An exploratory study to improve the predictive capacity of the Crop Growth Monitoring System as applied by the European Commission

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PROEFSCHRIFT

ter verkrijging van de graad van doctor
op gezag van de rector magnificus van Wageningen Universiteit,
Dr. C.M. Karssen,
in het openbaar te verdedigen op
vrijdag 7 januari 2000
des namiddags te 16.00 uur
in de Aula

door

Iwan Supit

DATA KONINKLIJKE BILIBLIOTHEEK, DEN HAAG

Supit, I., 2000.
An exploratory study to improve the predictive capacity of the Crop Growth Monitoring Systems as applied by the European Commission.
Doctoraal thesis, Wageningen University, Wageningen, The Netherlands, - With ref. – With summary in Dutch – 184 pages, 33 figures and 28 tables.

Keywords: production volume, prediction, wheat, solar radiation, aggregation, sowing dates, CGMS, simulation.

ISBN 90-5808-185-0 (this version)
ISBN 90-80 4443 –5-9 (distribution)

About the cover:

The author's impression of his own mental state when trying to locate the Tantiem, during Tai Chi practice.

Research described in this thesis took place at the Joint Research Centre, Ispra, Italy and was sponsored by the European Union. Other sponsors were PRIVATEERS N.V., TREEMAIL and EKOKON Nusantara.

Stellingen

1) Bij het voorspellen van de tarweopbrengst op nationaal niveau moet men er rekening mee houden dat veranderingen in de opbrengst niet evenredig zijn met de veranderingen in het areaal.

2) Voorspellingen met het *Crop Growth Monitoring System* (CGMS) van de tarweopbrengst op nationaal niveau zullen nauwkeuriger worden wanneer nauwkeurige en vooral snelle methoden om actueel landgebruik vast te stellen ontwikkeld worden.

3) Simpele voorspellingsmodellen zoals bijvoorbeeld een lineaire tijd-trend kunnen soms nauwkeurigere voorspellingen opleveren dan meer gecompliceerde modellen. Het voordeel van simpele modellen is dat zij minder investeringen behoeven.

4) Om aan te tonen dat het CGMS betrouwbare voorspellingen oplevert, moeten de resultaten van dit systeem met betrouwbare officiële opbrengstgegevens vergeleken worden. Het is dus noodzakelijk dat deze officiële statistieken voor alle landen van de Europese Unie op een consistente en goed gedocumenteerde manier verzameld worden.

5) De resultaten van simulaties van water-gelimiteerde productie uitgevoerd in CGMS dragen niet bij tot de voorspellingsnauwkeurigheid van tarweopbrengst op nationaal niveau in Noord-West Europa omdat in dat gebied de opbrengsten vooral bepaald worden door de kunstmestgift, temperatuur en globale straling.

6) Het is beter eerst te voorspellen en daarna te aggregeren dan andersom.

7) In semi aride gebieden rond de Middellandse Zee wordt de zaaidatum van regenafhankelijke gerst mede bepaald door de verwachte aanvang van het regenseizoen.

8) Het Italiaanse gezegde "è fatto dal muratore" geeft aan dat de kwaliteit van de Italiaanse huizen niet geweldig is.

9) De administratie en het personeelsbeleid van het Joint Research Centre van de Europese Unie leveren geen enkele bijdrage aan het scheppen van voorwaarden voor een soepele voortgang van projecten.

10) Werken in een ontwikkelingsland is een goede voorbereiding voor het werken voor de Europese Commissie.

Stellingen behorende bij het proefschrift: "An exploratory study to improve the predictive capacity of the Crop Growth Monitoring System as applied by the European Commission".

Wageningen, 7 januari 2000 Iwan Supit

Preface

The first time I heard of the Joint Research Centre (JRC) of the European Union (EU) in Ispra was when I worked in Bangladesh. I received a phone call from Derk Rijks, the chief of the Agrometeorological Department of the World Meteorological Organisation (WMO). He asked me if I was interested to work for WMO with JRC in Ispra. I did not know where Ispra was located and I had never heard anything about JRC. The only thing I knew was that an institution like the EU existed and that "interesting" things happened in the EU projects in Bangladesh.

I knew Derk Rijks from my days in Niger and Ecuador and the prospect to cooperate with him sounded rather attractive. I had to collect global radiation data from as many data sources in Europe as possible, and secondly, I had to identify methodologies to estimate daily global radiation from cloud observations. The only problem was that I lived in Bangladesh and part of the job had to be performed in Ispra. Consequently, I had to fly several times from Bangladesh to Italy because the digital highway in Bangladesh was a mere dirt road, a result of the rather bad telecom system in combination with the heavy rains.

In Ispra I collaborated with Paul Vossen, who at that time worked with the MARS project. At the end of my contract he offered me another small contract and then again another small one. After several small contracts he asked whether I was interested to do a Ph.D. in Ispra. Thank you, Paul, to ask me to write a thesis! I would never have done it if you had not asked me to do it! Thank you, also Dr. Rijks, for helping me with the first unsteady steps in the field of science.

To enter the JRC site in Ispra, I had to complete an awful lot of forms, write a proposal and find a University that would accept me as a Ph.D. student. Also I had to look for two supervisors who could guide me through the process of becoming a Doctor. Herman van Keulen (Group Plant Production Systems, and AB-DLO) and Michiel Jansen (Centre for Biometry, CPRO-DLO) became my supervisors for the Agricultural University Wageningen, Paul Vossen became the supervisor in Ispra. On December 1, 1994, 10 years and 3 months after I graduated from the Agricultural University, I became a "borsista", or a student, again. The first thing I had to do was to rewrite my proposal, since it was not exactly what JRC had in mind. They wanted me to improve their Crop Growth Monitoring System in such a way that it could be used for quantitative yield forecasting for various crops and for all the EU member states.

Unfortunately, Paul Vossen left Ispra after my first two years there. He was not replaced and I was left without a supervisor in JRC. Remained my supervisors in Wageningen. I am heavily indebted to them. They showed me what science is about and they maintained a scientific life-line. They were the only few people who honestly said that what I wrote was pretty close to ****. Not in these exact words, however, it came close. And to tell the truth, they were right! The first trials to write a paper were not readable and my supervisors undoubtedly had a hard time trying to understand what I wrote. However, being told that what I wrote was ****, was not exactly a new sensation to me. Several members of the Dutch Embassy in Bangladesh held a similar opinion. According to those people, everything I wrote in the magazine of the Dutch Club was complete nonsense and had to be censored. Threats to send my writings to the Ministry of Foreign Affairs (which according to insiders they really did???) or to throw me out of the Embassy did not stop me. As with that Dutch Club magazine, I kept trying with my thesis and I can assure that it was difficult. The scientific prose is completely different from the language used in that particular magazine. The hardest part was being serious.

Writing a thesis was not an easy job and I want to thank all those persons who stimulated me intentionally or unintentionally to keep writing. I would like to thank my wife and children for showing me that life is the only thing that counts. Finally, I would like to thank the European taxpayer for supporting me for three years, and for providing me with a huge salary and JRC for providing me with a desk, a chair and a PC with an internet connection. Special thanks to the boys from Privateers N.V. and Treemail, who always reminded me that I was the last one of the team who was not a Dr. Not anymore, boys!

Contents

1. General Introduction

Large area yield forecasting prior to harvest is of interest to government agencies, commodity firms and producers (Boote *et al.*, 1996). Early information on yield and production volume may support these institutions in planning transport activities, marketing of agricultural products or planning food imports. Moreover, at world scale, agricultural market prices are affected by information on the supply or consumption of foodstuffs (Marcus & Heitkemper, 1994). Market price adjustments or change in agricultural supplies in one area of the world often causes price adjustments in other areas far distant. The European Union (EU), through its Common Agricultural Policy (CAP), attempts to regulate the common agricultural market (e.g. set-aside regulations, export subsidies, etc.) to, among others, secure food supplies and provide consumers with food at reasonable prices.

The Directorate General for Agriculture (DG VI) of the EU is responsible for implementation and control of the CAP regulations. To manage the common agricultural market, to evaluate the consequences of these regulations as well as to estimate the subsidies to be paid, DG VI requires detailed information on planted area, crop yield and production volume (De Winne, 1994). The main crops of interest are wheat, barley, oats, grain maize, rice, potato, sugar beet, pulses for human consumption, soybean, oilseed rape, sunflower, tobacco and cotton.

Information on land use, land use changes and yields is routinely collected by various national statistical services that convey this information to the statistical office of the European Commission, EUROSTAT. Collection and compilation of these agricultural statistics is time consuming and laborious. In exceptional cases, these statistics are available some months after the season has ended, however, as a rule, it takes one or even two years before this information is available in the EUROSTAT databases. Consequently, at this stage these statistics are of limited use for evaluating policy or to estimate the amount of subsidies to be paid. Hence, more timely and accurate information is needed.

To support DG VI in executing its tasks, in 1988 the Monitoring Agriculture with Remote Sensing (MARS) project was initiated with the objective to generate monthly information on land use, land use changes, exceptional growing conditions such as water stress and expected yields. This information has to be provided for various crops for all member states of the EU. To realize this objective, the MARS project uses field surveys, high and low resolution satellite data and a crop growth simulation model, which in combination with a Geographical Information System (GIS) comprise the Crop Growth Monitoring System (CGMS). Remote sensing provides information on land use, inter-annual land use changes, area planted to various crops and possible occurrence of water stress, excess of water or (crop) diseases. The results of the field surveys are, amongst others, used to validate the satellite-derived information, and to gather information on fertilizer and irrigation application. These surveys also yield information on sowing dates and crop yields. CGMS provides information on crop status (i.e. water stress, biomass production, etc.) in the course of the growing season, and crop yield at the end of the season. Meteorological observations, soil and crop information are used as input. Examples of the use of simulation models for analysis of management practices and policies can be found, amongst others, in Kruseman & Bade (1998), van Keulen *et al.* (1998), Abrecht & Robinson (1996), Littleboy *et al.* (1996), Muchow *et al.* (1994), Bakema *et al.* (1994), Jørgensen (1994), Baird *et al.* (1993), Hodges *et al.* (1987) and Williams *et al.* (1984).

The Agriculture and Regional Information Systems (ARIS) unit of the Space Applications Institute (SAI) executes the MARS project that initially was set to last 10 years. It was divided in 2 stages of 5 years each. In the period 1988-1993 the methodology was developed and data necessary to execute the project collected. These data included information on land use, crops, yields, meteorological conditions, soil types and crop characteristics, necessary to run the crop monitoring system. In the second phase (1993-1998), the remote sensing methods were to be integrated into CGMS and the developed methodology had to be refined. Various researchers and research groups participated in the development and refinement of the methodology. In Chapter 2, the MARS project and its history are described.

This study started in December 1994, the second phase of the project. The objective was to explore methods to improve CGMS to make it applicable for quantitative yield prediction for all major crops and for all EU member states. CGMS until then had been used for a qualitative assessment of crop growth and development. During the growing season analysis, of CGMS results took place every 10 days. This information was processed into a monthly bulletin. It was assumed that changes in above-ground dry matter, leaf area, etc. and the onset of stress situations in consecutive 10-day periods could be observed on remote sensing images and in the CGMS output. Shorter periods were not feasible since it took several days to collect, correct and introduce the data in the initial versions of CGMS and analyze the results. In Chapter 3, CGMS, the input data, databases and the current operational yield forecasting method are described.

To provide reliable forecasts for all EU member states, insight in the production system of various crops is necessary. However, because of limited available means and manpower it was decided to concentrate mainly on wheat and barley. In Chapters 4, 5 and 7 wheat is considered, the most important cereal grown in the EU in financial terms and in the total production volume. Worldwide, wheat constitutes approximately 30 per cent of the total cereal production (FAO, 1992). Furthermore, this crop has been subject of extensive research and it is the only crop for which the crop growth parameters that are used in CGMS, have been calibrated using data from field experiments (Boons-Prins *et al.*, 1993). Insight gained in the present study may form the basis for adapting the crop growth monitoring system and its necessary input data for other crops. In Chapter 8 barley is studied since abundant field survey data were available in the examined region.

The year-to-year variation in yield and production volume is, amongst others, influenced by meteorological conditions and farming practices, such as crop rotation (e.g. Christen & Hanus, 1993; Ball & Miller, 1993; Christen *et al.*, 1992), type, method and timing of application of fertilizers (e.g. Mahler *et al.*, 1994; Mossedaq & Smith, 1994), pest management (e.g. Buhler *et al.*, 1995; Young *et al.*, 1994), etc. These practices vary in time and space in dependence of the techniques available, their interactions with weather and the flexibility of farmers to adopt innovations. As a result of these innovations the yield per unit area has increased during the last decades. This yield increase is referred to as technological trend. According to, amongst others, Young *et al.* (1994), Christen & Hanus, (1993) and Knowles *et al.* (1991), introduction of these innovations, and consequently of the occurrence of this trend, may be driven by agricultural policies, set by the local government or by the EU, market prices and subsidies, etc.

The operational verson of CGMS (see Section 3.6) assumes that the wheat yield per hectare, in any given year, is the sum of the expected wheat yield due to the average technological trend, variations from the technological trend curve due to weather variations plus an unexplained part (Odumodu & Griffits, 1980). The technological trend is described as a linear function of time. However, this function may not account for breaks in the trend in the yield series as a result of decreasing crop prices or increasing input prices. To account for these economic influences the following parameters are explored as trend functions: wheat selling prices, intervention prices, expenditure on crop protection agents and finally the fertilizer consumption per unit area (Chapter 4).

Furthermore in this chapter possible adaptations to the prediction model as applied in CGMS are explored. One of the goals of the MARS project is to predict production volumes for various crops and for each EU member state. Its basic assumption is that the production volume can be separated in a yield and a planted area component, which are estimated independently and subsequently multiplied. In this chapter the following assumption is investigated: the annual planted area and yield per unit area cannot be considered independent and should therefore be analyzed simultaneously. To test this hypothesis, planted area is included in the prediction model.

In Chapter 5 the hypothesis explored in Chapter 4 is further investigated. Soft and durum wheat production volumes are predicted for 12 EU member states and compared to the official yield and production statistics. The trend is described as either a function of time or a function of fertilizer consumption per unit area. To investigate whether simulation results improve the prediction accuracy, the predictions are also performed using trend functions only.

As described in Chapter 3, CGMS needs daily meteorological data as input. Global radiation is one of the driving forces. As this parameter is not measured at all stations and also irregularly broadcast via the Global Telecommunication System (GTS), alternative methods to derive this information have to be developed. In the current, operational version of CGMS the equation proposed by Ångström (1924) and modified to its present form by Prescott (1940), based on sunshine duration, is applied. The constants used in this equation are estimated as a function of latitude (Choisnel *et al.*, 1992).

As sunshine duration observations appeared not to be generally available, studies were executed in the first phase of the MARS project to identify alternative methods that could be used to estimate global radiation. These methods had to be simple and preferably should be based on cloud cover data, assuming that this information could be obtained via GTS or, alternatively, retrieved from remote sensing imagery. At the initiative of the project management, the method developed by Supit (1994) in the first phase of the MARS project was investigated (Chapter 6) and incorporated in CGMS. This method uses cloud cover data and a temperature range as input.

In Chapter 7 the results of Chapter 5, which suggest that the prediction level may influence prediction outcome, are examined. The models tested in Chapter 6 assume that variation in yield as a result of weather variation is similar in high production systems and low production systems. Research of Valdez-Cepeda (1993) suggests that variation in wheat yields over the years is proportional to the mean yield level. In this chapter this suggestion is explored. National production volumes of France are predicted either directly, or at regional and subregional level and subsequently summed to national values. Furthermore, prediction results established with the alternative method to estimate global radiation (Chapter 6) are compared with those obtained with the operational method. France was selected because it has reliable yield and production statistics at national, regional and subregional level. Furthermore, it accounts for approximately 40% of the total EU soft wheat production (Bradbury, 1994).

As mentioned earlier, in the framework of the MARS project field surveys are also carried out. These surveys yield information on land use, inter-annual land use changes, sowing dates, flowering dates, input use and yields. The land use information is used to estimate the area planted to various crops from which the land use changes are derived. The other information (such as yields, fertilizer application) is not used, however, it could be used to evaluate simulation results or to test assumptions. In Chapter 8, field survey data are analyzed with the aim to obtain indications whether in a semi-arid environment, sowing date variations of cereals grown under rainfed conditions result in significant yield variations. This information in turn may indicate whether in such environments sowing date variation should be accounted for in the applied yield forecasting system.

2. The MARS Project

2.1 The Common Agricultural Policy: a historical overview

In June 1960 the European Commission submitted a set of proposals to the Council of Ministers of the European Union with respect to the creation of a Common Agricultural Policy (CAP). Six months later, the first decisions to implement the CAP were taken. A year later, January 1962, the general orientations of the CAP were established, based upon the principles of (Fearne, 1997):

- A single agricultural market;
- Community preference, i.e., the competitiveness of farmers in the Community should not be threatened by third country imports;
- Financial solidarity and expenses have to be financed by the Community's own resources.

These three principles have been adhered to throughout the CAP´s existence and have been consistently defended by the Commission (Ritson & Fearne, 1984).

The CAP has been the most important Common Policy and a central element in the European Union's institutional system. It has served as a basis for the common market that ensures free movement of goods, services, capital and people in the member states of the Union. It is part of the political and economic cement that holds together the different parts of the Community. The objectives of the CAP, as set out in Article 39 of the Treaty of Rome were:

- to increase productivity
- to ensure a fair standard of living for the agricultural community
- to stabilize markets
- to guarantee food supplies
- to provide consumers with food at reasonable prices.

The CAP was created at a time when Europe was deficient in most food products and its mechanisms were designed to remedy that situation. The CAP supported internal prices and incomes, either through intervention and/or border protection (i.e. import tariffs). Where no border protection existed, variable subsidies (i.e. deficiency payments) were paid to farmers and processors of agricultural products from within the community. Furthermore, through the CAP attempts were made to provide farmers with a guaranteed income and to attain self-sufficiency for the most important agricultural products, such as cereals, milk and beef (de Bont, 1990).

Until the mid-1990s, the CAP was by far the most important EU policy instrument, especially in budgetary terms. The system that was appropriate in a deficit situation showed weaknesses as the Community moved towards a surplus situation for most agricultural products. Between 1973 and 1988, the volume of agricultural production in the EU increased by 2% annually, whereas internal consumption grew by only 0.5% per year. The self-sufficiency percentage for wheat in the EU, for example (i.e. percentage of the total EU requirement covered by internal EU production) increased from 90 % to 146% in the period 1972-1985 (Meester & Strijker, 1990). Moreover, changes in cattle fodder, with livestock increasingly fed on imported oilseeds, corn-gluten and cassava further stimulated cereal surpluses (Folmer *et al.*, 1993). This increment resulted in build-up of expensive surpluses in certain sectors, with depressing effects on market prices. In the period 1975-1987, the total expenditure of the European Agricultural Guarantee Guideline Fund (EAGGF) increased with 122% (CEC, 1987). In this context it is interesting to note that, according to Oskam & Stefanou (1997), a causal relation between the CAP and this production increase cannot unequivocally be established. In their analysis of the CAP market and price policy, these authors state that "it seems probable that the CAP has on balance stimulated productivity growth in agriculture, although this conclusion is very weak."

As was already foreseen by Mansholt at the Stresa conference in July 1958, tensions in the relations with various trading partners grew as a result of the impact of EU subsidized exports on their world market share and on world market prices (Fearne, 1997). Moreover, the intensive production techniques resulted in negative environmental effects in various regions (Ceccon *et al.*, 1995; de Wit, 1988). Furthermore, the system did not sufficiently support the incomes of the majority of small and medium-size family farms. This situation was difficult to accept in view of the ever-increasing costs of the EAGGF. In short, by the late 1980s, there was general agreement that reform was necessary (de Wit *et al.*, 1987). The CAP structure that was suitable for the 1960s and performed well into the 1970s showed serious weaknesses in the 1980s. Therefore, the European Union's Council of Agriculture Ministers in June 1992 reformed the CAP:

- To ensure competitiveness of Community agricultural production, over a three-year period, EU prices in the agricultural sector were to be reduced to come much closer to world market levels.

