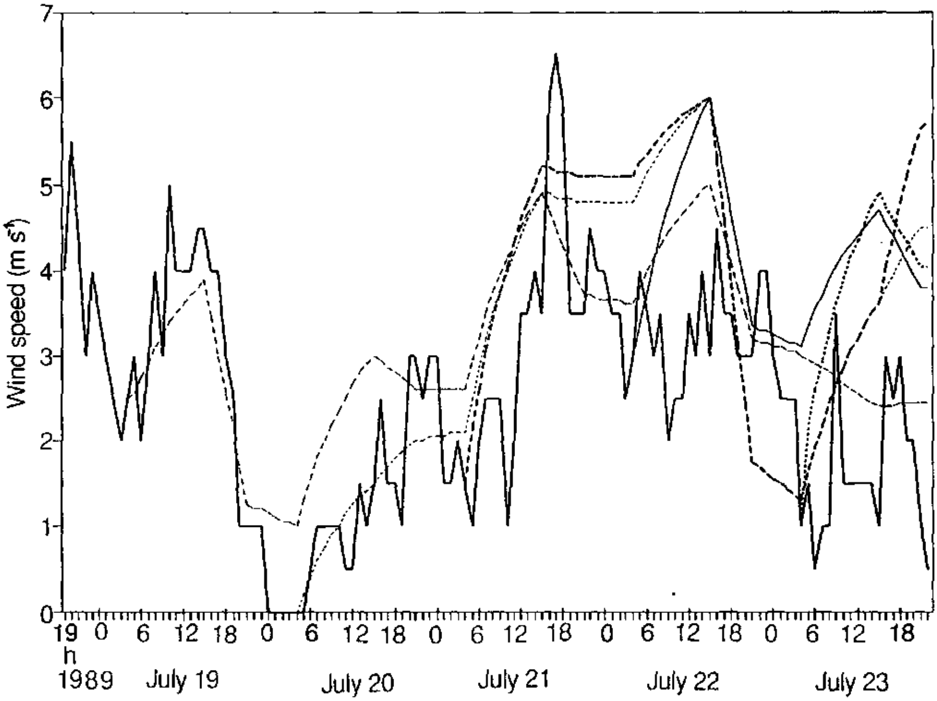

Fig 5: The course of the forecast and realised wind speed (m s^{-1}) for July 23, 1989.

----- *forecast on July 18 (5 days ahead)* —— *forecast on July 21 (2 days ahead)*
········ *forecast on July 19 (4 days ahead)* ········ *forecast on July 22 (1 day ahead)*
----- *forecast on July 20 (3 days ahead)* —— *realised*

References

[1] Atzema, A.J.; Jacobs A.F.G.; Wartena, L. Moisture distribution within a maize crop due to dew. Netherlands Journal of Agricultual Science 1990, 38: 117-129

[2] Atzema, A.J. Moisture content of cereals at harvesting time by comparing micro-climate values and standard weather data. Netherlands Journal of Agricultural Science 1993b, 41: 167-178

[3] Atzema, A.J. A model for the prediction of the moisture content of cereals at harvesting time with realtime weather data. Journal of Agricultural Engineering Research 1993a, 54: 245-256

[4] Monteith, J.L. Evaporation and environment. Proceedings, Symposium of the Society for Experimental Biology 1965, 19: 205-234

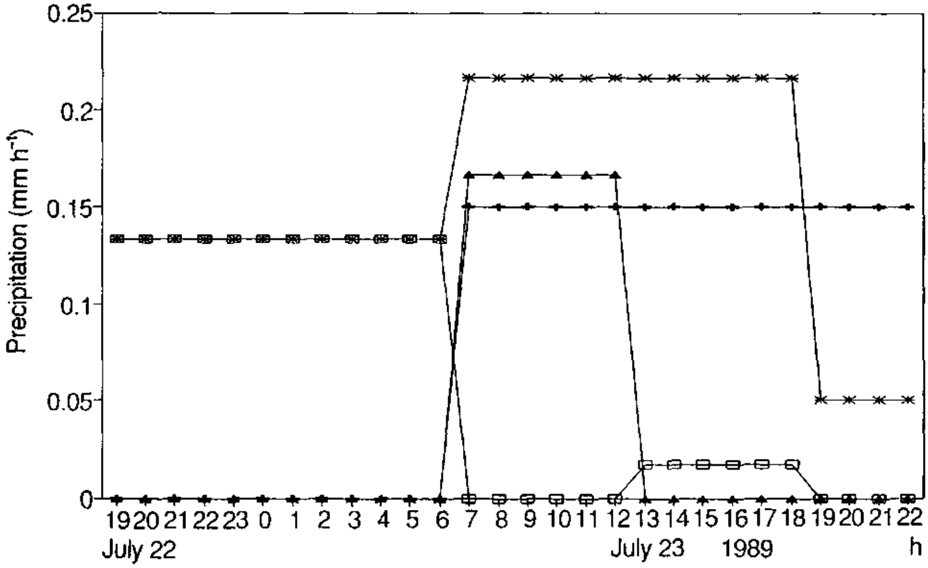

Fig 6: The course of the forecast and realised precipitation (mm h^{-1}) for July 23, 1989. It was dry on days not mentioned here.