- To preserve the economic viability of farmers, they received compensatory payments on a historical basis for the reductions in EU support prices.
- To reduce the production volume for cereals and other arable crops farmers received compensatory payments depending on the withdrawal of land from production (the "set-aside" premium). This has proved to be an effective production control tool.

The European Union also agreed on a set of complementary agri-environment, afforestation and early retirement measures. The agri-environment measures aimed at introduction of less intensive production methods leading to reduced impact on the environment.

2.2 *The EU's agricultural budget*

Since the creation of the CAP the EAGGF has been the biggest single item in its budget. The CAP resources are provided by the member states, irrespective of who will benefit most from the expenditures on agriculture. Each national contribution is determined by the economic performance of the member state. In addition to national contributions to the Community budget, revenues are also obtained from customs duties levied on imports from non-EU countries. The CAP itself also generates revenue, in the form of the duties on farm trade and the sugar levy.

The EAGGF consists of two parts, the Guarantee Section and the Guidance Section. The Guarantee Section finances the price and market policy, including CAP reform, compensatory payments and the accompanying measures. By far the largest part of EAGGF expenditure is the Guarantee Section - about 90% in 1995 - of which about half is being spent on direct payments to farmers. The Guidance Section contains the Community resources allocated to the subsidies for modernization of holdings, installation premiums to young farmers, subsidies for marketing, diversification, etc.

The EAGGF is a constant focus for debate when the Council and the European Parliament are taking decisions on the Community budget. In 1980, the EAGGF absorbed about 70% of the total EU budget (Le Roy, 1994). Control of agricultural expenditure is therefore a key objective of EU policy: in 1993 the proportion was reduced, however, it was still around 52% (Le Roy, 1994).

2.3 *MARS Project: history and activities*

2.3.1 *History*

Within the European Commission, the Directorate General for Agriculture (DG VI) is responsible for implementation of the CAP regulations, for evaluation of their consequences and for EAGGF control. According to De Winne (1994) collection of national and regional statistics on land use, land use changes and agricultural production is a prerequisite for this evaluation and control. This information may also provide insight in farmers' reactions to changes in the CAP and it allows estimating costs of the compensation payments for taking land out of production. Furthermore, De Winne remarked that early and accurate estimates of yield expectations are necessary for management of the common markets, for evaluation of the intervention measures and for developing the EU's agricultural policy in relation to the world market.

Information on land use, inter-annual land use changes and yields is routinely collected by various national statistical services, which convey this information to the statistical office of the European Commission, EUROSTAT. However, collection and compilation of these agricultural statistics is time consuming. In exceptional cases, these statistics are available some months after the end of the season, however, generally it takes one or even two years before this information is available in the EUROSTAT databases.

To assist DG VI and EUROSTAT in executing their tasks (i.e. EAGGF control, evaluation of the CAP effects on agriculture, collection of agricultural statistics), the Council of Ministers of the EU on 26th September 1988 approved a ten-year research and pilot project. Its main objective was to develop methods to produce timely statistics on land use, planted areas, and production volumes of various crops within the EU, using remote sensing techniques. This project is commonly referred to as the MARS project (Monitoring Agriculture with Remote Sensing). The Agriculture and Regional Information Systems unit (ARIS) of the Joint Research Centre (JRC) of the EU is responsible for its implementation. Approximately 100 institutions from 17 European countries have provided inputs to the MARS project (Vossen, 1994).

The techniques had to be developed to a stage where they could be put into operational use and had to be tested on large areas. The crops targeted were those with the biggest market share, excluding those consumed on the farm.

The project priorities were to produce:

- inventories of land use and land use changes
- inventories of agricultural production
- production forecasts

The MARS project was divided in two stages. In the period 1988 - 1993 two basic systems for crop state monitoring and yield forecasting had to be designed and implemented. One of these systems was to be based on observations at the earth's surface, using agrometeorological models and ground surveys. The other system had to use information provided by low and high resolution earth observation satellites. By the end of 1993 the first results had to be available. In the period 1994-1998 the system had to be improved and the two systems were to be integrated. Improvements anticipated were, amongst others, improved techniques for interpolation of rainfall data and the use of satellite derived data as input for agrometeorological models. To reach the objectives within the given time frame, the following strategy was proposed for the first stage (Meyer-Roux & Vossen, 1994):

- No new fundamental research would be carried out. Existing research results would be adapted for use at European scale. System refinement on the basis of more fundamental research would be realized in the second phase (1994-1998).
- Co-ordination would be the responsibility of as small a team as possible, taking full advantage of knowledge and experience available in other institutions and private companies in various member states.
- As proven methods that relate satellite imagery to quantitative crop yield forecasts at national level were not yet available, crop yield forecasting, at least in the initial stages of the project, would be based on agrometeorological crop growth simulation models.
- The use of remote sensing techniques to improve the precision and spatial resolution of outputs would be investigated in the second phase.

2.3.2 The main activities related to the MARS project

One of the main activities was the regional crop inventory: quantitative estimation of the area planted to various crops. The applied methodology consisted of the combined use of a limited number of ground observations and of high resolution satellite data (SPOT and Landsat-TM). Observations in sample areas were regressed on satellite observations and subsequently the regression results were used to estimate crop area from satellite data. Yield information was obtained through interviewing farmers. This activity was executed by national organizations, until 1993 in cooperation with JRC. On this activity, Vossen (1994) remarked that the applied method is "not to be recommended per se, not for reasons of technical feasibility, but because it requires too big an effort to implement...". Although JRC's participation came to an end, the ARIS unit continued to investigate methods to obtain planted area estimates for various crops, using radar satellite information (e.g. Lemoine & Kidd, 1998).

A second activity that is still on-going is qualitative monitoring of crop status and providing warnings in case abnormal growth conditions are observed, using data derived from the NOAA-AVHRR meteorological satellites. The most frequently used satellite-based indicators are vegetation indices and dynamics of the vegetation water status throughout the year. These indices can be applied as qualitative indicators for biomass development and consequently crop yield. In theory, the spatial resolution of these data is 1 x 1km, however, in practice the resolution is lower due to panoramic distortion as a result of sensor design and curvature of the earth. Data interpretation may cause additional problems, as a result of clouds and variable atmospheric water and aerosol content.

A third activity was the development, testing and implementation of a system that could produce timely yield forecasts per country and/or large region and that could also be used for crop state monitoring. This system had to account for weather and soil moisture influences on crop growth and development, assuming that as a result of these characteristics, it could produce more accurate predictions than the system applied by EUROSTAT, which is based on linear and quadratic trend functions. These forecasts had to be accurate at national level and possibly also at regional level. The system had to produce cartographic output of the spatial variation in crop growth parameters, and differences in those parameters with respect to the previous year or the mean over the past years. This output had to be produced at 10-day intervals, assuming that changes in crop growth and development, as well as the onset of stress situations can be identified on remote sensing images and in CGMS output, obtained in consecutive 10-day periods. CGMS was developed in the first stage of the MARS project. In the second stage the project objective was to refine CGMS, using amongst others remote sensing information as input.

This study was executed in the framework of this third activity with the aim to explore possibilities to refine CGMS in such a way that it could be used for quantitative yield forecasting. In the next chapter a description of CGMS is presented.

The objective of the last activity is the rapid estimation of changes in planted area relative to the preceding year of the major crops in the EU. In the framework of this activity 60 test sites (40 x 40 km) in 13 countries have been selected. To facilitate agricultural land use classification using satellite images, the test sites were selected in such a way that they coincided with a complete image of the SPOT satellite. Within each test site, 16 segments (1.4 x1.4 km) were selected. SPOT and alternatively Landsat-TM imagery were used for classification. Through photo- interpretation and field surveys within these 16 segments crop species are linked to the classes identified on the basis of satellite imagery and subsequently the planted areas are estimated. Year-to-year changes in planted area are extrapolated to European scale. The field surveys also provide information on yields, sowing dates of various crops and crop management, such as fertilizer and irrigation application. At the moment of writing of this thesis, this activity still continues.

3. The Crop Growth Monitoring System

3.1 Introduction

JRC requested the Winand Staring Centre (SC-DLO) and the Centre for Agrobiological Research (AB-DLO) in Wageningen, The Netherlands, to develop, adapt and calibrate new or existing agro-meteorological simulation models for:

- 10-day routine quantitative forecasting of national and regional yields (per unit area).
- Qualitative monitoring of the growth conditions for the whole EU for the following crops: wheat (spring, winter, soft and durum), oats, grain maize, rice, potato, sugar beet, pulses, soybean, oilseed rape, sunflower, tobacco and cotton. (Olives and grapes were covered by another subproject).

The WOFOST crop growth simulation model was selected (see Section 3.3) and linked to a GIS and a yield prediction routine to form CGMS. For each of the crops included in CGMS, standard values for crop parameters were collected representing region specific crop growth characteristics. Insufficient data were available for oats, tobacco and cotton, and consequently these crops were omitted.

Figure 3.1 presents a schematic overview of CGMS; three levels can be distinguished. The first level is the weather system. Historical and actual weather data are collected, corrected and subsequently interpolated to a 50 x 50 km grid, covering the whole of the EU. Historical, actual and interpolated data are stored in a database. The interpolated data are subsequently introduced in WOFOST. Maps of 10-day and monthly total precipitation, calculated evapotranspiration, temperature sums, 10-day and monthly totals of observed global radiation, etc. are produced, as well as maps indicating the deviation of these characteristics from a long time average value. Figure 3.2 presents a schematic overview of the weather system (Level 1). At the second level, crop growth simulation takes place (Figure 3.3). Interpolated data obtained at Level 1 are used as input for WOFOST. In addition to weather data, crop characteristics and soil information are needed.

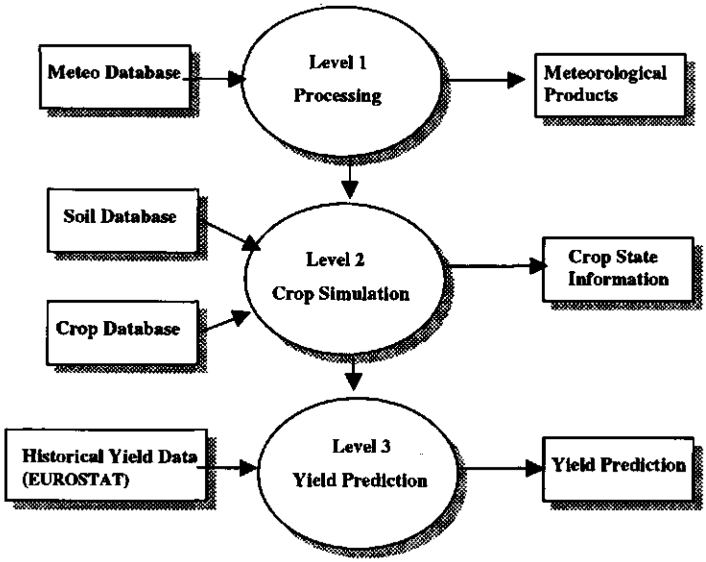

Figure 3.1. *Schematic overview of the Crop Growth Monitoring System.*

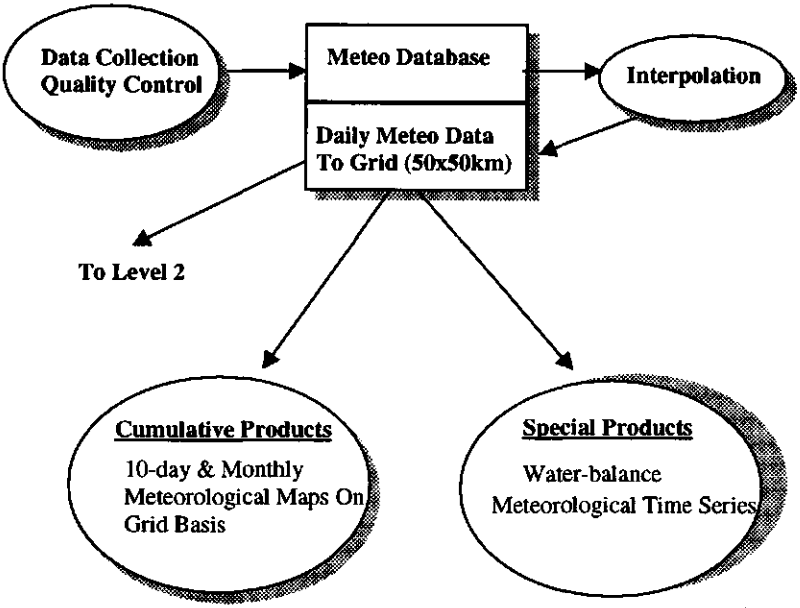

Figure 3.2. *Schematic overview of Level 1*

In Subsections 3.2.3 and 3.2.4 the crop and soil databases linked to CGMS are described. Simulations are performed per Elementary Mapping Unit (EMU), which is the intersection of a Soil Mapping Unit (SMU, see Subsection 3.2.4), a grid cell and an administrative region. The administrative regions are called Nomenclatures des Unités Territoriales Statistiques (NUTS). Simulation results are subsequently aggregated to subregional, regional and national level (see Section 3.4). In the current operational version of CGMS, simulation results are aggregated to national level and the national yield per unit area is predicted (Level 3, see Figure 3.4).

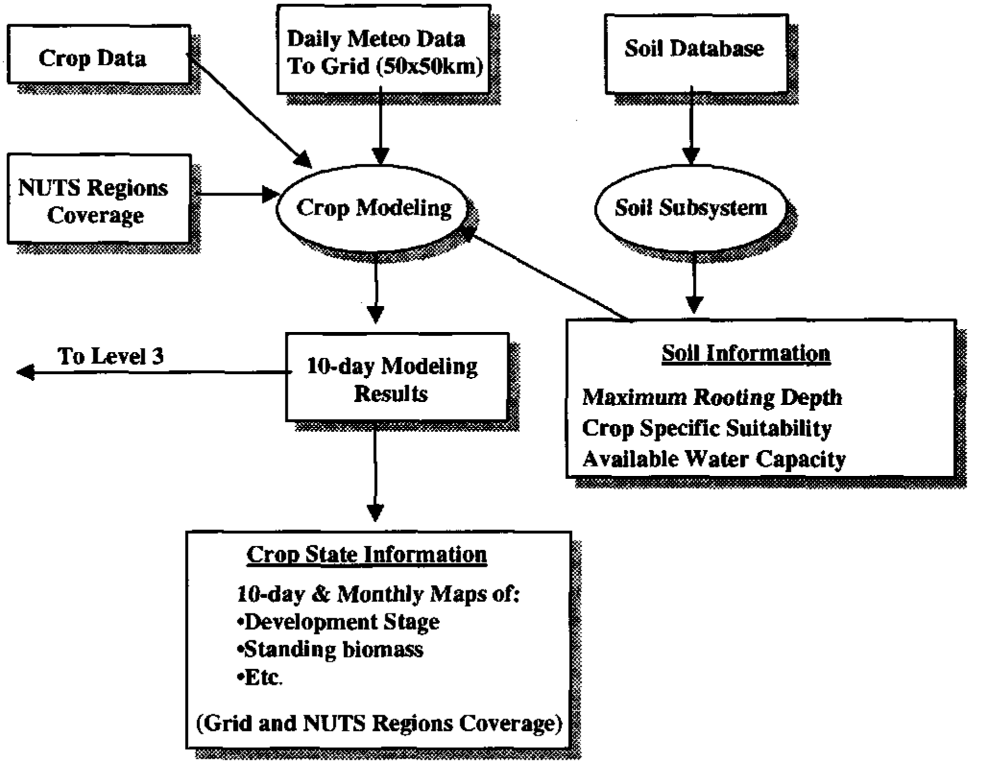

Figure 3.3. *Schematic overview of Level 2*

Various simulation results are regressed on historical yield observations. The simulation result yielding the highest coefficient of determination is selected as predictor and subsequently introduced in the prediction routine. In Sections 3.6 and Subsection 5.2.4, the prediction model and the applied prediction method are described, respectively. Yield and production volume prediction are performed every 10 days. (see Section 3.7).

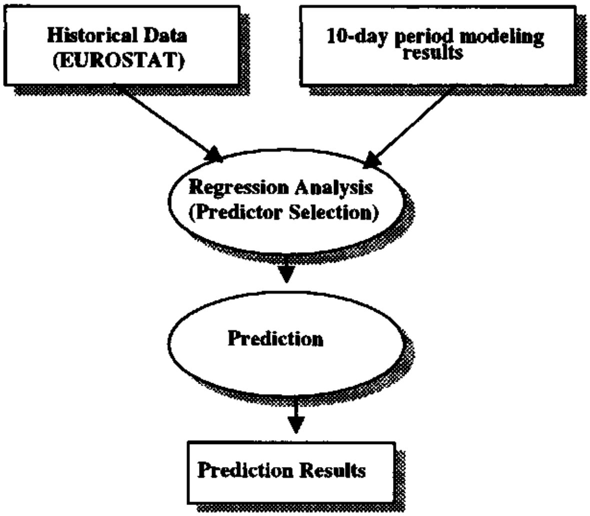

Figure 3.4. *Schematic overview of the prediction system (Level 3)*

3.2 Data and databases

One of the goals of the MARS project was to develop an operational system to forecast production volumes of various crops at European Union level, CGMS. For development of this system, it was essential to identify useful parameters that are measured across Europe and to check whether they are available at such a resolution that they could be used for regional crop growth modeling. For static variables, such as soil characteristics and long-term mean meteorological variables, existing data had to be inventoried to assess the possibility to compile and harmonize this information across the EU. For dynamic parameters, such as daily weather variables, data had to be limited to those that were regularly collected and could be received and processed in semi real time.

Based on these criteria a set of available input data was defined, consisting of historical daily meteorological data from approximately 380 stations, current season daily weather data from about 700 stations, topography at a 5 minute grid, regional crop parameters, historical crop statistics per administrative unit and the EU soil data base at a scale of 1,000,000. Compilation of the identified parameters and development of the MARS databases proceeded in parallel with the development of CGMS. Arc/Info and Oracle were selected as management tools for spatial and tabular data, respectively.

3.2.1 Meteorological data

Meteorological data used at Level 1 are received from the Global Telecommunication System (GTS) of the World Meteorological Organisation (WMO). The meteorological database is composed of three Oracle tables: STATIONS, METDATA and GRIDWEATHER. These tables contain information on the meteorological stations, daily meteorological data and interpolated data, respectively. The station information stored is WMO number, station name, longitude, latitude and altitude.

The METDATA table contains the meteorological observations obtained via GTS, comprising 29 different parameters, including various indicators for cloud cover, temperature and vapor pressure. Unfortunately, many stations across Europe measure only limited subsets of these parameters. Meteorological data used as input in CGMS are: minimum and maximum temperature, rainfall, windspeed, vapor pressure and global radiation or sunshine duration. Only stations that report at least this set of variables on a daily basis are included in the database. Daily potential evapotranspiration is calculated from these data and is also included in the database.

The subproject to compile historical meteorological data stretched over a period of 5 years. The historical datasets (1949-1991) were ordered directly from the national meteorological services. Data from all EU member states and from Poland and Slovenia were acquired, converted to consistent units and scanned for inconsistencies (e.g. minimum temperature higher than maximum temperature).

In 1992, daily meteorological data were received from approximately 750 stations. In 1998 this number had increased to over 1200. Figure 3.5 presents part of the network of meteorological stations included in the meteorological database.

Meteorological data are preprocessed using the AMDAC software package (Meteo-Consult, 1991), which decodes the incoming data and checks their consistency. Individual meteorological parameters are compared to those of surrounding stations and to other observations that are obtained on the same day for the same station. Obvious errors in the observations are corrected automatically, possible errors are marked for manual correction later on and a message is written to a log file.

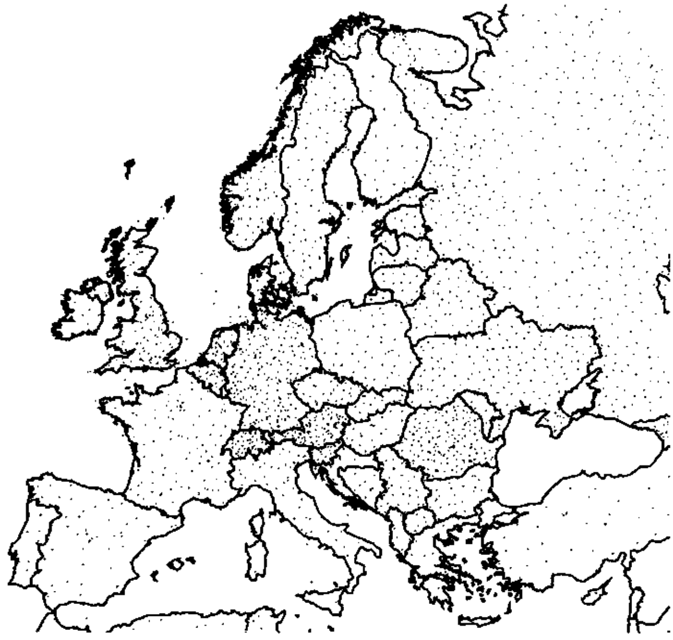

Figure 3.5. *Network of meteorological stations that broadcast data via GTS and whose data are stored in the meteorological database.*

Missing values are replaced through temporal and spatial interpolation, provided sufficient "surrounding" information is available, otherwise they remain blank.

Meteorological input for CGMS is based on a 50 x 50 km grid. A methodology for data interpolation from the existing network of meteorological stations to the grid center was developed on the basis of the studies of Beek *et al.* (1992) and van der Voet *et al.* (1993). The interpolation procedure selects an optimum set of stations and an average value of observed data is attributed to the grid center, without weighting for distance. Rainfall is taken from the nearest station. Selection of the optimum set of stations is based on the following criteria: proximity to other stations, similarity in altitude and distance to the coast, position in relation to climatic barriers (i.e. mountain ranges) and a regular configuration surrounding the grid center. The interpolated data are stored in the GRIDWEATHER table.

3.2.2 Topographic data

National survey agencies in many European countries have produced maps and/or digital datasets on topography at national scale. However, these maps and datasets have never been harmonized into a European topographic dataset. Topographic information used as input for CGMS was extracted from the ETOPOS-5 dataset distributed by the National Geophysical Data Center (NGDC) of the National Oceanographic and Atmospheric Administration (NOAA) of the United States.

3.2.3 Crop characteristics database and crop knowledge base

Data describing the specific growth potentials of individual crops are an essential input to any crop growth simulation model. A subproject was launched to collect and compile all data that could possibly be transformed to either crop characteristics, used as input in CGMS, or information to be included in the crop knowledge base. This knowledge base provides information on (i) meteorological and other types of hazards likely to affect crop yield, (ii) crop requirements with respect to soil characteristics, climatic zones, etc. The collected data can be divided in the following categories:

- Basic non-region specific crop physiological data such as rooting depth, temperature threshold for growth, etc. This information was derived from literature.
- Agronomic data such as: varieties grown in a region and the earliest and latest dates of sowing and harvest for these varieties; maximum altitude at which a crop is grown, etc.
- Detailed physiological information such as heat sums to reach various phenological stages, energy conversion, partitioning of assimilates over various plant organs, etc. This information was derived from literature. For wheat, information was also derived from field trials executed in Belgium, United Kingdom and the Netherlands. For other countries, no detailed field observations were available and consequently calibration of the crop characteristics could not be executed (Boons-Prins *et al.,* 1993).

Results of this subproject are presented by Russell & Wilson (1994), Carbonneau *et al.* (1992), Falisse (1992), Narisco *et al.* (1992), Bignon (1990), Falisse & Decelle, (1990), Hough (1990) and Russell (1990). Boons-Prins *et al.* (1993) used these results and constructed crop files used as input in CGMS, including also information from van Heemst (1988) and van Diepen & de Koning (1990).

Crop files have been constructed for: winter wheat, spring wheat, barley, rice, potato, sugar beet, field beans, soybean, oilseed rape and sunflower. For some crops, crop files for specific varieties grown in certain regions have been constructed. In addition, each crop is assigned to one of the following crop groups: grasses, cereals and root crops. Requirements of these crop groups with respect to soil-related characteristics such as phase, texture, alkalinity, salinity, etc. are stored in the crop database.

3.2.4 European soil and geographical database

To make optimal use of regional soil information, the existing 1:1,000,000 European soil database was updated and completed. The National Agricultural Research Institute (INRA) in France performed this task in cooperation with the "Support group on soils and geographical information systems". The original data collected for its construction in 1985 were used. At the time of writing, parts of the soil and geographical database are still under construction. In Heineke *et al.* (1998), a detailed description of the present situation is presented. The database consists of four parts:

- The meta-database, containing information on the soil surveys executed in Europe. It provides a catalogue with information on national maps and datasets.
- The geographical database, containing the list of Soil Typological Units (STU), i.e. all soil types within the EU identified on the basis of the FAO-UNESCO (1974) legend. The STUs are described by soil attributes with a harmonized coding, such as: FAO soil name, parent material, slope, etc. STUs are generally too small to be distinguished on a map at scale 1:1,000,000. Therefore, they are clustered in Soil Mapping Units (SMU). The concept of SMU is related to that of soil associations postulated by Simonson (1971).
- The soil profile analytical database, containing soil profile descriptions, including results of physical and chemical analyses (Madsen & Jones, 1996). Data are stored in two categories, the first containing the measured data from georeferenced profiles, the second contains estimated data. About 300 profiles are currently available, representing the most important STUs.
- The knowledge database, containing the pedotransfer rules, i.e. simple deductive functions to derive soil parameters from available data (King *et al.*, 1994b) and to formalize empirical interpretation when using soil maps (Jones & Hollis, 1996; Van Ranst *et al.*, 1995)

The soil database and the crop knowledge databases are used to identify areas where a given crop can possibly grow and to estimate available water capacity (AWC) for those soils on which that crop is cultivated, using the pedotransfer rules. However, the uncertainty with respect to soil types within the mapping units, low reliability of the pedotransfer rules for the soil units, lack of supporting analytical soil data and profile descriptions and also the wide range in soil water holding classes make quantification of AWC rather speculative.

3.2.5 Historical yield and planted area data

Statistics on planted area, yield and production volume as applied at Level 3 (see Figure 3.4) have been collected from national statistical services of all EU member states by EUROSTAT. Within the EU, no single Community system to establish these statistics exists: the methods applied vary from country to country. Through article 3 of CAP regulation 837/90, the Commission attempts to harmonize these methods and to stimulate the use of scientific procedures. This regulation prescribes amongst others that censuses or representative sample surveys shall obtain data on planted area, yield and production volume for all significant crops. Bradbury (1994) investigated the applied methods to establish these statistics for cereals for various EU member states. The following presents a summary of his findings.

Germany accounts for about 16% of the EU's cereal production volume. Information on planted area is derived from an annual census of a sample of holdings, followed by a sample survey to establish yield and production volume. Cereal statistics are established through a very thorough procedure. Area, yield and production volume estimates, are refined in the course of the year, from an early indicator value through provisional data to final results. Some doubts exist with respect to the frequency and thoroughness of updating the holdings register. More information on the magnitude of the sampling errors is necessary. There are indications that these errors are subjectively estimated rather than calculated. Germany is the only member state to base the final yield survey results on objective physical samples.

Italy accounts for about 11% of the EU's cereal production volume. Fairly large sample surveys to collect data on planted area, yield and production volume are applied. The national statistical office administers the surveys. Doubts exist: the surveys are based on a register that is liable to become progressively outdated between decennial censuses. Moreover, the quality of the data underlying the stratification method is questionable, the farmers' response rate is only barely adequate to avoid bias, and there appears to be no checking of data errors back to the farmer.

France accounts for about 30% of the EU's total cereal production volume and for about 40% of the soft wheat production volume. The French system to generate agricultural statistics is of high quality, if costly. The annual survey of land use is based on extensive sampling of some half a million points. The enumerators make direct observations at these points, such as type of crop, planted area, etc. This survey is the first step in the yield and production volume survey, which uses a sample of the holdings identified as cereal producers. About 300 holdings per *département* are selected for the yield/production volume survey. In total 61 out of 95 *départements* are sampled. The Ministry of Agriculture designs and organizes these surveys, however, the results are subject to subjective adjustment at *département* level.

The Netherlands contributes less than 1% to the EU's total cereal production volume. Planted area is derived from an annual census. Yield and production volume figures are derived from a survey of local districts. The authorities go to great lengths to ensure that yield and production volume estimates are done in depth, with carefully managed interaction between the parties involved. However, the yield and production assessing method is still rather subjective.

Belgium contributes just over 1% to the EU's cereal production volume. An annual census of a selection of holdings, which includes planted areas, is applied. The census itself has an almost complete response and although preliminary results are rapidly produced, the final data appear only after a long delay. Formerly, local experts made yield and production volume estimates, recently, trained interviewers perform this task.

Luxembourg obviously accounts for a very small proportion of the EU's total cereal production volume. As in Germany, planted area is derived from an annual census of a sample of holdings, followed by a sample survey to establish yield and production volume. The applied methodology is based on postal returns from about 30% of the holdings that maintain full farm accounts. These holdings represent a special group and it is conceded that they tend to be larger than average, with older farmers under-represented. This could imply that yield figures based on this group are biased upwards.

The UK produces about 13% of the EU's cereal production volume and maintains a generally reliable statistical system. The applied sampling methods are similar to those in Germany, with crop areas being derived from an annual census. The yield and production volume survey use current year's census as a basis for the composition of the sample. Response rate to the census and survey is high but not complete, which may lead to some bias.

Ireland produces just over 1% of the EU's cereals. The statistical system has been changed recently, as the existing method of local enumeration by the police force could no longer be used. In 1991 a general agricultural census was held. The new annual sample system for estimating crop areas by postal returns is based upon this census. The yield and production volume survey is based on subjective crop reports from government officers using information from farmers. No detailed information on design and operation of the annual area survey, nor on the efficacy of the yield and production volume survey, with its possible bias towards some types of farmers could be provided.

Denmark produces about 5% of the EU's cereal production volume. Its surveys are based on a closely controlled central register of holdings, which is regularly updated from various sources. The yield and production volume survey is based on a smaller sample of holdings drawn from the major sample of areas of the preceding year. Both surveys are operated by mail. The applied methods are of a high standard, however, the data sources, used for detailed selection of holdings for the area, yield and production volume survey are not entirely clear.

Greece produces about 3% of the EU's cereal production volume. Its statistical system is the least developed in the EU and is based on information provided by local municipalities and communes, where groups of knowledgeable people provide subjective estimates of planted area, yield and production volume. Data from communes and municipalities are aggregated to higher administrative levels and finally to national values. Two similar systems are operated in parallel, one by the Ministry of Agriculture and the other by the national statistical service. The quality of the data is highly dependent on the local standards and practices.

Spain produces about 10% of the EU's cereal production volume. In the 1990's Spain has introduced a new system of statistics, based on area sampling. It can be considered a variation of the French system with direct on-the-spot observation to determine land use and planted areas, followed by survey of a subsample to estimate yield and production volume. The yield and production volume estimation system is subjective. To improve the final figures farmers provide additional information.

Portugal produces less than 1% of the EU's cereal production volume. The yields are the lowest in the EU. Similarly to Italy, a combined sample survey for area, yield and production volume is applied. The system of sampling holdings has recently been introduced and is still under development.

Bradbury (1994) concluded that "most member states attempt to estimate sampling errors, and usually manage to show that the margins are close enough to those set out in regulation 837/90, but with greater or lesser amount of convincing detail. For judgmental assessment of yield (and for Greece, of area as well) no fully satisfactory methods to establish the estimating error are available, for the simple reason that it is not a scientific method."

3.3 The crop growth simulation model

The heart of CGMS is the WOFOST crop growth simulation model, whose underlying principles have been discussed by van Keulen & Wolf (1986). The initial version of this model was developed by the Centre for World Food Studies and AB-DLO (van Diepen *et al.*, 1989; 1988). Implementation in CGMS and its structure is described by Supit *et al.* (1994). Technical descriptions and user manuals have been prepared by van Raaij & van der Wal (1994), van der Wal, (1994) and Hooijer *et al.* (1993).

WOFOST calculates first the instantaneous photosynthesis at three depths in the canopy for three moments of the day, which is subsequently integrated over the depth of the canopy and over the light period, to arrive at daily total canopy photosynthesis. After subtracting maintenance respiration, assimilates are partitioned over roots, stems, leaves and grains as a function of the development stage, which is calculated by integrating the daily development rate, described as a function of temperature and photoperiod. Assimilates are then converted into structural plant material taking into account growth respiration. Growth is driven by temperature and limited by assimilate availability. Figure 3.6 presents a schematic overview of these processes.

Aboveground dry matter accumulation and its distribution over leaves, stems and grains on a hectare basis are simulated from sowing to maturity on the basis of physiological processes as determined by the crop's response to daily weather (rainfall, solar radiation, photoperiod, minimum and maximum temperature and air humidity), soil moisture status (i.e. T_a/T_p in Figure 3.6) and management practices (i.e. sowing density, planting date, etc.). Water supply to the roots, infiltration, runoff, percolation and redistribution of water in a one-dimensional profile are derived from hydraulic characteristics and moisture storage capacity of the soil.

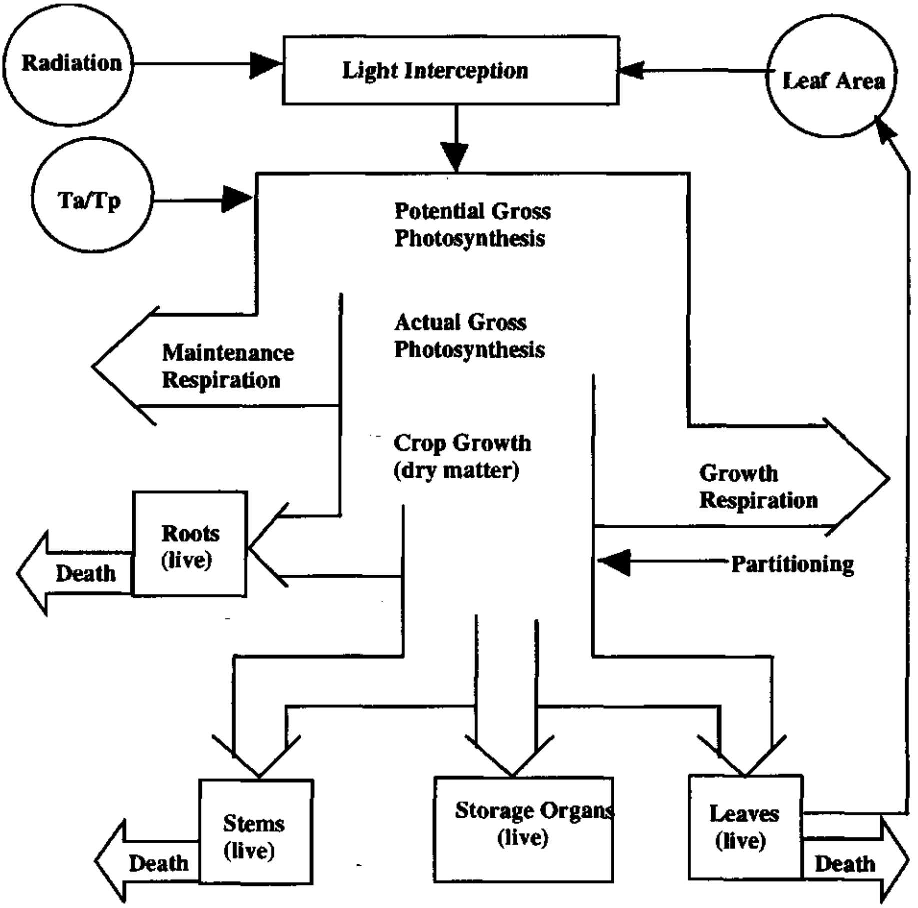

Figure 3.6. *Crop growth processes simulated by WOFOST.* T_a *and* T_p *are actual and potential transpiration rate (de Koning et al., 1993).*

The required inputs per grid cell (50 x 50 km) are daily weather data, soil characteristics and management practices (i.e. sowing density, planting date, etc.). Daily weather data are obtained from the GTS and interpolated to the grid-center (see Section 3.2).

CGMS simulates two production situations: potential and water-limited. The potential situation is defined by temperature, daylength, solar radiation and crop characteristics (e.g. leaf area dynamics, assimilation characteristics, dry matter partitioning, etc.). The water-limited situation is characterized by the aforementioned factors plus: water availability derived from root characteristics, soil physical properties, rainfall and evapotranspiration. In both situations, optimal supply of nutrients is assumed and for each situation, total aboveground dry matter and grain dry matter per hectare are calculated.

As input for the prediction models the following simulation results may be used: potential grain yield, water-limited grain yield, potential aboveground biomass and water-limited aboveground biomass. One of these variables is selected as predictor. The selection procedure and prediction method are described in Section 5.2.4

3.4 Aggregation

Simulations are performed per Elementary Mapping Unit (EMU), the intersection of a Soil Mapping Unit (SMU), grid cell and administrative region, Nomenclatures des Unités Territoriales Statistiques (NUTS). Figure 3.7 presents a schematic outline of an EMU. SMUs are derived from the Soil Map of the European Communities, scale 1:1,000,000 (see Subsection 3.2.4). The NUTS system is organized as follows: the highest level, the whole country, is called NUTS-0, which is divided in regions: NUTS-1. Regions are subdivided in NUTS-2 subregions. EMU simulation results are aggregated to NUTS-2 yields via:

$$Y_{T2} = \sum_{i=1}^{n} c_{e,i} A_{e,i} Y_{T,e,i} \,/\, \sum_{i=1}^{n} c_{e,i} A_{e,i} \tag{3.1}$$

where subscript e stands for EMU, Y_{T2} is simulated average NUTS-2 yield (ton.ha^{-1}) in year T, $Y_{T,e,i}$ simulated EMU yield (ton.ha^{-1}) in year T, A_e EMU area (ha) and c_e percentage of the EMU area suitable for wheat cultivation, n is the number of EMUs in a NUTS-2 subregion. No information on land use at EMU level is available, therefore c_e is used. This value is derived from the Soil Typological Unit (STU) table that describes soil characteristics of a SMU such as slope, texture, etc., (King *et al.*, 1994a, b) and is invariable in time. NUTS-2 yields in year T are aggregated to NUTS-1 yield via:

$$Y_{T1} = \sum_{j=1}^{k} c_{2,j} A_{2,j} Y_{T2,j} \,/\, \sum_{j=1}^{k} c_{2,j} A_{2,j} \tag{3.2}$$

where subscript 2 stands for NUTS-2, A_2 NUTS-2 area (ha), c_2 is percentage of the NUTS-2 area suitable for wheat cultivation and k is the number of NUTS-2 subregions per NUTS-1 region.

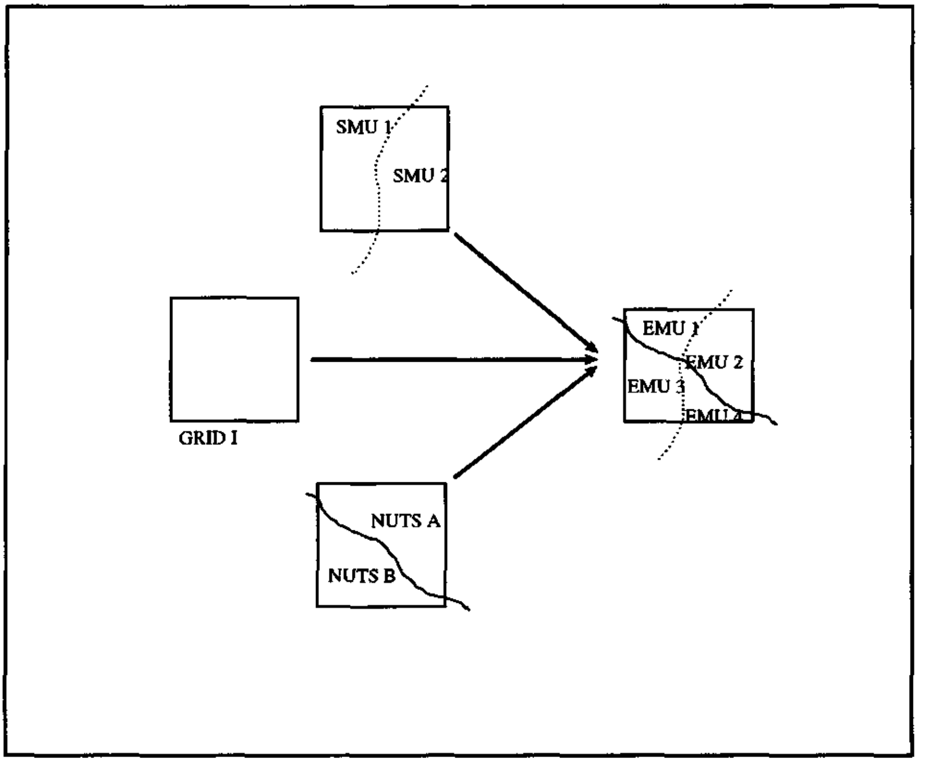

Figure 3.7. *Schematic outline of the Elementary Mapping Unit (EMU), the intersection of a Soil Mapping Unit (SMU), grid cell and administrative region, Nomenclatures des Unités Territoriales Statistiques (NUTS).*

Simulated average NUTS-0 yield is obtained in a similar way. Although information on actual land use at NUTS-2 level is available, in the operational version of CGMS these data are not used for aggregation of simulation results from NUTS-2 to NUTS-1 to NUTS-0 yield. Currently, the operational version of CGMS aggregates simulation results to NUTS-0 level and these values are introduced in the yield prediction routine.