—+— forecast on July 18 (5 days ahead) —✳— forecast on July 20 (3 days ahead)
—⊟— forecast on July 19 (4 days ahead) —▲— realised

[5] Holtslag, A.A.M.; van Ulden A.P. A simple scheme for daytime estimates of the surface fluxes from routine weather data. Journal of Climate and Applied Meteorology 1983, 22: 517-529

[6] Henderson, S.M. A basic concept of equilibrium moisture, Agricultural Engineering 1952, 33: 29-32

[7] Anonymous, Moisture relationships of grains. Agricultural Engineers Yearbook, ASAE D245.4 1982, 314-318

[8] Siegel, S; Castellan N.J. Nonparametric statistics. Singapore: McGraw-Hill Book Company 1988: 399 p.

[9] Thompson, N. Modelling the field drying of hay. Journal of Agricultural Science, Cambridge 1981, 97: 241-260

[10] Atzema, A.J. The effect of the weather on the drying rate of cut diploid and tetraploid perennial ryegrass (*Lolium perenne, L.*) and diploid hybrid ryegrass (*Lolium perenne x L. multiflorum*). Grass and Forage Science 1993c,48: 362-368

Summary

Part 1

The aim of the study of grass is to forecast the drying of cut grass up to five days ahead, hourly. The first investigated problem is the response of the drying of cut grass to the weather elements. Next a simple model and an advanced model for the drying of cut grass are presented. Errors in the elements of the weather forecast which are important for the drying of grass, are discussed.

During three growing seasons the drying of grass in the field was observed from cutting to ensiling. The experiments were carried out on sixteen different plots at the same location. Every hour samples of grass were taken to determine the moisture content of grass. The grass species examined were diploid and tetraploid perennial ryegrass (*Lolium perenne L.*) and diploid hybrid ryegrass (*Lolium perenne x Lolium multiflorum*) var. Barcolte. The perennial ryegrasses were a mixture of different varieties. All the grasses examined were in the vegetative state. Also the cutting time and the swath treatments were examined.

Simultaneously with the samples of grass, meteorological data were gathered on the experimental plots: air temperature (1.5 m height), dew point temperature (1.5 m height), surface temperature of the grass, temperature within the grass swath and wind speed (2 m height). These meteorological data were compared with the standard meteorological data that were taken hourly from the nearest weather station.

Apart from the weather, the drying depended on the grass species and the yield. In general, the moisture content of grass at the time of cutting was 3% higher when cut in the morning than when cut in the late afternoon. Hybrid ryegrass had a lower initial moisture content at cutting and dried faster compared with perennial ryegrass. Diploid varieties dried faster than tetraploid at the same yields. Within the same varieties a low yield dried faster than a high yield. Frequent tedding did not influence the rate of drying significantly.

The temperature within the swath was comparable to the standard air temperature at 1.5 m. The standard air temperature at 0.1 m was a good indicator of the grass surface temperature. The grass surface temperature was mainly determined by global radiation and responded rapidly to its changes, but it was also influenced by the wind speed and the moisture content of the grass. A low moisture content of the grass allowed an increase of the grass surface temperature. Increasing wind speed had an adverse effect on the drying rate of grass.

The simple grass drying model uses no crop parameters and needs only three standard (forecast) weather elements: air temperature, dew point temperature and quantity of rain. In dry weather the moisture content of grass is calculated hourly during daytime from 10.00 h to 19.00 h (local time) by modelling the saturation deficit. Dew formed during the night is assumed to be compensated by the drying

of grass early in the evening and in the morning before 10.00 h. Roughly this model gives an indication of the forecast moisture content of cut grass.

The advanced model uses some crop parameters and standard (forecast) weather elements. Crop parameters used are yield and the times of cutting, tedding and windrowing. Standard weather elements used are: air temperature, dew point temperature, global radiation, cloud cover, wind speed and quantity of rain. No differences in grass species are made through which the model can be used generally. When grass dries freely, absorbed water is lost by evaporation and transpiration. Condensation and precipitation increase the moisture content of grass. The formula of Penman-Monteith is used as basis for the calculation of the moisture content. In the model the grass swath is divided into two layers, and the upper layer is kept at a constant mass. So, during drying the upper layer grows in thickness by incorporating dry matter and water from the lower layer.

Favourable agreement was found between the advanced model calculation and the measured moisture content of grass in the field. Usually forecast weather elements do not have exactly the same value as the corresponding past weather elements. Errors in the forecast moisture content of grass are mostly caused by errors in the forecast air temperature, global radiation and precipitation. Errors in the forecast dew point temperature and wind speed play a minor role. Generally, the forecast of the moisture content of cut grass is significantly better for one day ahead than for more days ahead.

Part 2

The aim of the study of cereals is to forecast the moisture content of wheat and barley up to five days ahead, hourly. The first investigated problem is the relationship between standard weather data and the microclimate of wheat and barley during harvesting time. Next, a model for the calculation of the moisture content of wheat and barley is presented. Errors in the elements of the weather forecast which are important for the moisture content of cereals are discussed.

The moisture content of mature barley and wheat (from growth stadia DC 91) and the meteorological elements have been observed during three harvesting seasons. The experiments were carried out at three different sites in the Netherlands. Meteorological elements measured on the experimental plots were: air temperature, dew point temperature, surface temperature of the ears and global radiation. Air temperature and dew point temperature were measured at two heights: at the height of the ears and at 1.5 m height above the soil. The measurements were performed each hour from dawn till dusk. These local meteorological data were compared with standard meteorological data that were observed hourly at the nearest weather station.

SUMMARY

Both in wheat and in barley no significant difference is present in the dew point temperature (1.5 m height) between the experimental plot and the nearest standard weather station. However, at the same height the air temperature above wheat and barley is higher than that in the screen. In daytime, for wheat as well as for barley, the maximum difference between the calculated moisture content is 0.5 %, using the air temperature at 1.5 m height from the nearest standard weather station and the surface temperature of the ears. Barley had as a relatively high equilibrium moisture content during the night and a low one in daytime, and therefore a greater daily cycle in the moisture content of the grains than wheat.

The model for the calculation of the moisture content of cereals uses some crop parameters and standard (forecast) weather elements. Crop parameters used are: kind of cereals, yield and initial moisture content. Standard weather elements used are: air temperature, dew point temperature, global radiation, cloud cover, wind speed and quantity of rain. When drying, cereals lose free and absorbed water by evaporation and transpiration, respectively. Condensation and precipitation provide the grains with free water. Diffusion of free water from the reservoir in the grain provides absorbed water within the grains. The formula of Penman-Monteith is used as bases for the calculation of the moisture content. The minimum quantity of absorbed water of the grains depends on the temperature and dew point temperature of the surrounding air. This moisture content is called the equilibrium moisture content, and it is the amount of water in the grains which is bound too strongly to be evaporated. The maximum moisture content of the grains is 34% wet base.

Favourable agreement was found between the model calculation and the measured moisture content of cereals in the field. Usually forecast weather elements do not have exactly the same value as the corresponding past weather elements. A high moisture content of the grains can be due to a low air temperature, a low global radiation, a high dew point temperature, a high wind speed and precipitation. The quality of the moisture content forecasts of wheat and barley is decreasing with increasing time lag. Up to four days ahead the moisture content forecast is significantly useful.

Samenvatting

Deel 1

Het doel van dit onderzoek is de uurlijkse droging van gemaaid gras te verwachten tot vijf dagen vooruit . Eerst is het verband tussen het drogen van gemaaid gras en de weerselementen onderzocht. Een eenvoudig model en een meer geavanceerd model voor het drogen van gemaaid gras zijn ontwikkeld. Er is aandacht geschonken aan de fouten in de elementen van de weersverwachting die belangrijk zijn voor het drogen van gras.

Drie seizoenen lang is het drogen van gras in het veld vanaf het maaien tot aan het inkuilen bestudeerd. De experimenten zijn uitgevoerd op 16 verschillende velden die bij elkaar lagen. Elk uur zijn monsters van het gras genomen om het vochtgehalte te bepalen. Onderzocht zijn: diploïd en tetraploïd Engels raaigras (*Lolium perenne L.*) en diploïd gekruist raaigras (*Lolium perenne x Lolium multiflorum*) var. Barcolte. Mengels van verschillende typen Engels raaigras zijn gebruikt. Bij het maaien was het gras nog in het vegetatieve stadium. De invloed van maaitijdstippen en bewerkingsmethoden werden in het onderzoek betrokken.