3.5 Omissions in CGMS

Reddy (1995) states that crop yields depend on several factors such as altitude (e.g. Reddy, 1989), soil type (e.g. Reddy, 1983; Seetharama & Bidinger, 1979), crop variety (e.g. Batts *et al.*, 1998; Frère & Popov, 1979), management practices (e.g. Mahler *et al.*, 1994), etc. According to Reddy (1995): "models to be more meaningful, in physical and practical sense, and to be more applicable in a wider environmental context, should be addressed under holistic systems by taking into account abundantly available information in the literature on all principal components of a model." However, caution is needed; according to Monteith (1996) crop models cannot be built without invoking a set of hypotheses and this set cannot be rigorously tested without measurements that describe crop performance over a wide range of environments. Such information is rarely available and this author argues that models or submodels may become rather speculative when these tests cannot be executed. Furthermore, according to Reynolds & Acock (1985) as cited by Passioura (1996), the contribution to total model error of model parameters, and beyond a certain point total model error itself, increases as model complexity increases. Therefore, it can be argued that yield reducing factors and growth processes that are difficult to quantify or for which insufficient data are available should not be included in CGMS.

One of the processes not accounted for in CGMS is the ability of plants to adapt to low resource conditions by modifying their morphology and physiology. This capability for adjustment derives from the ability of plants to partition their assimilated energy among various morphological structures and physiological processes. Functioning of this mechanism is not clearly understood. According to Sinclair & Park (1993):"mechanistic crop models, which account for the effects of environmental variations on crop responses, have not led to a singular understanding of the resource limitations on crop yield other than a realization that a number of factors must be considered." CGMS may overestimate drought effects since this adaptive mechanism is not accounted for.

Yield reducing factors not accounted for in CGMS are amongst others: water-logging, erosion, frost. In addition, sowing date variation, occurrence of pests and diseases and harvest and storage losses are also not accounted for. Many of these factors are important at local scale and may lead to variation in yields. CGMS however, assumes that at regional level these local influences compensate each other (van Diepen & van der Wal, 1995).

Sowing date variations or occurrence of re-sowing in response to, for example, drought may occur at regional scale or even at national scale. However, information on these phenomena is not included in the EUROSTAT databases and consequently, a pattern of sowing dates over crops, regions, and/or soil types could not be established. Therefore, per crop and per region an average sowing date is assumed (see Chapter 8).

Information on current season's land use is not available. Areas suitable for growing crops are estimated from the soil map. CGMS assumes a constant spatial distribution of crops over these areas and over time. Also, information on fertilizer and plant protection applications per crop type at regional or national level is difficult to obtain and consequently these characteristics are not considered in CGMS. It is assumed that nutrient availability and diseases do not limit crop yields. To account for effects not considered in the crop growth simulation model, a trend function is applied in the prediction model (see Section 3.6).

3.6 Prediction model

3.6.1 History

Observed national, regional and subregional yields per unit area show a trend in time. This trend may be attributed to increased fertilizer application, improved crop management methods, new high yielding varieties, etc. Various authors have proposed to subdivide crop yield in three components: mean yield, a trend in time and residual variation (e.g. Vossen, 1989; Dagnelie *et al.*, 1983; Dennet *et al.*, 1980; Odumodu & Griffits, 1980). It is assumed that the interacting effects of climate, soil, management, technology, etc. determine mean yield. The trend is mainly due to long-term economic and technological dynamics. The third component, the residual variation, is considered to be the variation among years (Dennet *et al.*, 1980). The residual variation can be studied as a function of weather variables.

According to Dennet *et al.* (1980) and Odumodu & Griffits (1980), the technological time trend should be removed from the crop time yield series, assuming that the residual variation is independent of that trend. This approach can be summarized as (Vossen, 1989):

$$Y_T = \overline{Y} + f(T) + e \qquad (3.3)$$

$$\hat{Y}_T = \overline{Y} + f(T) \qquad (3.4)$$

$$Y_T - \hat{Y}_T = e \qquad (3.5)$$

$$e = f(weather) \qquad (3.6)$$

where Y_T is observed yield per unit area in year *T*, $\overline{Y}$ mean yield per unit area, $\hat{Y}_T$ estimated yield per unit area in year *T*, *f(T)* technological trend as a function of time, *e* residual, not explained by trend, *f(weather)* function of weather variables (e.g. 10-day rainfall, total monthly radiation, etc.)

Palm & Dagnelie (1993) fitted various time trend functions to national yield series of several crops for 9 EU member states. Regressions were executed for the period prior to 1983 and a forecast for 1983 was made. This procedure was repeated for successive years up till 1988. The prediction results were compared with national yield values (see Section 3.4). Of the tested trend functions a quadratic function of time performed best. However, differences with a simple linear trend function were small.

In a next step, these authors removed the trend from the yield series using a quadratic time trend function. The residuals for the period prior to 1983 were regressed on various meteorological parameters and a prediction for 1983 was made. Again, this procedure was repeated for successive years up till 1988. This was done for 19 *départements* in France. Comparing the predicted and national yield series demonstrated that the applied meteorological variables did not improve the prediction accuracy. Comparable accuracy, sometimes better results were obtained using the trend function only.

Swanson & Nyankori (1979) for corn and soybean production in the USA, Sakamoto (1978) for wheat production in South Australia and Aggrawal & Jain (1982) for rice yields in the Raipur District in India, considered the technological time trend dependent on the residual variation. According to Winter & Musick (1993), Hough (1990) and Smith (1975), weather affects farm management practices such as planted area, timing of field operations, application of inputs, etc. Hence, the time trend should be analyzed simultaneously with the explaining variables. This approach can be summarized as (Vossen, 1989):

$$Y_T = b_0 + f(T) + f(weather) + e \tag{3.7}$$

where b_0 is 'theoretical' yield in the absence of a trend and weather influences. Swanson & Nyankori (1979) showed that the trend was underestimated when weather data were not analyzed simultaneously with the time trend. Similar results were found for millet in Botswana (Vossen, 1989). Equation (3.7) does not account for either the interaction between crop growth and weather variability, root characteristics or soil physical properties. Therefore, Vossen (1990a, 1992) proposed to use crop growth simulation results to describe year-to-year yield variation. In a crop growth simulation model weather and soil characteristics are summarized and crop characteristics, including yield, form the output. The simulation results quantitatively represent the influence of weather variables on crop growth. Yield can be written as:

$$Y_T = b_0 + f(T) + f(simulation) + e \tag{3.8}$$

where *f(simulation)* is a function of crop growth simulation results that accounts for weather variability and soil influences.

3.6.2 *The actual prediction model*

As mentioned in the previous section, Vossen (1992, 1990b) proposed a combination of a linear time trend (Palm & Dagnelie, 1993; Swanson & Nyankori, 1979) and crop growth simulation results to account for the trend in yield series and weather variability, respectively. The prediction model applied in CGMS is based on this proposal. It can be described as:

$$\hat{Y}_T = b_0 + b_1 T + b_2 S_T \tag{3.9}$$

where $\hat{Y}_T$ and S_T are estimated yield and simulation result (ton.ha^{-1}) in year T, respectively, and b_0, b_1 and b_2 are regression constants. The production volume $\hat{P}_T$ (ton), in year T, can thus be estimated as:

$$\hat{P}_T = \hat{Y}_T \hat{A}_T \tag{3.10}$$

where $\hat{A}_T$ is the estimated planted area. Equation (3.9) assumes additive effects of weather on yield, i.e. yield variability as a result of weather influences, is similar under a high fertilizer input regime and under a low fertilizer input regime. Equation (3.10) assumes a linear relation between planted area and production volume, or in other words, similar yield on the total area planted. These assumptions may be challenged and in Chapters 4, 5 and 7 these issues will be discussed and alternatives will be presented.

The prediction method applied in CGMS is similar to the one described in Section 5.2.4. Historical yield values are regressed according to equation (3.9), and the obtained regression constants are subsequently used in the prediction model. It is assumed that these historical values correctly represent national yields. However, each EU member state has its own methods to establish these values and, as mentioned by Bradbury (see Subsection 3.2.5), the estimation errors are not always known. Caution should therefore be exercised when comparing the quality of the prediction results among the individual countries.

3.7 *CGMS and the MARS forecasting system*

The objective of the MARS project is to predict production volumes of the major crops at national level and possibly at regional level for all EU member states. Production volume is divided in a yield and a planted area component, which are estimated separately and subsequently multiplied. Planted area is estimated using high resolution imagery and ground surveys (Scot Conseil, 1994), yield is predicted subjectively.

Production volume predictions are refined in the course of the year, from an early indicator value through provisional data to final results. A panel of analysts performs these predictions on a monthly basis, form March till September. Every ten days, they also assess crop growth conditions, such as occurrences of droughts, excess rain, etc. It is assumed that changes in crop growth and development as a result of for example stress situations, can be detected by CGMS and on remote sensing images, obtained in consecutive ten-day periods. The first predictions are based on extrapolated yield and planted area time series. In the course of the season, information provided by various sources is analyzed and combined (see Figure 3.8). Predictions and assessment are subjective and based on analysis and synthesis of:

- The rapid surface estimate system that provides estimates of the year-to-year changes in planted area of the major crops. The field surveys executed in the framework of this system provide additional information on yield and planted area.
- CGMS products produced at the Levels 1, 2 and 3 (see Figure 3.1).
- Information on vegetation status (NDVI or surface temperature) using NOAA-AVHRR imagery processed with the SPACE/SCAN software package.
- Information from farmer magazines and experts.

Where possible, information of each source is compared to information of preceding years obtained in the same 10-day period and to information obtained in the 10-day period in which the crops reached a similar simulated development stage. CGMS results included in the analysis consist of cartographic material, representing the simulation results per grid cell obtained at Levels 1, 2 and 3 (e.g. maps of temperature sums, maps of development stage, etc.; see Figure 3.9). To gain insight into how current year's crop growth and development compare to those of previous seasons, current year's simulation results are also compared to the long time average simulation results (see Figures 3.9 and 3.10 bottom part) and to results obtained from simulations performed with average meteorological input values. The simulation results used in this analysis are: total weight of aboveground biomass, total weight of storage organs, leaf area index, crop growth development stage, water use and soil moisture content.

Furthermore, information on occurrence of pests, diseases, droughts and yield indications in individual EU member states, is retrieved from agricultural magazines (e.g. Boerderij, Silon Belge, Scottish Farmer, etc.) and included in the analysis. Based on the analysis, the panel of analysts decides on magnitude of the production volume. Experts in various member states are requested to comment on these predictions.

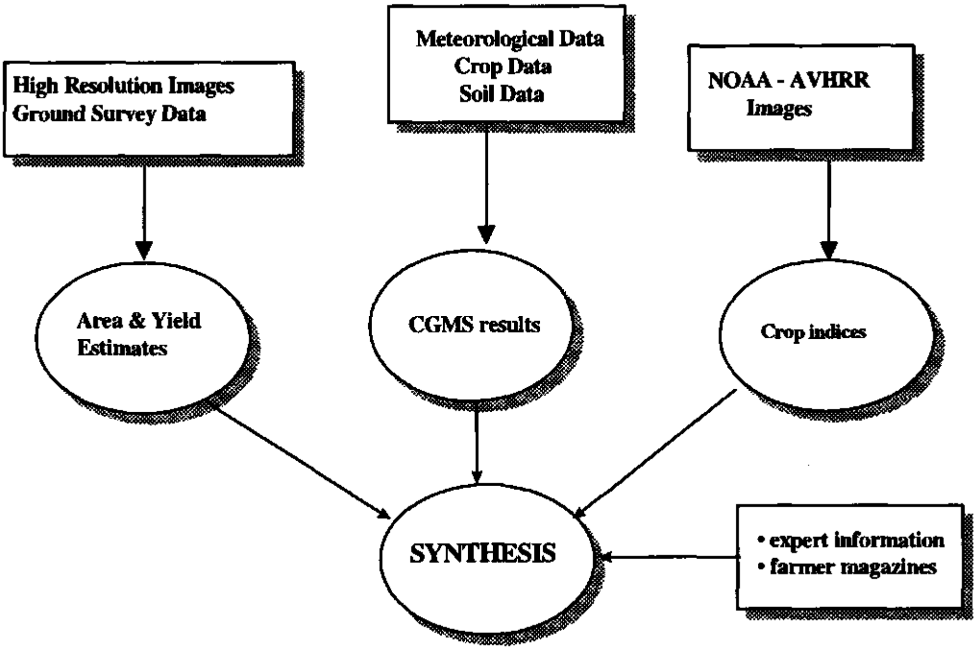

Figure 3.8. *MARS yield forecasting system.*

Prediction results obtained at Level 3 (i.e. the prediction model; see Subsection 3.6.2), indicate how crops may have reacted to weather influences. The analysts adapt these results when, in their opinion, other factors should be accounted for or when the predicted value is deemed to be incorrect. For prediction, one of the following simulation results is selected: potential yield, potential biomass, water-limited yield and water-limited biomass. Selection procedure and prediction routine are similar to those described in Section 6.2.

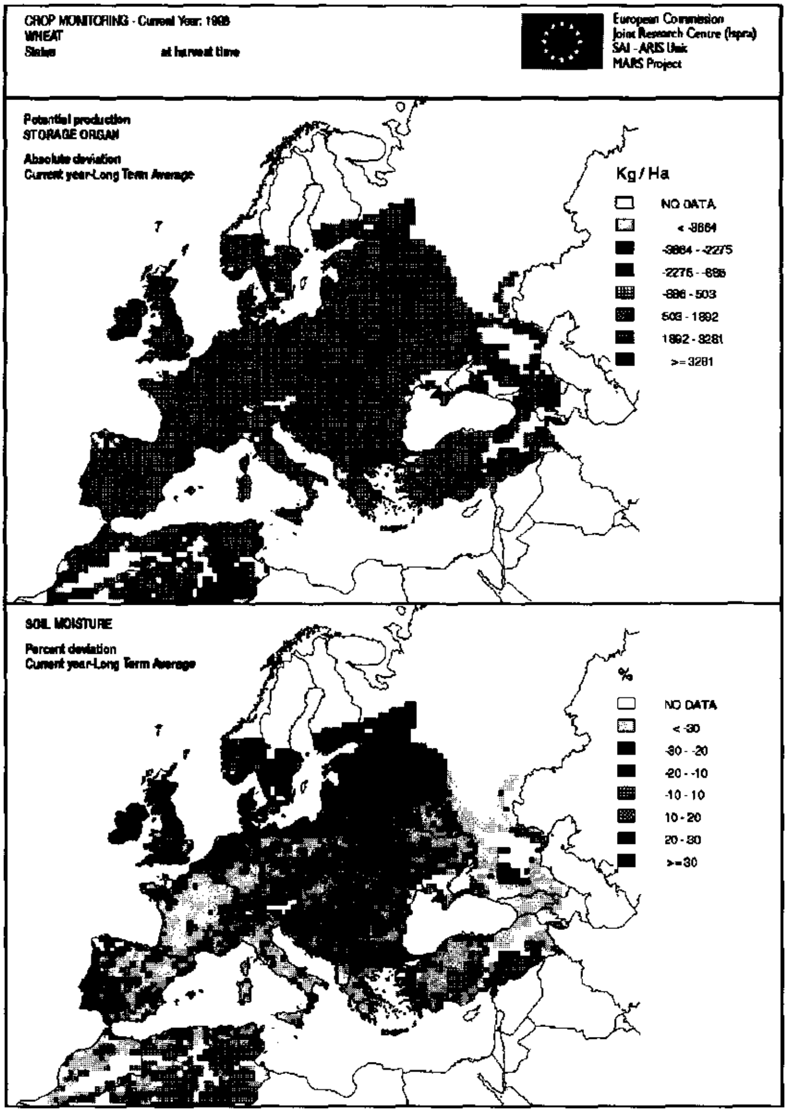

Figure 3.9. *CGMS results on a 50 x 50 km grid. The upper part of this figure presents the deviation of the production per unit area at harvest time from the long-term average (i.e. the mean over 15-30 years, depending on the available data). The bottom part presents deviation of the soil moisture calculations with respect to the long-term average (i.e. the mean over 15-30 years, depending on the available data)*

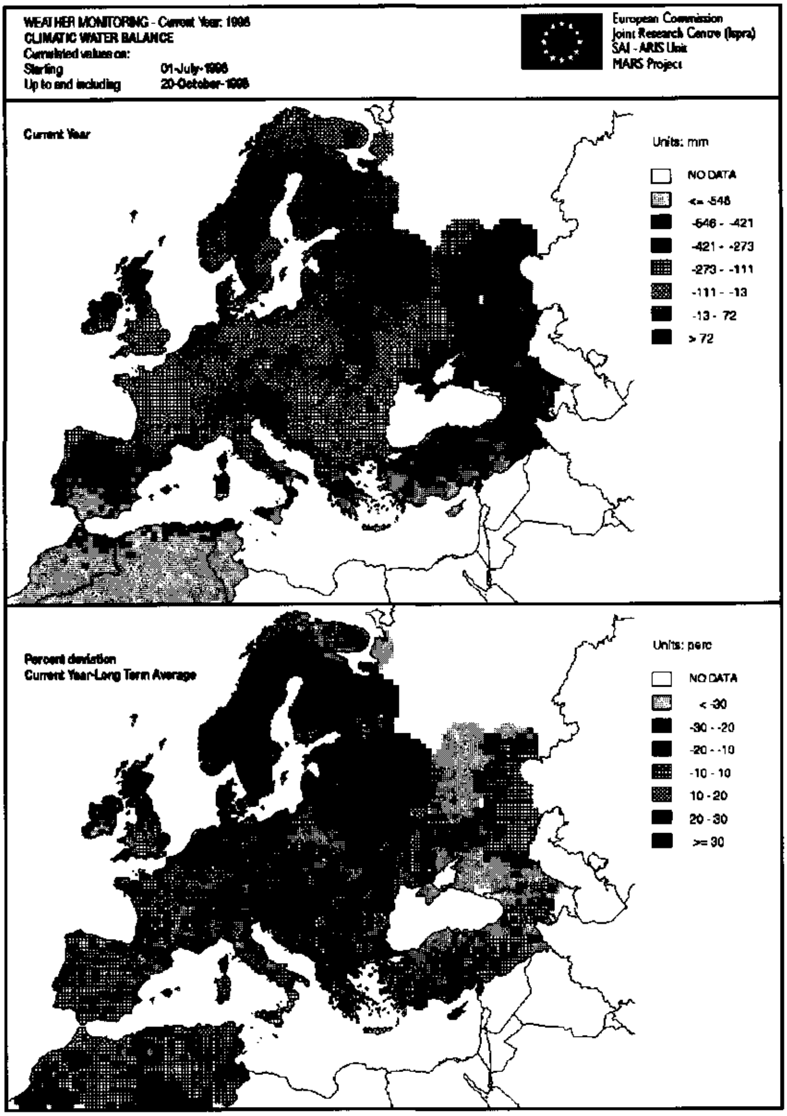

Figure 3.10. *Results of the water-balance calculations, i.e. water deficit or water excess (mm) executed on a 50 x 50 km grid. The upper part of this figure presents the results from the 1st of July to the 20th of October 1996. The bottom part of this figure presents the deviation of these results from the long term average (i.e. the mean over 15-30 years, depending on the available data)*

4. Analysis of some economic factors and fertilizer applications

4.1 Introduction.

De Koning *et al.* (1993) tested equation (3.9) for operational quantitative yield prediction. The test was carried out for: wheat, potato, spring barley, grain maize, rice, sugarbeet, oilseed rape and sunflower. Predictions were executed at NUTS-0 and NUTS-1 level for: Belgium, Denmark, Germany, France, Greece, Ireland, Italy, Luxembourg, the Netherlands, Spain and the UK. The authors concluded that a simple linear trend predicted equally well or sometimes more accurately than equation (3.9). In most cases, crop growth simulation results were not significantly associated with the annual variation in national yield per unit area. This negative result could be the consequence of, amongst others: (i) errors in the applied model; (ii) errors in the methods to establish agricultural statistics (see Subsection 3.2.5); (iii) errors in the spatial interpolation of meteorological data; (iv) errors in the estimated global radiation; (v) local weather effects, that can be obscured as a consequence of aggregation of simulation results, obtained at Elementary Mapping Unit (EMU) level, into subregional, regional and national values (see Section 3.4); (vi) application of new techniques or varieties that reduce the yield-reducing effects of weather.

In Chapter 6 a new method to calculate global radiation will be discussed and in Chapter 7 attention will be paid to, amongst others, the effects of aggregation of the simulation results. In this chapter, two adaptations to the applied prediction model, equation (3.9), are explored. The first adaptation is the model itself. One of the main goals of the MARS project is to predict national production volumes as accurately as possible at the end of the growing season. The method applied in CGMS first predicts national yield per unit area, which is subsequently multiplied by the planted area (see equation (3.10)). This method assumes that national production volume is proportional to the planted area. In this chapter, methods to estimate the national production volume directly are explored for the following two reasons. First, soils are an economic commodity and farmers may vary planted area on the basis of expected crop prices, fertilizer prices, set-aside subsidies, etc. Since soil fertility and soil physical properties are variable, even over a short distance (Addiscott, 1995), the production volume may not be proportional to the planted area. Binswanger *et al.* (1987) as cited by van Keulen *et al.* (1998) found that a 1% increase in output prices leads to a 1.1% increase in planted area and to 0.1% increase in yield per unit area. Secondly, it is well known that weather affects field operations such as ploughing and planting (e.g. Winter & Musick, 1993; Hough, 1990; Smith, 1975). In general, dry weather conditions in early autumn lead to a larger area sown to wheat and, according to Russell & Wilson (1994), early autumn sowings tend to give the highest yields. The extent of the planted area may thus be seen, amongst others, as an indication of the initial conditions of the wheat-growing season and should be analyzed simultaneously with the yield per unit area.

The second adaptation refers to the applied trend function. As demonstrated by Palm & Dagnelie (1993) and de Koning *et al.* (1993), a linear time trend alone may yield equally good or more accurate prediction results than a linear time trend in combination with either meteorological parameters or simulation results. However, a linear time trend, as applied in equation (3.9), cannot account for trend breaks in the yield series as a result of changes in CAP regulations or changing prices of farm inputs, etc. To account for such changes, the hypotheses that wheat prices (i.e. selling and intervention prices), expenditure on crop protection agents and average nitrogen fertilizer application per unit area are associated to wheat production volume variation, are investigated.

In Section 4.2 the hypothesis that intervention or selling prices in combination with crop growth simulation results multiplied by the planted area account for the variation in production volume is investigated. The expenditure on plant protection agents and nitrogen fertilizer applications in relation to the production volume is examined in Sections 4.3 and 4.4, respectively.

National wheat production volumes (period 1975-1991) are examined. The countries considered are, Germany (D), France (F), Italy (I), The Netherlands (NL), Belgium (B), United Kingdom (UK), Ireland (IRL), Denmark (DK), Greece (GR) and Spain (E).

4.2 Intervention prices and selling prices

Economic influences on agricultural production have been extensively studied and documented. Oude Lansink & Peerlings (1996) examined the effects of the new CAP regulations, introduced in 1992, for a cereals and oilseeds regime in The Netherlands, using a simulation model. Their simulation results demonstrated a decrease in pesticide and fertilizer applications with 2.8% and 6.7%, respectively. In Sweden in 1991, a reduction of 33% in the wheat area was observed as a result of an increase of 30% in fertilizer and crop protection agent taxes (Russel & Wilson, 1994). According to Falisse (1992), the use of inorganic nitrogen fertilizer in the Benelux has increased by a factor between three and four in the last three decades as a result of the economic situation. Rutten (1989) investigated the relation between agricultural prices and technological change. Haun (1982) showed in an analysis of maize yields in the United States a decrease in the coefficient of determination, R^2, from 0.94 to 0.83 when the years 1974-1977 were added to the period 1950-1983. This decrease of R^2 was attributed to the energy crisis in the early seventies and the simultaneously increased fertilizer prices.

According to van Keulen *et al.* (1998), prices may influence allocation of resources for agricultural production in four ways: (i) area expansion; (ii) increased input use; (iii) technological change (input substitution); and (iv) crop choice adjustment. Prices vary with time and fluctuate according to supply and demand and may differ among various regions. The selling prices considered in this chapter represent the average annual wheat selling price per country as provided by EUROSTAT.

When the market price drops below the intervention price, farmers can sell their wheat against the intervention price to the national intervention offices. After 1992 however, intervention prices were to be gradually reduced to the world market price. Tables A1, A2 and A3 in the annex present the annual intervention and the selling prices (source: EUROSTAT). In this section, intervention prices as set by the EAGGF are examined; national currency parities or monetary compensation are not considered.

According to Debeye (1998), Oude Lansink & Peerlings (1996) and Weber (1995), agricultural production and the use of inputs respond to expectations about profits and prices formed by past experience, i.e. by production costs and prices in preceding years. Jongeneel (1997), for example, in his analysis of producer supply responses to price changes for, amongst others, the EU cereal and oilseed production, used expected prices that were calculated as a linear function of lagged intervention and selling prices. However, according to Kruseman & Bade (1998) and Weber (1995), econometric supply analyses have demonstrated that price influences on production volume are hardly noticeable after 3 years. In this section it is hypothesized that production volume, P_T, is influenced by the preceding year's selling or intervention price, Z_{T-1}:

$$P_T = b_0 + b_z Z_{T-1} + b_2 A_T S_T \tag{4.1}$$

where A_T is the area planted to wheat in year T, S_T is a crop growth simulation result in year T, and b_0, b_z and b_2 are regression constants. The crop growth simulation results applied are potential yield, water-limited yield, potential biomass and water-limited biomass.

Production volumes are regressed according to equation (4.1). Only the regression results of the simulation output that provided the highest adjusted coefficient of determination are presented in Table 4.1.

The results demonstrate that for some of the major soft wheat producing countries (*i.c.* France and the UK) and for all the examined durum wheat producing countries, prices fail to demonstrate an association with the annual production volume. However, the soft wheat t-values for all the other countries, except for Denmark, do suggest a relation between prices of the preceding year and production volume. Generally, for soft wheat the t-values obtained with intervention prices, except for Greece, are higher than t-values obtained with selling prices, which may suggest that price certainty has a stronger influence on production volume variation and increase than selling prices. In this context, it is interesting to note that Oskam & Stefanou (1997) concluded that, although the incentive of increased profitability at farm level can be considered the main driving force behind technology change, it is price certainty that may have caused the annual increase in production volume.

Table 4.1. *Adjusted coefficients of determination* (R^2) *and t-values* (t_z, t_2) *of the regression according to equation (4.1). Intervention prices and selling prices are considered. Period 1975-1991.*

		Intervention Prices plus $A_T S_T$			Selling Prices plus $A_T S_T$		
	Country	R^2	t_z	t_2	R^2	t_z	t_2
Soft wheat	B	0.77	3.82	3.64	0.69	2.67	4.55
	D	0.87	3.73	8.03	0.80	1.93	7.87
	DK	0.98	0.06	18.28	0.98	0.24	23.36
	E[1]	*	*	*	0.30	2.31	2.57
	F	0.85	1.73	3.55	0.82	0.20	4.21
	GR	0.87	2.02	7.88	0.90	2.96	11.40
	I	0.79	2.62	6.65	0.79	2.61	6.65
	IRL	0.90	3.45	6.85	0.89	3.13	7.35
	NL	0.83	5.86	4.94	0.69	3.54	3.47
	UK	0.95	1.05	6.09	0.95	0.66	10.92
Durum wheat	E[1]	*	*	*	0.95	1.79	13.92
	F	0.97	1.58	21.16	0.96	-0.34	19.17
	GR	0.93	1.40	14.98	0.93	1.17	12.85
	I	0.55	1.16	3.99	0.60	1.75	4.10

([1]) Spain joined the EU in 1986. The system of price intervention was not applicable (*) before this year.

Caution should be exercised when trying to explain farmers' behavior from a limited set of economic variables. This may lead to biased results; some economic variables may 'pick up' effects of omitted other economic variables (Jongeneel, 1997).

Hypothesizing that an agro-economic model summarizes the effects of economic variables on land use, fertilizer application, use of crop protection agents, etc., further research should aim at integrating such a model with CGMS and constructing a bio-economic model, similar to those models used for policy analysis of sustainable land use (e.g. Kruseman & Bade, 1998; Ruben *et al.*, 1998). In this context the SPEL (Sektorales Produktions- und Einkomensmodell der Landwirtschaft der Europäischen Union) (Henrichsmeyer, 1994) and the ECAM (European Community Agricultural Model) model (Folmer *et al.*, 1993), should be examined for possible integration. Both models operate at country level and are developed as supporting tools to evaluate the EU policy for the agricultural sector. According to Keyzer & Voortman (1998) the system could be refined through integration of models at household and regional level, which may lead to a better understanding.

4.3 Crop protection agents

As a result of innovative combinations of plant breeding, water management practices, fertilizer applications, and weed control practices, the annual wheat yield expansion increased from a few kilogram per ha before World War II to about 70 $kg.ha^{-1}.yr^{-1}$ (de Wit *et al.*, 1987). According to Russell & Wilson (1994), new wheat cultivars did not contribute to the increased yield per unit area after 1960. However, according to Austin *et al.* (1989) between 1978 and 1986, a limited yield increase of 0.4 to 0.8% per year as a percentage of the 1975 yields did occur as a result of genetic improvement. According to Christen & Hanus (1993), McEwen *et al.* (1989), Prew *et al.* (1986) and Widdowson *et al.* (1985), nutritional problems in Northern European cropping systems have been largely eliminated through high levels of fertilizer inputs, and yield reductions in cereal rotations are mainly attributed to the incidence and severity of soil and trash borne diseases, such as *Take-all* (*Gaeumannomyces graminis* var. *tritci*) and *Eyespot* (*Pseudocercosporella herpotrichiodes*). According to Garrett (1970) as cited in Trolldernier (1981) and Sieling & Hanus (1992), *Take-all* and *Black rust* (caused by *Puccinia graminis*) are the major causes of yield reduction in wheat. Lever (1990) estimated that the use of broad-spectrum fungicide mixtures has increased wheat yields in France by over 15% and the use of fungicides in Western Europe has resulted in an extra 2-3 10^6 ton production of cereals per year. According to Hough (1990) "increased applications of nitrogen fertilizer are made possible by using fungicides and herbicides to control weeds and diseases". Table 4.2 presents the expenditure on crop protection agents for various EU member states, collected by the European Centre for Agricultural, Regional and Environmental Policy Research (EUROCARE). The lowest expenditures are observed in Italy and Spain, countries where also the lowest production per hectare is noticed. For Greece the expenditures decreased in the observed period.

Table 4.2. *Expenditure on crop protection agents for wheat (Euro.ha^{-1})*

Year	B	DK	D	E	F	GR	IRL	I	NL	UK
75	44.65	20.37	23.71	4.10	54.89	43.22	4.13	0.02	26.84	38.28
76	44.34	23.02	29.38	3.73	61.05	37.01	5.53	0.02	30.05	34.19
77	47.73	27.06	44.06	4.06	64.83	54.95	7.59	0.02	29.09	33.01
78	57.76	31.05	50.31	4.07	70.11	42.87	11.42	0.02	27.61	36.27
79	69.32	41.82	58.85	4.97	76.25	44.59	14.88	0.02	34.42	59.98
80	74.59	41.72	65.67	5.42	82.32	33.42	16.54	0.03	41.48	61.34
81	73.89	45.73	58.72	5.18	88.26	26.02	18.60	0.02	41.32	65.35
82	69.53	56.82	60.44	5.19	88.29	23.98	18.70	0.02	41.03	87.44
83	71.77	75.82	60.18	5.34	87.47	19.88	18.93	0.02	42.57	97.22
84	78.62	90.76	62.38	5.42	90.90	13.98	21.54	0.02	45.92	95.86
85	79.12	79.37	73.13	5.82	98.17	13.30	22.45	0.02	45.71	100.38
86	82.76	70.73	79.11	5.73	105.79	9.07	21.40	0.03	49.78	85.70
87	88.46	62.48	83.51	5.70	108.12	9.12	21.57	0.03	65.57	81.74
88	87.69	64.71	90.43	6.95	117.07	8.13	25.79	0.03	67.32	102.00
89	95.17	72.37	95.20	7.31	130.65	8.15	26.64	0.03	61.42	107.22
90	103.10	72.67	77.20	8.57	131.76	7.23	30.21	0.03	59.14	88.07
91	106.08	63.61	82.54	8.46	126.41	6.61	30.92	0.03	53.80	77.16

Source: EUROCARE

The following hypothesis is tested: the expenditure on crop protection products in combination with crop growth simulation results multiplied by the planted area contributes to the trend and annual production volume variation. According to Falisse (1992), in the Benelux and neighboring regions, application of crop protection products takes place at the end of February and at the end of April, therefore the current year's expenditure is considered. National production volume, P_T, can thus be described as:

$$P_T = b_0 + b_E E_T + b_2 A_T S_T \tag{4.2}$$

where E_T is the expenditure on crop protection agents in year T, A_T the area planted to wheat in year T, S_T is a crop growth simulation result in year T and b_1, b_E and b_2 are regression constants. National production volumes (1975-1991) are regressed according to equation

(4.2). As crop growth simulation results potential yield, water-limited yield, potential biomass and water-limited biomass are used.

Regression results referring to the crop growth simulation output yielding the highest adjusted coefficients of determination, R^2, are presented in Table 4.3. The regression analysis demonstrates that expenditures on crop protection products are not significantly associated with soft wheat production volume (5% t-test) for Denmark, Spain, UK, Italy and Greece. For durum wheat crop protection expenditure is only significant for France (5% t-test). Information on price evolution, quantities and types of crop protection products applied, is not available in the EUROSTAT database; therefore this path is not further pursued.

Table 4.3 *Adjusted coefficients of determination* (R^2)*, t-values* (t_E, t_2) *of the regression according to equation (4.2). Period 1975-1991.*

	Country	R^2	t_E	t_2
Soft wheat	B	0.72	2.99	1.07
	D	0.84	2.81	5.43
	DK	0.98	0.45	17.68
	E	-	-	-
	F	0.93	4.49	5.76
	GR	0.86	-2.05	6.46
	I	0.74	-1.59	3.70
	IRL	0.94	5.19	6.19
	NL	0.68	3.44	4.79
	UK	0.95	-0.53	7.58
durum wheat	E	0.94	1.23	10.08
	F	0.98	3.51	15.19
	GR	0.94	-1.55	7.80
	I	0.54	0.97	3.50

(-) regression not significant at 5 %

4.4 Nitrogen fertilizer application

The effects of nutrients on cereal development and growth have been studied extensively. For example, Foulkes *et al.* (1998) studied the response of winter wheat cultivars to applied nitrogen. Gavin Humphreys *et al.* (1994) studied the effects of nitrogen fertilizer application and seeding date on the quality of oats. Bänziger *et al.* (1992) studied genotype variability in grain protein content as affected by nitrogen supply. Darwinkel (1983) and Camberato & Bock (1990) studied the single ear yield of wheat as influenced by fertilizers. In the context of this study, it is interesting to note that Thompson (1975) used nitrogen fertilizer application records to justify the use of a linear time trend to describe the annual corn yield increase in the United States.

Table 4.5 presents the average nitrogen fertilizer application per hectare to wheat, for the EU member states dealt with in this chapter (source: EUROCARE). High applications are observed in the UK and The Netherlands, the lowest in Italy, Greece and Spain. In 1987 the EU adopted regulations aiming at a reduction in farm inputs (Slot, 1990). According to this table these regulations had limited effect on nitrogen fertilizer application. However, doubts exist on the data quality and caution is needed when interpreting these figures (EUROCARE, pers. comm., 1996).

At farm level, various fertilizer models can be fitted to yield series (Cerrato & Blackmer, 1990). According to Nelson *et al.* (1985), no single model can be recommended for all situations. However, the quadratic trend has been most commonly used (Weber, 1995; Buresh & Baanante; 1993; Nelson *et al.*, 1985). The following hypothesis is tested: nitrogen fertilizer application plus crop growth simulation results multiplied by area account for the trend and annual production volume variation. The national production volume, P_T, of wheat can thus be described as:

$$P_T = b_0 + b_F F_T + b_2 A_T S_T \tag{4.3}$$

where F_T is the amount of applied nitrogen fertilizer (kg.ha^{-1}) in year T, A_T the area planted to wheat in year T, S_T a crop growth simulation result in year T and b_o, b_F and b_2 are regression constants. National production volumes (1975-1991) are regressed according to equation (4.3). As crop growth simulation results potential yield, water-limited yield, potential biomass and water-limited biomass are tested. The results presented in Table 4.4, demonstrate that for all countries, except Belgium, both nitrogen fertilizer application and crop growth simulation results multiplied by an area estimate are significantly associated with the annual production variation (5% t-test).

4.5 Conclusions

The results suggest that in some cases prices and expenditure on crop protection are associated to production volume. However, the analysis fails to demonstrate a relation between soft wheat production volume and selling or intervention price for two of the major producing countries. Intervention and selling price are not significantly associated with the durum wheat production volume (5% t-test) either. Furthermore, for soft wheat for 5 out of the 10 investigated countries and for durum wheat, for 3 out of the 4 investigated countries, the expenditure on crop protection agents is not significantly associated with the production volume.

The tested economic variables are not generally applicable and should therefore not substitute the linear time trend as applied in equation (3.9). Further research should aim at expanding CGMS with an agro-economic submodel that accounts for the economic influences on production volume. Fertilizer application per unit area can be applied as trend function, however, doubts exist concerning the applied collection methods and care should be exercised when using these data. Crop growth simulation results multiplied by the planted area for all investigated countries, except Belgium, are associated with production volume variation (5% t-test), supporting the hypothesis that planted area and yield are dependent and should be analyzed simultaneously. In Chapter 5, fertilizer application per unit area and simulation results multiplied by planted area will be examined for prediction of national production volumes for various countries.