Ten tijde dat de grasmonsters genomen zijn, werden er eveneens meteorologische metingen verricht. Luchttemperatuur (1,5 m), dauwpunt (1,5 m), oppervlaktetemperatuur van het gras, zwadtemperatuur en windsnelheid (2 m) zijn gemeten. Deze gemeten waarden zijn vergeleken met de uurlijkse waarden van het dichtstbijliggende standaardweerstation.

Niet alleen het weer, maar ook de grassoort en opbrengst spelen een rol bij het drogen van gras. Wanneer het gras 's morgens gemaaid wordt, is het vochtgehalte meestal 3 % hoger dan dat van gras wat aan het eind van de middag gemaaid wordt. Gekruist raaigras heeft bij het maaien een hoger beginvochtgehalte en droogt sneller dan Engels raaigras. Bij eenzelfde opbrengst drogen diploïde rassen sneller dan tetraploïde rassen. Binnen dezelfde grassoort verloopt het droogproces sneller naarmate de opbrengst lager is. Vaak schudden beïnvloedt de droogsnelheid niet.

De zwadtemperatuur komt overeen met de standaardluchttemperatuur op 1,5 m hoogte. De standaardluchttemperatuur op 0,1 m geeft een goede indicatie van de oppervlaktetemperatuur van het gras. Deze oppervlaktetemperatuur wordt grotendeels bepaald door de globale straling en reageert snel op de veranderingen, maar de temperatuur wordt ook beïnvloed door de windsnelheid en het vochtgehalte van het gras. Bij een laag vochtgehalte kan de oppervlaktetemperatuur van het gras gemakkelijk oplopen. Veel wind kan de droogsnelheid van het gras vertragen.

Het eenvoudig grasdroogmodel heeft geen gewasparameters, maar drie standaard (verwachte) weerselementen nodig: luchttemperatuur, dauwpunt en neerslaghoeveelheid. Bij droog weer wordt met behulp van het verzadigingsdeficiet het vochtgehalte van gras overdag van 10 tot 19 uur uurlijks berekend. In het model wordt aangenomen dat droging van gras vroeg in de avond en 's ochtends voor 10 uur gecompenseerd wordt door dauw die 's nachts gevormd wordt. Dit model geeft een indruk van het verwachte vochtgehalte van gemaaid gras.

Het geavanceerde model heeft enkele gewasparameters en standaard (verwachte) weerselementen nodig. Gebruikte gewasparameters zijn opbrengst en tijdstippen van maaien, schudden en harken. Gebruikte standaardweerselementen zijn: luchttemperatuur, dauwpunt, globale straling, bewolkingsgraad, windsnelheid en neerslaghoeveelheid. Er is geen onderscheid gemaakt in de verschillende soorten gras, waardoor het model algemeen gebruikt kan worden. Bij het drogen van gras wordt er vrij en gebonden water onttrokken door respectievelijk verdamping en transpiratie. Condensatie en neerslag verhogen het vochtgehalte van het gras. De formule van Penman-Monteith wordt gebruikt als basis voor de berekening van het vochtgehalte. In het model wordt het zwad opgedeeld in twee lagen, waarbij de massa van de bovenste laag constant wordt gehouden. Dus bij het drogen wordt de bovenlaag dikker door het toerekenen van drogestof en water uit de onderlaag.

De berekeningen van het geavanceerd model komen goed overeen met de gemeten vochtgehalten van het gras in het veld. Meestal komen de verwachte weerselementen niet precies overeen met de werkelijk opgetreden waarden. Fouten in de verwachte vochtgehalten van het gras worden meestal veroorzaakt door fouten in de verwachte luchttemperatuur, globale straling en neerslag. Fouten in de verwachte dauwpunten en windsnelheden spelen een minder belangrijke rol. In het algemeen is de verwachting van het vochtgehalte van gras één dag vooruit significant beter dan die voor meer dagen vooruit.

Deel 2

Het doel van het onderzoek is uurlijks het vochtgehalte van granen te verwachten tot vijf dagen vooruit. Eerst is het verband tussen standaardweerselementen en het microklimaat van tarwe en gerst tijdens de oogsttijd onderzocht. Een model voor het berekenen van het vochtgehalte van tarwe en gerst is ontwikkeld. Er is aandacht geschonken aan de fouten in de elementen van de weersverwachting die belangrijk zijn voor het vochtgehalte van granen.