Table 4.4. *Adjusted coefficients of determination* (R^2)*, t-values* (t_F, t_2) *of the regression according to equation (4.3). Period 1975-1991.*

	Country	R^2	t_F	t_2
Soft wheat	B	95.5	11.44	1.86
	D	88.5	4.13	4.24
	DK	98.6	5.87	10.66
	E	70.4	6.28	4.34
	F	98.3	11.53	8.24
	GR	87.8	2.63	10.84
	I	84.8	3.8	7.66
	IRL	94.2	5.58	6.92
	NL	86.4	6.87	6.26
	UK	97.2	3.48	6.06
Durum wheat	E	97.5	5.82	18.93
	F	98.2	4.52	17.6
	GR	94.8	3.95	13.64
	I	65.1	2.37	3.64

Table 4.5. *Nitrogen fertilizer (organic plus inorganic) applied to wheat.*

	Nitrogen fertilizer application $kg.ha^{-1}$													
	Soft wheat										Durum wheat			
Year	B	DK	D	E	F	GR	IRL	I	NL	UK	E	F	GR	I
75	91.4	140.7	146.0	42.2	89.5	79.8	40.4	82.8	135.1	101.5	37.4	71.1	72.5	64.5
76	109.2	133.6	154.7	44.5	106.2	89.3	49.4	92.6	150.7	95.5	39.8	76.5	78.2	55.2
77	105.7	147.4	163.2	43.1	101.0	71.8	68.5	81.6	140.6	122.1	49.8	67.6	57.8	54.4
78	136.4	152.0	166.9	47.9	125.2	95.0	92.0	97.6	176.1	134.8	60.1	85.6	87.2	70.2
79	135.0	156.1	183.7	50.8	122.1	87.0	102.3	97.1	165.0	139.0	62.9	89.9	72.6	78.9
80	125.6	147.2	198.3	63.0	135.2	96.3	111.5	102.8	177.1	159.9	77.5	104.0	99.9	78.7
81	143.8	169.2	187.9	42.0	129.7	88.4	126.2	110.0	194.9	162.7	41.2	99.7	90.5	76.4
82	164.9	200.9	184.0	53.4	145.0	98.2	139.5	119.7	218.5	176.1	81.5	99.3	90.7	75.5
83	152.1	200.1	188.5	59.6	145.6	73.6	163.6	117.1	219.1	193.7	61.8	112.5	74.7	75.8
84	200.9	228.8	188.7	85.4	191.6	103.0	180.4	121.5	235.7	238.3	123.9	146.4	108.3	93.8
85	188.6	184.3	197.8	84.1	180.4	85.6	185.2	116.7	211.1	206.8	102.5	149.4	65.7	86.3
86	207.8	200.0	206.1	72.5	169.3	89.3	201.2	119.5	269.3	226.4	94.2	137.3	99.1	88.2
87	174.0	190.2	211.0	91.3	176.0	87.4	217.2	140.1	235.7	264.3	112.5	158.9	94.0	92.3
88	210.2	224.5	227.4	98.6	200.4	102.5	230.1	129.6	249.7	203.4	127.0	147.4	80.0	88.2
89	220.7	248.8	212.0	86.0	210.2	102.1	252.6	133.8	259.3	223.9	116.8	166.6	104.5	79.0
90	203.1	257.5	218.8	88.9	219.6	77.7	271.9	148.9	260.4	237.2	120.6	188.3	69.4	86.3
91	228.8	251.5	238.8	94.0	232.6	108.7	262.4	155.5	272.5	252.8	129.6	203.5	124.7	125.9

Source: EUROCARE

5. Prediction[1]

5.1 Introduction

Timely and accurate information about total wheat production volume is an important management instrument for the European Union's Directorate General for Agriculture. Through the Common Agricultural Policy (CAP) the European Union (EU) attempts to regulate the common agricultural market (e.g. set-aside regulations, export subsidies, etc.).

Agrometeorological models, drought indices and trend extrapolations have proven to be useful tools for yield forecasting in various continents and under various climatic conditions (e.g. Vossen, 1990a; Palm & de Bast, 1987; Place & Brown, 1987; Dagnelie *et al.* 1983; Haun, 1982; Forest, 1982; Dagneaud *et al.*, 1981; Sakamoto, 1978; Brochet *et al.*, 1975). However, most of these models do not account for the influences of weather on crop growth and development. To overcome this shortcoming, Vossen (1992, 1990b), proposed the combined use of a linear time trend (Swanson & Nyankori, 1979) and results of a crop growth simulation model to explain the annual variation in the yield per unit area.

Crop growth simulation models integrate weather and soil influences on crop growth and simulate crop variables, such as leaf area index, phenological development stage, etc. Various methods to describe the trend in yield series have been tested by Palm & Dagnelie (1993). Their conclusion was that a simple linear time trend is sufficient in most cases, confirming thus the findings of Swanson & Nyankori (1979).

The model proposed by Vossen (1992, 1990b) was developed into the Crop Growth Monitoring System, CGMS[2] (Hooijer & van der Wal, 1994; Vossen, 1990b), which is currently operational at the Joint Research Centre (JRC) of the EU. It is used for the prediction of national yield per unit area for various crops for all EU member states. These yield predictions are subsequently multiplied by a planted area estimate, which results in predicted production volumes (see Subsection 3.7). The prediction method applied is similar to the method described in the next section.

De Koning *et al.* (1993) evaluated CGMS for various crop-country combinations. Their conclusion was that crop growth simulation results for most of the tested crop-country

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[1]Supit, I., 1997. *Predicting national wheat yields using a crop simulation and trend models.* Agricultural and Forest Meteorology, 88:199-214.
[2]See Chapter 3

combinations were not significantly associated with variation in national yield per hectare and the prediction accuracy did not improve when compared to prediction results derived from a linear time trend. These conclusions could, amongst others, be related to the methods applied to produce the agricultural statistics. Various methods exist to establish these statistics (see Subsection 3.2.5): in some countries detailed field observations are executed, in other countries less field observations are performed and additional yield information is retrieved from intervention offices, farmers co-operations, export firms, etc. The national yield per hectare is derived from the total harvested area and national production volume. Also, the applied method to establish these figures may be a source of uncertainty.

The objective of this chapter is to examine whether crop growth simulation results can be used for prediction of the soft and durum wheat production volume at country level. As an alternative to the linear time trend, the mean national nitrogen application to wheat ($kg.ha^{-1}$) is tested. The nitrogen application may reflect the farmers' reaction to the economic situation and may thus account for breaks in the trend as a result of the changing production environment.

5.2 Methodology

5.2.1 Simulation results and production volumes

In this chapter, simulation results provided by the operational version of CGMS are applied. The applied prediction models and the prediction method are described in Subsection 5.2.2 and 5.2.4, respectively.

Two situations are simulated: the potential and the water-limited situation. The potential situation is determined by temperature, daylength, solar radiation and crop characteristics, which are crop growth model input variables. The water-limited situation, in addition to the above-mentioned factors, is also determined by water availability derived from soil physical properties and rainfall. In both situations an optimal supply of nutrients is assumed. For each situation, both total above-ground dry matter per hectare and grain dry matter per hectare are calculated. Total dry matter is a more robust predictor than grain weight, since it is less sensitive to modelling errors in the distribution of assimilates (de Koning *et al.*, 1993). Multiplication by the area planted to wheat results in simulated values of national potential and national water-limited production volume of grains and biomass.

For various countries in Europe, a trend in the national production volume level has been observed over the last 30 years. This trend can be attributed to an expansion of the area planted to wheat and to an increase of the yield per hectare. This yield increase can be attributed to improved or new plant protection techniques, increased fertilizer application and new varieties (e.g. Falisse, 1992; Vossen, 1992, 1990b; Hough, 1990). According to Russell & Wilson (1994) however, new cultivars have had a limited contribution to the increased wheat production per hectare after the late 1960s. These authors attribute the production increment in the last decades mainly to increased application of fertilizer, crop protection products and growth regulators. It should be mentioned that the expansion of the area planted to wheat did not occur everywhere. For Greece, Spain and Italy, the area planted to soft wheat has decreased, leading in some cases to a decline of the national production volume.

The trend in the yield per hectare can be described as a function of time (Palm & Dagnelie, 1993; Palm & De Bast, 1988) or as a response to nitrogen fertilizer application (Weber, 1995; Buresh & Baanante, 1993; Cerrato & Blackmer, 1990; Nelson *et al.*, 1985). According to Swanson & Nyankori (1979) a linear time trend is sufficient, however, such a function may not account for breaks in the trend in the yield series due to changing regulations or a changing economy. Alternatively, the nitrogen fertilizer application may be seen as the result of the farmers' attempt to optimize his income, taking farming regulations and the economic situation into consideration. However, according to Nelson *et al.* (1985) no single fertilizer application model can satisfactorily describe all situations. In this chapter a simple linear relation is applied.

5.2.2 Models tested

In this chapter the following models have been evaluated:

Model I $$\hat{P}_T = b_0 + b_1 T + b_2 \hat{A}_T S_T \qquad (5.1)$$

Model II $$\hat{P}_T = b_0 + b_{1F} F_T + b_2 \hat{A}_T S_T \qquad (5.2)$$

Model III $$\hat{Y}_T = c_0 + c_1 T + c_2 S_T \qquad (5.3a)$$

$$\hat{P}_T = \hat{Y}_T * \hat{A}_T \qquad (5.3b)$$

Model IV $$\hat{Y}_T = c_0 + c_F F_T + c_2 S_T \qquad (5.4a)$$

$$\hat{P}_T = \hat{Y}_T * \hat{A}_T \qquad (5.4b)$$

where $\hat{P}_T$ is predicted production volume (ton) for year T, $\hat{Y}_T$ the predicted national yield per hectare for year T, (ton.ha^{-1}), b_0, b_1, b_F, b_2, c_0, c_1, c_2 and c_F, are regression constants, F_T the fertilizer application (kg.ha^{-1}) in year T, S_T a crop growth simulation result in year T (ton.ha^{-1}).

Models I and II include the cultivated wheat area in the prediction. These models assume that both planted area and weather contribute to the variation in production volume. Furthermore, it is assumed that weather, area and trend are not independent (e.g. Russell & Wilson, 1994; Swanson & Nyankori, 1979; Sakamoto, 1978). According to Winter & Musick (1993), Hough (1990) and Smith (1975) weather affects farm management practices such as timing of field operations, extent of the planted area, application of inputs, etc. According to Russell & Wilson (1994), early autumn sowings tend to give the highest yields. The extent of the area may, amongst others, be seen as an indication of the initial conditions of the wheat growing season

Models III and IV first predict the national yield per hectare, which is subsequently multiplied by the planted area. It is implicitly assumed that area does not contribute to the variation in yield per hectare. Model III has been evaluated by De Koning *et al.* (1993) using an earlier version of CGMS, assuming a constant initial soil moisture content for all countries at the beginning of the crop growth simulation. In this chapter, Model III is tested again using the most recent data and a version of CGMS, which estimates the initial soil moisture content at the beginning of the simulation. The initial soil moisture content is derived from water balance calculations taking soil type and weather of the previous days into account.

In evaluating a model, one would like to know how the prediction results compare with those of another simple base-line model. According to Weber (1995), trend extrapolations, although not very sophisticated, are rather successful in predicting yield, especially when "yield increase is driven by technical progress". Increased fertilizer application may mask the effects of yield variation due to weather variations. To demonstrate the usefulness of simulation results for predictions, each model should perform better than predictions based on trend functions or averages. Each complete model (i.e. trend plus simulation results or trend plus simulation multiplied by a planted area value) is hence compared to models based on either the time trend or the nitrogen fertilizer application (trend-only or base-line models).

5.2.3 Data

Within the framework of the MARS project, daily meteorological data for more than 600[3] weather stations, all over Europe, are routinely collected. Crop growth characteristics used in CGMS have been established by Boons-Prins *et al.* (1993). For calibration, data from field trials in the Netherlands, UK and Belgium have been used. These trials were carried out in the early eighties. Information regarding production volume (ton) and area planted to wheat (ha) is obtained from the regional databases[4] of EUROSTAT for 1975-1995. For Germany, production volume and area data of the provinces of the former DDR are entered in the official statistics from 1991 onward. The mean national nitrogen application estimates in $kg.ha^{-1}$ as applied in the SPEL model (Weber, 1995) are used. These data have been provided by EUROCARE, Bonn, Germany. Doubts exist on the quality of these data (EUROCARE, pers. comm.). Hence, care should be taken when interpreting the results.

The countries considered are Germany (D), France (F), Italy (I), The Netherlands (NL), Belgium (B), Luxembourg (L), United Kingdom (UK), Ireland (IRL), Denmark (DK), Greece (GR), Portugal (P) and Spain (E).

5.2.4 Prediction method

The prediction method described by Vossen & Rijks (1995) is applied. The following crop growth simulation results (on hectare basis) are examined: potential grain yield, water-limited grain yield, potential total above-ground dry matter yield and water-limited above-ground dry matter yield. For the period 1975-1994, for a moving window of 10 years, the regression coefficients are established and subsequently used for prediction of production volume or yield per hectare of the 11th year. The crop growth simulation result yielding the highest adjusted coefficient of determination over each 10-day period is used for prediction.

A smooth trend of any type over a large number of years assumes a continuity which might be unrealistic (de Koning *et al.*, 1993; Vossen, 1992; 1990b). The recent agricultural policy of the EU aims at a reduction of production volume and subsidies for various crops, including wheat (Vossen & Rijks, 1995). According to these authors the predictor should only be based on data from the recent past. The length of the series should nevertheless be long enough to give a sufficient number of degrees of freedom in the regression analysis. Gradual

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[3] Currently, daily observations from over 1200 weather stations are collected.

[4] Cronos and Regio database

shift in the time trend is allowed for by the shortness of the time series, used to derive the predictor.

Prediction starts in 1985. The regression analysis starts with the complete model, i.e. a trend function plus one crop growth simulation result or a trend function plus a crop growth simulation result multiplied by the area. The significant variables (5% t-test) are selected and non-significant variables omitted. If none of the explaining variables is significant, average production volume (Models I and II) or average yield (Models III and IV) over the last five years is used as predictor.

Generally, official area and nitrogen application figures are available one year or even two years after the growing season has ended. Therefore, these figures cannot be applied for timely prediction. To circumvent this problem, the following strategy was adopted. First, the observed area and nitrogen application data of the current year are introduced in the models. Subsequently, for those countries for which trend plus S_T or $A_T S_T$ provide more accurate prediction results than trend-only models, predicted area and nitrogen application values are applied. The following prediction methods for the nitrogen application and area values are tested:

- The official estimates of the previous season (i.e. the most recent information available) are used.
- In the period 1975-1994 for a moving window of 10 years, area and nitrogen applications are regressed on time, subsequently the regression coefficients are used for prediction of the 11th year. If the regression is not significant (5% t-test) the average over the last 5 years is used.

The prediction results are compared against the official data and for each country the results of the best performing method are introduced in the models.

5.2.5 Prediction criterion

Various approaches to quantify prediction accuracy exist. A distinction can be made as to how well a model fits to data and how well it predicts independent series (Power, 1993). Allen & Raktoe (1981) proposed the root mean square error, applied for accuracy analyses of economic forecasts (Theil, 1966; 1961), as an accuracy measure for predictions:

$$RMSE = \sqrt{\frac{1}{n}\sum_{T=1}^{n}\left(\hat{P}_T - P_T\right)^2} \qquad (5.5)$$

RMSE comprises a single value that summarizes the information from a comparison of observed and predicted values (Colson *et al.*, 1995). De Koning *et al.* (1993) normalized RMSE into the relative root mean square error (RRMSE):

$$RRMSE = \frac{\sqrt{\frac{1}{n}\sum_{T=1}^{n}\left(\hat{P}_T - P_T\right)^2}}{\overline{P}} \tag{5.6}$$

5.3 Results and discussion

Figures 5.1 and 5.2 present the sum of the production volumes of the twelve examined countries (EUR12) predicted with respectively the complete models and the trend-only models. Table 5.1 presents the RRMSE and RMSE for each individual country, as well as the total production volume for the twelve countries. Official area and nitrogen application values of the current year are considered.

The predicted production volumes for EUR12 were established by summation of the prediction results of the individual countries. Models applying trend plus crop growth simulation results were only considered for summation if they improved the prediction results in comparison to the trend-only model. If this was not the case the trend-only results were selected. The EUR12 predicted production volumes were compared with observed production volumes. Results demonstrate that Model IV provides the best prediction results. However, it can also be seen that for this model only for France (soft and durum wheat), Greece (soft and durum wheat) and the UK trend plus simulation results were selected; for the other crop-country combinations, crop growth simulation results did not improve prediction results. Differences between Model IV (trend-only or complete) and Model III (trend only or complete) are small. In contrast to Models I and II, crop growth simulation results do not improve the prediction accuracy for Model III at EUR12 level. The models that apply nitrogen application (Model II and IV) perform better than those that apply a linear time trend (Model I and III).

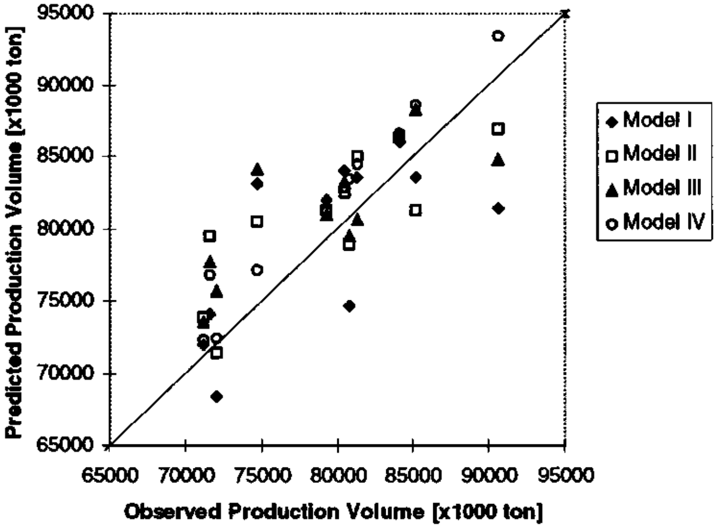

Figure 5.1. *Sum of the predicted production volumes (1985-1994) of the twelve examined countries plotted against the sum of the observed production volumes. Prediction results of trend plus crop growth simulation model are considered. Observed values of area and nitrogen application are applied.*

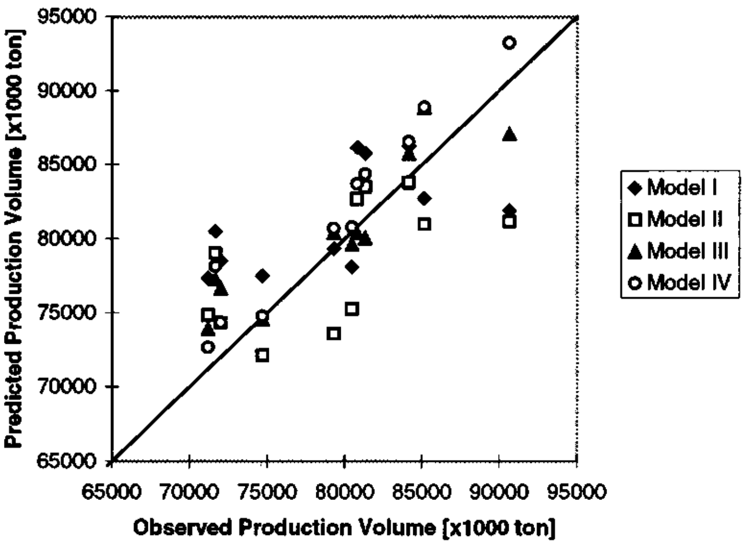

Figure 5.2. *Sum of the predicted production volumes (1985-1994) of the twelve examined countries plotted against the sum of the observed production volumes. Prediction results of the trend models (base-line models) are considered. Observed values of area and nitrogen application are applied.*

Table 5.1. *Prediction criteria* RRMSE *and* RMSE, *1985-1995. Current season's area and nitrogen application values have been applied.*

		Model I				Model II				Model III				Model IV			
	Country	Complete		Trend Only (T)		Complete		Trend Only (F)		Complete		Trend Only (T)		Complete		Trend Only(F)	
		RRMSE	RMSE x1000 ton	RRMSE	RMSE x1000 ton	RRMSE	RMSE x1000 ton	RRMSE	RMSE x1000 ton	RRMSE	RMSE x1000 ton	RRMSE	RMSE x1000 ton	RRMSE	RMSE x1000 ton	RRMSE	RMSE x1000 ton
Soft Wheat	B	0.088	120	0.088	120	0.075	102	0.066	90	0.113	154	0.113	154	0.077	105	0.074	100
	D	0.122	1630	0.119	1585	0.105	1396	0.132	1759	0.072	954	0.072	954	0.055	738	0.055	738
	DK	0.105	339	0.102	332	0.112	362	0.217	704	0.108	351	0.109	353	0.081	262	0.081	262
	E	0.247	1067	0.220	948	0.152	656	0.231	995	0.289	1244	0.200	863	0.165	710	0.136	588
	F	0.081	2344	0.099	2866	0.062	1801	0.083	2403	0.067	1936	0.056	1615	0.037	1074	0.038	1110
	GR	0.122	114	0.439	410	0.109	101	0.399	373	0.115	107	0.127	118	0.071	66	0.073	68
	I	0.100	434	0.123	538	0.070	303	0.127	552	0.058	252	0.058	252	0.022	97	0.022	97
	IRL	0.136	73	0.238	128	0.129	69	0.227	122	0.140	75	0.142	76	0.148	79	0.136	73
	L	0.149	6	0.070	3	0.094	4	0.097	4	0.107	4	0.093	4	0.092	4	0.085	4
	NL	0.136	131	0.174	168	0.133	129	0.155	150	0.086	84	0.086	84	0.047	45	0.047	45
	P	0.291	121	0.255	106	0.116	48	0.258	107	0.197	82	0.197	82	0.113	47	0.113	44
	UK	0.087	1165	0.117	1559	0.135	1800	0.121	1617	0.108	1445	0.103	1367	0.102	1355	0.105	1403
Durum Wheat	F	0.079	108	0.487	668	0.082	112	0.352	483	0.079	108	0.102	140	0.029	40	0.051	71
	E	0.581	364	0.717	449	0.394	247	0.616	386	0.709	444	0.628	393	0.398	249	0.397	248
	I	0.184	754	0.147	602	0.188	771	0.193	790	0.170	697	0.175	718	0.125	512	0.121	494
	GR	0.206	290	0.289	407	0.141	198	0.321	452	0.152	214	0.205	289	0.124	175	0.140	197
Total	EUR12	0.052	4153	0.067	5283	0.041	3248	0.050	3991	0.035	2779	0.035	2775	0.034	2674	0.037	2955

RMSE = root mean square error
RRMSE = relative root mean square error
(T) = time
(F) = nitrogen application

As a test, crop growth simulation results were aggregated to EUR12 scale, using the area planted to wheat of each individual country as a weighting factor. The same prediction procedure to predict EUR12 production volumes as for the individual countries was followed. The results were compared with the observed production volumes. The RRMSE for the complete models was 0.082, 0.060, 0.073 and 0.036 for Model I, II, III and IV, respectively. For trend-only the RRMSE was 0.066, 0.065, 0.043 and 0.047 for Model I, II, III and IV respectively. These results demonstrate that in contrast to Models I and III, the complete Models II and IV provided more accurate results than the trend-only models, suggesting that, at least at EUR12 level, depending on the type of trend function, the use of simulation results may yield more accurate prediction results.

Furthermore, comparison of these two methods to predict EUR12 production volumes suggests that, generally more accurate prediction results can be obtained using summation of national predicted values. The use of aggregated crop growth simulation results for yield and production volume prediction at European scale may add an extra source of uncertainty to the predictions. Crop growth varies in different climatological regions and the production volume may not be predicted correctly using only one predictor describing crop growth for the whole of Europe. For one region the water-limited yield could be the best predictor, for another region the potential yield could perform best.

Summation of individual prediction results may also reduce the prediction error in the EUR12 production volume, due to error compensation. It should be tested if production volume predictions for regions within a country could provide more accurate prediction results for national production volume when summed to national values (See Chapter 7).

For the individual countries Table 5.1 can be summarized as follows:

Model I: For soft wheat, the prediction model including crop growth simulation results plus a trend (complete model) performed better than the prediction based on trend-only for France, Greece, Italy, Ireland, The Netherlands and the UK. For durum wheat, for France, Spain and Greece the complete model predicted more accurately than the trend only.

Model II: For soft wheat, for all the investigated countries, except for Belgium and the UK the complete prediction model performed better than predictions based on nitrogen application alone. For durum wheat the complete model predicted more accurately than the prediction model based on nitrogen application alone for all the investigated countries.

Model III: For soft wheat, for Denmark, Greece and Ireland the complete prediction model predicted more accurately than the prediction based on trend-only, although differences are sometimes small. For the other countries, crop growth simulation results are either not significant (5% t-test) or do not improve the prediction results. For durum wheat the complete model performs better than the trend based prediction model for France, Greece and Italy.

Model IV: For soft wheat, only for France, Greece and the UK the complete model performed slightly better than the predictions based on fertilizer application alone. For durum wheat, the complete model performs better than the trend based model for France and Greece.

Comparison of Models I and III with respectively Models II and IV shows that for a majority of the crop-country combinations, models that use the nitrogen application predicted more accurately than models that apply a linear time trend. For comparison of Model I with Model II exceptions are Denmark, Luxembourg and the UK for soft wheat, and France and Italy for durum wheat. For these crop-country combinations Model I, either trend-only or complete, yielded more accurate results. For the comparison of Model III with Model IV the exception is Ireland (complete) and the UK (trend-only). A possible explanation for the northern European countries may be leaching of the applied fertilizers due to excessive rainfall during the growing season.

Comparison among the models demonstrates that the most accurate results are obtained using the nitrogen application only. The high RRMSE for Spain for durum wheat can be attributed to the very long and severe dry spell in the early nineties. The effect of the water shortages is underestimated by CGMS. Furthermore, for prediction of 1995 the potential biomass was selected as predictor and therefore water stress was not accounted for. Table 5.2 presents the number of times that trend, crop growth simulation results and average values were selected for prediction.

Table 5.2. *Number of times trend* (T), *crop growth simulation results* (S) *and the average* (AVG) *are selected for prediction. Maximum number of cases is 176.*

	Complete Model				Trend Only Model			
	I	II	III	IV	I	II	III	IV
T	73	144	89	164	105	114	79	162
S	136	152	62	50	-	-	-	-
Avg	16	2	60	11	71	62	97	14

In contrast to Models I and II, Models III and IV predict production volume much more often with the trend or average values. This may confirm the earlier made assumption that errors in the production volume and area observations may obscure the variation in the national yield per hectare, accounted for by weather. It may also confirm the assumption that the extent of the planted area partially accounts for the variation in yield and production volume, which may also be illustrated by the adjusted coefficient of determination of the complete models, averaged over the number of significant regressions, presented in Table 5.3. Generally, the adjusted coefficients of determination of Model I (complete) are higher than for Model III (complete) and those of Model II (complete) are higher than for Model IV (complete). Exceptions are Italy, Portugal and Spain (soft wheat) when time trend is applied (Model I and III) and Italy (soft and durum wheat) when the nitrogen application is used (Model II and IV). Furthermore, Table 5.3 presents t-values and significance, averaged over the number of significant regressions. Negative t-values for the time trend are observed for Spain, Greece and Italy for Model I trend only. However, when crop growth simulation results are added to the trend, the t-values change sign, indicating that the production volume reduction, observed in these countries, could also be related to weather. For several countries the complete models demonstrate a higher regression coefficient than the trend-only models. However, this does not necessarily imply that these models provide more accurate predictions. Predictors were selected based on regression analysis over the ten preceding years. For the current year another predictor could be more suitable. Crop growth simulation results may add an extra source of error to the predictions.

The results presented in Table 5.1 and Table 5.2 for Model III are similar to the findings of de Koning *et al.* (1993). In their research the initial soil moisture content at the beginning of the simulations was set to a fixed value. In this chapter the initial soil moisture content was derived from water balance calculations. However, better prediction results were not obtained using Model III. This may also be inherent to the selection of the predictors. Generally, water-limited yield or water-limited biomass production were rarely chosen as predictors, which may suggest that water balance calculations add an extra source of error to the crop growth simulation and thus the predictions.

Table 5.3. *Adjusted coefficients of determination* (R^2), *t-values* (t_t, t_c) *and significance* (sig.) *averaged over the number of significant regressions.*

	Country	Model I							Model II						
		Complete				Trend Only (T)			Complete				Trend Only (F)		
		R^2	t_t	t_c	sig.	R^2	t_t	sig.	R^2	t_t	t_c	sig.	R^2	t_t	sig.
Soft Wheat	B	0.56	3.62	-	0.010	0.56	3.62	0.010	0.87	9.89	3.02	<0.001	0.86	9.06	<0.001
	D	0.86	7.32	8.03	<0.001	0.78	6.28	0.001	0.68	3.29	6.65	0.009	0.57	3.72	0.011
	DK	0.96	9.18	13.27	<0.001	0.93	11.97	<0.001	0.99	6.45	12.56	0.000	0.72	5.06	0.002
	E	0.55	3.08	3.46	0.017	0.33	-2.34	0.047	0.86	7.36	5.78	0.001	0.50	3.29	0.019
	F	0.77	3.52	4.94	0.006	0.58	4.39	0.019	0.92	7.35	4.53	0.000	0.73	7.07	0.007
	G	0.86	3.32	8.31	0.001	0.65	-4.51	0.007	0.84	2.52	8.43	0.003	-	-	-
	I	0.62	2.34	4.44	0.017	0.54	-3.59	0.016	0.78	3.29	5.70	0.003	-	-	-
	IRL	0.78	3.19	5.09	0.001	0.52	3.57	0.021	0.80	3.03	5.32	0.001	0.62	4.27	0.010
	L	0.69	4.40	4.05	0.007	0.53	3.97	0.016	0.84	5.70	4.77	0.002	0.50	3.23	0.015
	NL	0.65	5.36	3.66	0.008	0.65	6.29	0.011	0.78	6.60	5.36	0.002	0.65	5.52	0.015
	P	0.57	3.71	3.65	0.014	0.58	3.69	0.006	0.78	5.18	5.75	0.003	0.48	3.08	0.018
	UK	0.81	3.49	9.47	0.005	0.68	5.64	0.010	0.84	13.27	6.03	0.002	0.75	11.71	0.006
Durum Wheat	F	0.98	4.03	20.77	<0.001	0.80	6.57	0.001	0.99	7.14	25.01	<0.001	0.70	5.10	0.003
	E	0.75	4.08	5.77	0.004	0.50	3.16	0.015	0.95	9.03	9.92	<0.001	0.78	6.80	0.001
	I	0.76	4.23	5.28	0.004	0.36	2.48	0.040	0.86	5.97	3.87	0.001	0.76	5.95	0.002
	GR	0.86	2.97	7.42	<0.001	0.72	4.97	0.002	0.92	3.68	9.16	<0.001	0.54	3.79	0.022
Total	Eur12	0.76	7.93	7.99	0.005	0.66	4.09	0.010	0.85	6.75	8.65	0.002	0.67	5.72	0.008

(T) = time
(F) = nitrogen application
t_t = t-value of trend
t_c = t-value of simulation result
\- = not significant (5% t-test)

Table 5.3 (continued). *Adjusted coefficients of determination* (R^2), *t-values* (t_t, t_c) *and significance* (sig.) *averaged over the number of significant regressions.*

	Country	Model III							Model IV						
		Complete				Trend Only (T)			Complete				Trend Only (F)		
		R^2	t_t	t_c	sig.	R^2	t_t	sig.	R^2	t_t	t_c	sig.	R^2	t_t	sig.
Sof t Wheat t	B	0.56	3.74	-	0.017	0.56	3.74	0.017	0.77	8.67	2.31	0.003	0.77	8.43	0.003
	D	0.78	6.06	-	0.001	0.78	6.06	0.001	0.47	3.09	-	0.021	0.47	3.09	0.021
	DK	0.51	3.75	2.77	0.019	0.50	3.23	0.018	0.87	9.27	2.57	<0.001	0.86	8.85	<0.001
	E	0.64	3.91	3.24	0.013	0.39	2.62	0.034	0.84	9.75	4.15	0.002	0.80	7.34	0.002
	F	0.65	4.26	2.72	0.008	0.54	3.53	0.014	0.91	12.01	4.39	<0.001	0.88	8.79	<0.001
	GR	0.50	-	3.22	0.015	-	-	-	0.64	4.33	3.75	0.007	0.63	4.23	0.007
	I	0.64	4.32	-	0.007	0.64	4.32	0.007	0.94	15.34	-	<0.001	0.94	15.34	<0.001
	IRL	0.53	4.19	2.51	0.025	0.64	4.81	0.016	0.54	3.59	2.60	0.023	0.52	3.77	0.023
	L	0.60	3.68	2.35	0.010	0.56	3.64	0.012	0.76	6.43	3.39	0.004	0.71	5.56	0.004
	NL	0.59	4.21	-	0.014	0.59	4.21	0.014	0.76	7.03	-	0.003	0.76	7.03	0.003
	P	0.58	3.79	-	0.009	0.58	3.79	0.009	0.73	5.44	-	0.004	0.73	5.44	0.004
	UK	0.71	6.39	3.42	0.006	0.65	4.91	0.011	0.76	12.01	3.33	0.011	0.73	10.33	0.013
Durum Wheat	F	0.77	4.70	3.81	0.003	0.58	3.78	0.009	0.95	12.10	3.85	<0.001	0.87	8.97	<0.001
	E	0.54	3.58	3.04	0.022	0.39	-1.02	0.032	0.90	12.22	4.95	<0.001	0.88	8.94	<0.001
	I	0.67	5.02	4.45	0.009	-	-	-	0.87	7.25	4.05	<0.001	0.74	5.80	0.004
	GR	0.57	-	3.68	0.011	-	-	-	0.80	5.24	3.33	0.001	0.70	5.34	0.004
Total	Eur12	0.60	4.58	3.97	0.012	0.59	3.92	0.013	0.68	7.12	6.36	0.004	0.62	6.33	0.004

(T) = time
(F) = nitrogen application
t_t = t-value of trend
t_c = t-value of simulation result
\- = not significant (5% t-test)

5.3.1 Using predicted area and nitrogen application estimates

Generally, official area and nitrogen application figures are available one or sometimes two years after the end of the growing season. Therefore, as is done in the operational practice, for each country area and nitrogen application values were predicted and the results of the best performing method (i.e. trend-average or the official value of previous year) were used as input in the prediction models. Figure 5.3 and Figure 5.4 present the EUR12 production volumes predicted with the complete models and the trend-only models. Crop growth simulation results for Model III did not improve the prediction results for the twelve countries grouped together, using area values of the current year. Therefore the complete model was not considered. Table 5.4 presents the RRMSE and RMSE for each individual country as well as the total for the twelve countries. Predicted area and nitrogen application values for individual countries were only used if the complete models performed better than trend-only models when observed values for the area and nitrogen application were used.

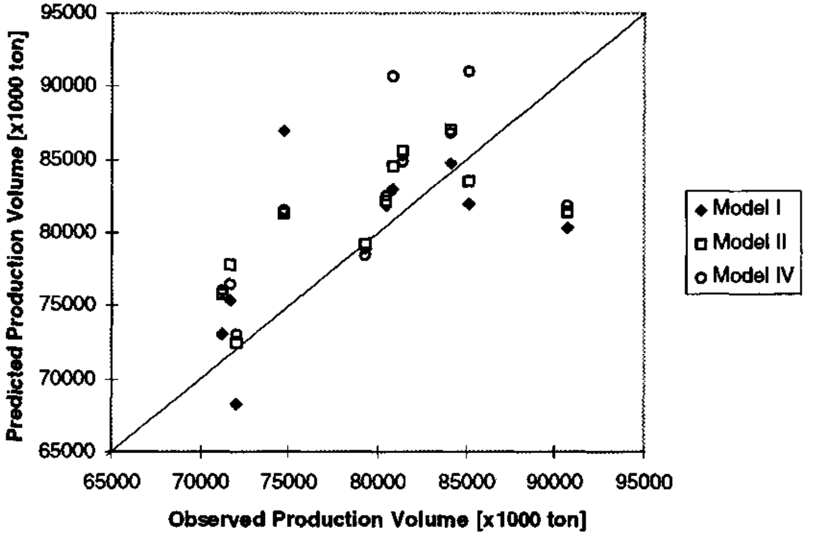

Figure 5.3. *Sum of the predicted production volumes (1985-1994) of the twelve examined countries plotted against the sum of the observed production volume. Prediction results of trend plus crop growth simulation model are considered. Predicted area and nitrogen applications are applied.*

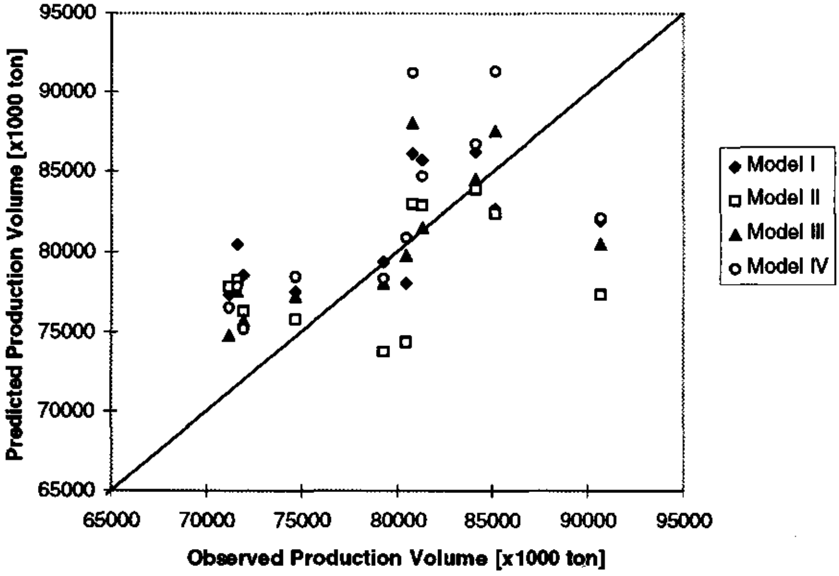

Figure 5.4. *Sum of the predicted production volumes (1985-1994) of the twelve examined countries plotted against the sum of the observed production volumes. Prediction results of the trend models (base-line models) are considered. Predicted area and nitrogen applications are applied.*

The EUR12 production volume was best predicted with the trend-only of Model III. However, differences with Model I (complete) and Model II (complete) are small. Model IV, either complete or trend-only, proved to be more sensitive to variation in the area and nitrogen application values than the others, and provided the least accurate prediction results.

Comparison of Tables 5.1 and 5.4 shows that generally Model III and IV are more sensitive to errors in the area and nitrogen application estimates than Model I and II. Therefore, from an operational point of view, for production volume prediction at national level, one could decide that a model that includes crop growth simulation results multiplied by an area estimate plus a trend function is more useful for production volume prediction. It should be mentioned that the choice, which model to apply, also depends on data availability at prediction time.

Table 5.5 presents a summary of the best performing models, applying predicted area and nitrogen application values. Comparison of Model I and Model III results at national level demonstrates that for most crop-country combinations, except for Spain (durum wheat) and Italy (soft wheat), Model I, either complete or trend-only, performs better than Model III. However, for the twelve countries grouped together, the trend-only of Model III performs best. Comparison of Model II and Model IV results at country level demonstrates that Model

II, either complete or trend-only, performed better than Model IV in 10 out of 16 crop-country combinations. For the twelve countries grouped together the complete Model II performed best.

5.3.2 Improvements to CGMS

Durum wheat production in France and Italy is mainly concentrated in the south. Better prediction results may be expected if CGMS results are aggregated over grid cells where durum wheat predominates. Currently, all grid cells covering the whole of France and Italy are being used. According to Russell & Wilson (1994) excess of water is more important than water shortage in limiting wheat growth in the wetter parts of Europe. Excessive rainfall may also lead to leaching of the applied fertilizers, resulting in a reduction of production. Currently, oxygen stress caused by excess of water in the root zone is not taken into account in CGMS and neither is the leaching of fertilizer caused by excessive rainfall.

Weights attributed to the land use systems included in CGMS do not change from year to year, which is not according to reality. Land use may change over time and therefore the attributed weights should change accordingly.

Calibration of CGMS crop input parameters is based on field trials in Belgium, United Kingdom and the Netherlands. Calibration of these parameters for other countries was not possible due to lack of information (Boons-Prins *et al.* 1993). Field trials for both soft and durum wheat in the other countries may improve input parameter estimation and hence the predictions.

The prediction results were compared against official statistics. Uncertainty exists about the quality of the official data. This may obscure the performance of the tested models. Methods applied to establish these statistics differ from country to country, which may bias the comparison among countries. A better appreciation of the tested models may be obtained when a uniform system to establish these statistics were to be introduced.