Het vochtgehalte van rijpe gerst en tarwe (vanaf groeistadium DC 91) evenals de bijbehorende meteorologische elementen zijn gedurende drie oogstseizoenen gemeten. De experimenten zijn op drie verschillende plaatsen in Nederland uitgevoerd. In het veld zijn de volgende meteorologische elementen gemeten: luchttemperatuur, dauwpunt, oppervlaktetemperatuur van de aren en globale straling. De luchttemperatuur en het dauwpunt zijn op twee hoogten gemeten: ter hoogte van de aren en op 1,5 m hoogte boven de grond. De metingen zijn elk uur van 's ochtends vroeg tot 's avonds laat bij daglicht uitgevoerd. Deze gemeten waarden zijn vergeleken met de standaard meteorologische data van het dichtstbijliggende weerstation.

Zowel bij tarwe als bij gerst is geen significant verschil aanwezig in het dauwpunt (1,5 m hoogte) tussen de waarden in het veld en die van het dichtstbijliggende standaardweerstation. Echter op gelijke hoogte is de luchttemperatuur boven tarwe en gerst hoger dan die in de (standaard) weerhut. Zowel voor tarwe als gerst is het verschil tussen het berekende vochtgehalte maximaal 0.5 %, wanneer de standaard luchttemperatuur enerzijds en de oppervlaktetemperatuur van de aren anderzijds wordt gebruikt. Gerst heeft een hoger evenwichtsvochtgehalte in de nacht en een lager evenwichtsvochtgehalte overdag, en dientengevolge een grotere dagelijkse gang in het vochtgehalte dan tarwe.

Het model voor de berekening van het vochtgehalte van granen heeft enkele gewasparameters en standaard (verwachte) weerselementen nodig. Gebruikte gewasparameters zijn: graansoort, opbrengst en beginvochtgehalte. Gebruikte standaardweerselementen zijn: luchttemperatuur, dauwpunt, globale straling, bewolkingsgraad, windsnelheid en neerslaghoeveelheid. Bij het drogen verliezen de graankorrels vrij en geabsorbeerd water door respectievelijk verdamping en transpiratie. Condensatie en neerslag vullen de graankorrels met vrij water. In de graankorrels kan het geabsorbeerd water toenemen door diffusie van vrij water uit het reservoir in de korrel. De formule van Penman-Monteith wordt gebruikt als basis voor de berekening van het vochtgehalte van de graankorrels. De minimum hoeveelheid geabsorbeerd water in de graankorrels hangt af van de temperatuur en het dauwpunt van de omringende lucht. Dit vochtgehalte wordt het evenwichtsvochtgehalte genoemd, het is de waterhoeveelheid in de korrels die te sterk is gebonden om te kunnen verdampen. Het maximale vochtgehalte van het graan is 34 % (natte basis).

De modelberekeningen komen goed overeen met de gemeten graanvochtgehalten in het veld. De verwachte weerselementen komen meestal niet precies overeen met de werkelijk opgetreden waarden. Een hoog graanvochtgehalte kan veroorzaakt worden door een lage luchttemperatuur, een lage globale straling, een hoog dauwpunt, een hoge windsnelheid en neerslag. Een langere verwachtingsperiode verlaagt de kwaliteit van de verwachting van het vochtgehalte van tarwe en gerst. Tot vier dagen vooruit is de verwachting van het graanvochtgehalte significant beter dan voor een langere verwachtingsperiode.

Curriculum vitae

Aafke Jantine Atzema werd geboren op 27 september 1959 op een Oldambster boerderij in Weiwerd (gem. Delfzijl). In 1975 behaalde zij haar MAVO-diploma in Delfzijl en in 1977 volgde het HAVO-diploma in Appingedam. Na een jaar met goed gevolg de lerarenopleiding "Ubbo Emmius" in Groningen met de vakken Wiskunde, Natuurkunde en Scheikunde achter de rug te hebben, ging zij naar de Hogere Landbouw School in Groningen. Met dit diploma op zak toog zij naar Wageningen. Haar interesse ging vooral uit naar Landbouwtechniek, Meteorologie en Planteziektenkunde. Nadat zij de sfeer in Wageningen had geproefd, begon zij in 1983 aan de studie Planteziektenkunde aan de toenmalige Landbouwhogeschool in Wageningen. Na een volledige studie met als hoofdvakken Meteorologie en Fytopathologie studeerde zij in november 1987 af. In februari 1988 werd bij de toenmalige vakgroep Natuur- en Weerkunde (thans vakgroep Meteorologie) van de Landbouwhogeschool (thans Landbouw Universiteit) begonnen met het promotieonderzoek, waarvan het resultaat nu voor u ligt. Naast dit onderzoek werkt zij vanaf maart 1988 bij het particulier weerbureau Meteo Consult in Wageningen. Bovendien werkt zij met veel plezier op het ouderlijk akkerbouwbedrijf met de granen als hoofdgewas.