Table 5.4. *Prediction criteria* RRMSE *and* RMSE, *1985-1995. Estimated values of area and nitrogen application are applied.*

		Model I				Model II				Model III				Model IV			
	Country	Complete		Trend (T)		Complete		Trend (F)		Complete		Trend (T)		Complete		Trend (F)	
		RRMSE	RMSE x1000 ton	RRMSE	RMSE x1000 ton	RRMSE	RMSE X1000 ton	RRMSE	RMSE x1000 ton	RRMSE	RMSE x1000 ton	RRMSE	RMSE x1000 ton	RRMSE	RMSE x1000 ton	RRMSE	RMSE x1000 ton
Soft	B	-	-	0.088	120	-	-	0.086	117	-	-	0.103	140	-	-	0.089	122
Wheat	D	-	-	0.119	1585	0.133	1768	0.133	1755	-	-	0.139	1861	-	-	0.142	1894
	DK	-	-	0.102	332	0.137	445	0.170	552	0.136	442	0.143	465	-	-	0.142	474
	E	-	-	0.220	948	0.268	1154	0.268	1162	-	-	0.232	1001	-	-	0.256	1105
	F	0.094	2728	0.099	2866	0.087	2533	0.107	3106	-	-	0.080	2319	0.085	2456	0.093	2676
	GR	0.147	137	0.439	410	0.182	170	0.399	373	0.147	177	0.194	182	0.203	188	0.198	184
	I	0.115	500	0.123	538	0.121	525	0.127	552	-	-	0.095	413	-	-	0.099	433
	IRL	0.202	108	0.238	128	0.194	104	0.228	122	0.211	113	0.223	120	-	-	0.223	120
	L	-	-	0.070	3	0.090	4	0.059	5	-	-	0.094	4	-	-	0.075	3
	NL	0.138	133	0.174	168	0.134	130	0.173	168	-	-	0.144	140	-	-	0.137	132
	P	-	-	0.255	106	0.285	118	0.279	116	-	-	0.281	116	-	-	0.301	125
	UK	0.112	1492	0.117	1559	-	-	0.130	1726	-	-	0.117	1574	0.129	1722	0.126	1682
Durum	F	0.328	451	0.487	668	0.321	440	0.422	580	0.328	388	0.368	506	0.307	422	0.358	492
Wheat	E	0.658	412	0.717	449	0.556	349	0.626	392	-	-	0.633	397	-	-	0.625	391
	I	-	-	0.147	602	0.160	657	0.179	732	0.161	466	0.171	702	-	-	0.177	723
	GR	0.205	290	0.289	407	0.179	252	0.300	422	0.206	252	0.222	313	0.190	272	0.219	308
Total	EUR12	0.060	4743	0.067	5283	0.059	4654	0.063	4969	-	-	0.058	4586	0.067	5335	0.069	5465

\- = crop growth simulation results do not improve the prediction
RMSE = root mean square error
RRMSE = relative root mean square error
(T) = time
(F) = nitrogen application

Table 5.5. *Summary of the best performing prediction models when respectively a linear time trend and the nitrogen application are used to describe the trend in yield and production volume. Predicted area and nitrogen application values are applied.*

		Time Trend				Nitrogen Application			
	Country	Model I		Model III		Model II		Model IV	
		Complete	Trend Only	Complete	Trend Only	Complete	Trend Only	Complete	Trend Only
soft wheat	B		X						X
	D		X				X		
	DK		X			X			
	E		X						X
	F	X				X			
	GR	X				X			
	I				X				X
	IRL	X				X			
	L		X						X
	NL	X				X			
	P		X				X		
	UK	X							X
durum wheat	F	X				X			
	E			X		X			
	I		X						X
	GR	X				X			
	EUR12				X	X			

5.4 Conclusions

Crop growth simulation results may not be significantly associated with variation in yield per hectare, however, for a majority of the tested countries, crop growth simulation results multiplied with planted area are associated with the variation in the production volume. For several countries crop growth simulation results can be used for timely prediction of national production volumes. The prediction results depend on the selection of the trend function. For some countries better prediction results may be obtained from a model applying only nitrogen application as predictor, however, this model appeared to be less robust. Doubts about the accuracy of the nitrogen application data may result in a rejection of this model in favor of another model.

Although the CGMS prediction results are not always more accurate when compared to results obtained with trend extrapolations or simple averages, the use of CGMS in combination with a trend function certainly holds a promise for further improvement. Time trend models or average functions are easy to apply and can hardly be improved, however, they cannot account for weather effects on crop growth and development. Also, breaks in the trend in yield and production volume series as a result of changes in the economic situation or regulatory changes in the CAP cannot be accounted for. In that respect a model combining nitrogen fertilizer application and crop growth simulation results offers better perspectives.

6. Global Radiation[5]

6.1 Introduction

The Common Agricultural Policy (CAP) of the European Union (EU) seeks to improve the management of agricultural resources within Europe. Therefore, a realistic assessment of the potential and actual productivity of European agriculture is required. Understanding the factors influencing the productivity is hence essential. Weather is one amongst these factors, it determines the potential, or may reduce the actual growth of crops.

Within the framework of the MARS project (Monitoring Agriculture with Remote Sensing) of the Joint Research Centre (JRC) of the EU the weather impact on crop growth and phenological development is monitored with the Crop Growth Monitoring System (CGMS). This system operates on grid cells of 50 x 50 km covering the whole of Europe. For each grid cell, the required inputs are soil characteristics and management practices (i.e. sowing density, planting date, etc.) and daily meteorological data: maximum and minimum temperature, vapor pressure, windspeed and global solar radiation. These data are obtained from interpolation of observations from the existing network of meteorological stations, and are retrieved from the Global Telecommunication System (GTS). The MARS project and the CGMS are described in Chapters 2 and 3, respectively.

Solar radiation provides the energy for photosynthesis and transpiration of crops and is one of the meteorological factors determining potential yield. However, daily measurements of solar radiation are far too scarce and dispersed for operational use in crop growth simulation models. Test on data received via the GTS for the first six months of 1997 revealed that none of the 1200 recording stations had reported global radiation. Various alternatives exist to solve this problem: (i) the use of average values, (ii) spatial interpolation, (iii) estimation global radiation values from remote sensing data or (iv) estimation of these values from other climatic variables.

Nonhebel (1993) studied the consequences of using average values in a crop growth simulation model. This author concluded: "Due to the variation in daily and annual global radiation and the nonlinear relation between radiation and photosynthesis, the use of average data (even over short periods) to replace missing data must be avoided."

[5] Supit, I., Kappel, R.R. van, 1998. *A simple method to estimate global radiation.* Solar Energy, 63:147-160.

Spatial interpolation is not always an option since the density of recording stations is too sparse in various regions in Europe and Northern Africa. According to Hubbard (1994), to account for more than 90% of the spatial variation in global radiation in the high plains of the USA, distance between the observing station and the location for which the value has to be interpolated, should be less than 30 km.

In recent years, advances in processing satellite data for estimating global radiation at the ground surface have been made (Ceballos *et al.*, 1997; Perez *et al.*, 1997; Noia *et al.*, 1993a,b; Shmetz, 1989; Cano *et al.*, 1986). Iehlé *et al.* (1997) reviewed various methods to retrieve global radiation from satellite data, with the aim to identify and subsequently test a method that could be applied operationally in CGMS. As a requisite, the method had to be accurate over an extended period of time without external adjustment (i.e. sensor calibration) and valid for the whole of Europe and Northern Africa. The Heliosat method using Meteosat B2 data was tested. Although the results were promising, the overall quality of the estimates was not sufficient for operational use.

Alternatively, global radiation may be estimated from other climatic variables such as sunshine duration (Boisvert *et al.*, 1990; Soler, 1990; Rietveld, 1978; Ångström, 1924); air temperature range (De Jong & Stewart, 1993; Hargreaves *et al.*, 1985; Bristow & Campbell, 1984), precipitation (De Jong & Stewart, 1993) and cloud-cover (Barker, 1992; Davies & McKay, 1988; Brinsfield *et al.*, 1984).

In CGMS the equation postulated by Ångström (1924) and modified by Prescott (1940) to its present form is applied:

$$H = H_o\left(a_a + b_a \frac{n}{D}\right) \tag{6.1}$$

where H is daily global radiation ($MJ.m^{-2}.d^{-1}$), H_o daily extra terrestrial radiation ($MJ.m^{-2}.d^{-1}$), n daily sunshine duration (h), D the astronomical daylength (h) and a_a and b_a are empirical constants. The constants a_a and b_a have been derived for many locations (Martinez-Lozano *et al.*, 1984; Golchert 1981; Cowley 1978). Various attempts have been undertaken to model these constants (Abdel Wahab, 1993) and improve the equation. However, according to Gueymard *et al.* (1995): "Few authors have introduced new elements that would generalize Ångström's concept and replace the present "educated guess" exercise for choosing the right coefficients with a true model incorporating enough physical underpinning and climatological input so that such a modified equation could acquire worldwide validity." Although the Ångström-Prescott equation can be improved and more accurate results are possible

(Gueymard *et al.*, 1995), it is used for many agro-meteorological applications (e.g. van Keulen & Wolf, 1986; Frère & Popov, 1979) and the results are considered to be sufficient, especially when integrated over, for example, the length of the growing season.

Provided that values of the constants are available, the Ångström-Prescott method is easy to apply. However, for many locations daily sunshine duration is not observed or irregularly broadcasted via GTS, and therefore the Ångström method, or any other method applying sunshine duration (e.g. Soler, 1990), is not always applicable. Test on data received via GTS for the first six months of 1997 demonstrated that on average 500 of the 1200 recording stations had reported sunshine duration.

The objective of this chapter is to develop a simple method to provide daily estimates of global radiation, as input for CGMS, when sunshine duration data are not available and hence methods applying this parameter cannot be used. The method to be developed should use meteorological observations readily available on GTS. As a requisite, the method should also use cloud observations that could alternatively be retrieved from meteorological satellite data.

A simple empirical model to estimate daily global radiation was developed and has been tested for various locations in Europe, ranging from Finland to Spain. Cowley (1978) demonstrated that for the UK constants of the Ångström-Prescott equation, interpolated to a grid of 40 x 40 km, could be used for the estimation of global radiation. Similar to this author, the spatial variation in the regression constants for the UK and Ireland has been studied. Finally, for some selected locations, regression constants have been interpolated and used as an estimator for global solar radiation.

6.2 Method

A simple method that relates the difference between maximum and minimum temperature to global radiation (Hargreaves *et al.*, 1985) is:

$$H = a_h H_o \sqrt{(T_{\max} - T_{\min})} + c_h \qquad (6.2)$$

where T_{max} is maximum temperature (°C), T_{min} is minimum temperature (°C), and a_h and c_h are empirical constants. This model has been validated for the Senegal River Basin (Hargreaves *et al.*, 1985). The advantage of this model is that temperature observations are always available on GTS. However, the estimation accuracy, applying this model for locations in Europe is limited (Choisnel *et al.*, 1992)

Clouds and their accompanying weather patterns are among the most important atmospheric phenomena restricting the availability of solar radiation at the earth's surface. Various studies to estimate global solar radiation from observations of various cloud layer amounts and cloud types have been executed (e.g. Barker, 1992; Davies & McKay, 1988). Most of the models proposed in these studies require detailed knowledge of local hourly sums of direct and diffuse radiation for clear skies as well as hourly cloud cover observations (Brinsfield *et al.*, 1984). Since this information is not available on GTS, these models cannot be considered as an alternative for estimation of daily global radiation.

Analysis of cloud cover and global radiation showed a nonlinear relationship. According to Wörner (1967) and cited by Kasten & Czeplak (1980), square root equations could be used for relating global radiation to different cloud amounts. In this chapter we propose a simple empirical model which can be considered a combination of the Wörner and Hargreaves *et al.* model:

$$H = H_o \left\{ a_n \sqrt{(T_{max} - T_{min})} + b_n \sqrt{(1 - C_w/8)} \right\} + c_n \tag{6.3}$$

where C_w is the mean of the total cloud cover of the daytime observations (octa) and a_n, b_n and c_n are empirical constants. Daily global radiation, sunshine duration, minimum and maximum temperature and total cloud cover data were collected for a large number of stations in Europe for the period 1970 - 1995. Hubbard (1994) demonstrated that the length of the data series should be more than one year "to characterize the seasonal patterns in spatial variability". In this chapter a fifteen year period was assumed to be sufficient to eliminate possible effects due to changes in atmospheric transparency as a result of changes in air pollution (Cowley, 1978). Constants of the proposed method were established with data of the period 1970-1985, using the least square method. For the same period, constants for the Ångström method, equation (6.2) and the cloud term of equation (6.3), were established (results are not presented in this chapter). The regression analysis pertained to the entire year. In some cases, however, shorter data series were available. Data after 1985 were used for testing. However, for Switzerland, Sweden and for most stations of the Czech Republic no data were available before 1981, 1983 and 1984, respectively. For these stations, different periods to establish the constants and to test the method have been selected. H_o values were established using the subroutine applied by Penning de Vries *et al.* (1989). This routine is valid for latitudes below 67° N, therefore stations north of this latitude were not selected in this chapter. Daily global radiation values were estimated and compared with observed values using data series not used for establishing the regression constants. To assess the predictive accuracy for daily radiation estimates, the root mean square error (RMSE) and the mean bias error (MBE) were calculated. The RMSE is calculated similar to equation (5.5). MBE is calculated as:

$$\mathrm{MBE} = \frac{\sum\left(H - \hat{H}\right)}{N_{obs}} \tag{6.4}$$

where N_{obs} is the number of observations. CGMS, and crop growth simulation models in general, simulate daily assimilation using intercepted daily global radiation. These assimilates are subsequently integrated over the length of the growing season. Errors in the estimates should be as low as possible and systematic over- or underestimation of the input data should be avoided. For graphical presentation and to demonstrate that the proposed model does not systematically over- or underestimate, for various locations monthly values were calculated through summation of daily estimates. The estimated monthly values were compared with observed values. Monthly values for one year were calculated and the selected year was not used for establishing the regression constants.

Due to a lack of global radiation observations for various meteorological stations used in CGMS, no regression constants are available. For application in CGMS, these constants have to be estimated and subsequently used to estimate global radiation. It is, therefore, necessary to show that accurate estimates of global radiation can be achieved using interpolated regression coefficients. A pilot study was carried out to analyze the estimation accuracy. This study concentrated mainly on the United Kingdom and Ireland. For 55 stations for which daily observations of cloud cover, global radiation and minimum and maximum temperature were available, regression statistics were calculated. Only those stations where the coefficient of determination, $R^2 > 0.85$ and the standard error of estimate < 3.0 $MJ.m^{-2}.d^{-1}$ were used for interpolation of the regression constants. The interpolation was made to a 50 x 50 km grid using Kriging. For a number of test stations, which were not used to calculate the regression constants, daily global radiation values were estimated. The constants for these stations were read directly from the maps shown in Figures 6.5, 6.6 and 6.7.

6.3 Results and discussion

Table 6.1 presents the regression statistics. The average coefficient of determination, R^2, is 0.91, indicating that the proposed model accounts well for the variability in daily global radiation. Average R^2 applying the Ångström-Prescott method is 0.95. Furthermore, it is demonstrated that the variability of the regression constants for all the tested locations is limited. For a number of stations lower R^2 values are observed. The standard error of estimate for these stations is in most cases higher than average, indicating an increased effect of outliers in the data.

In this chapter the presented R^2 values are higher than those presented in other studies (e.g. Cowley, 1978). This is a consequence of the regression method applied. In this study H_o, plus H_oX were regressed on H, where X is the fraction of sunshine duration, the square of the temperature range or the second term of equation (6.3). Prior to testing the Ångström-Prescott and the proposed method on the independent data set, this regression method was compared to the regression of X on H/H_o. The correlation between the residual and H_o, the distribution of the residuals and the standard error of estimate were examined. This analysis included the entire year and all locations. The results demonstrated that the independent variables multiplied by H_o provided a better fit to H, which may suggest that yearly regression coefficients are not independent of H_o. In Table 6.2 a summary of performance statistics of both the Ångström-Prescott and the proposed method is presented. The MBEs for both methods are generally low, indicating that for either method the systematic under- or overestimation is small. Generally, the difference in RMSE between the two methods is about 1 $MJ.m^{-2}.d^{-1}$. On the whole, the performance statistics presented in Table 6.2 demonstrate that the Ångström-Prescott method compares favorably to the proposed method. Differences, however, are small. Average RMSE and MBE for the tested locations using the proposed method are 2.48 $MJ.m^{-2}.d^{-1}$ and -0.25 $MJ.m^{-2}.d^{-1}$ respectively. For the Ångström-Prescott method these values are 1.92 $MJ.m^{-2}.d^{-1}$ and -0.22 $MJ.m^{-2}.d^{-1}$.

Average coefficients of determination, R^2, for the temperature range (i.e. first term) and the cloud term (i.e. second term) of equation (6.3) for the tested locations are 0.80 and 0.86, respectively. Average RMSE and MBE for the temperature range are 3.61 $MJ.m^{-2}.d^{-1}$ and -0.17 $MJ.m^{-2}.d^{-1}$, respectively. For the cloud term these values are 2.99 $MJ.m^{-2}.d^{-1}$ and -0.27 $MJ.m^{-2}.d^{-1}$, respectively. The lowest accuracy is observed for the temperature range term, confirming thus the findings of Choisnel *et al.* (1992). Concerning cloud observations Harrison & Coombes (1986) remarked that: "the weather observer generally overestimates cloud cover compared to cloud cover inferred from sunshine data". According to Brinsfield *et al.* (1984) observers have a tendency to underestimate low overcast conditions and overestimate high overcast conditions. "Human biasing" accounted for most of the differences in their study. The method proposed in this chapter is less sensible to "human" biasing than the cloud term of equation (6.3) since it also includes a temperature range term.

Table 6.1. *Regression coefficients, a_n, b_n, c_n, standard errors* (s.e.), *and coefficient of determination* R^2 *of the regression of daily global radiation according to the proposed method.*

Country	Location	Regression coefficients							Period
		a_n	(s.e.)	b_n	(s.e.)	c_n	(s.e.)	R^2	
Czech R.	Hradec K.	0.083	0.0012	0.368	0.0049	-0.674	0.056	0.92	01-JAN-70 - 31-DEC-85
	Ostrava P.	0.066	0.0019	0.364	0.0081	-0.410	0.094	0.90	01-JAN-84 - 31-DEC-89
	Luka	0.072	0.0016	0.391	0.0077	-	-	0.91	01-JAN-84 - 31-DEC-89
	Svratouch	0.083	0.0016	0.375	0.0078	-	-	0.89	01-JAN-84 - 31-DEC-89
	Kucharovice	0.078	0.0019	0.364	0.0080	-0.440	0.090	0.92	01-JAN-84 - 31-DEC-89
	Kocelovice	0.078	0.0019	0.387	0.0087	-0.330	0.092	0.91	01-JAN-84 - 31-DEC-89
	Praha	0.079	0.0018	0.361	0.0079	-0.561	0.088	0.91	01-JAN-84 - 31-DEC-89
	Tusimice	0.066	0.0022	0.373	0.0091	-0.293	0.096	0.90	01-JAN-84 - 31-DEC-89
	Churanov	0.068	0.0022	0.418	0.0086	0.176	0.106	0.88	01-JAN-84 - 31-DEC-89
	Usti Nad Lab.	0.077	0.0023	0.388	0.0089	-1.003	0.097	0.90	01-JAN-84 - 31-DEC-89
Finland	Helsinki-V.	0.052	0.0016	0.557	0.0069	-0.207	0.0486	0.94	01-JUL-71 - 31-DEC-85
	Jokioinen	0.056	0.0014	0.545	0.0070	0.197	0.0471	0.93	01-JAN-71 - 31-DEC-85
	Jyvaskyla	0.033	0.0015	0.615	0.0071	0.189	0.0440	0.94	01-JAN-71 - 31-DEC-85
France	Ajaccio	0.074	0.0016	0.484	0.0055	-0.452	0.0853	0.91	01-JUL-70 - 31-DEC-85
	La Rochelle	0.080	0.0017	0.477	0.0059	0.478	0.0728	0.90	01-JUL-70 - 31-DEC-85
	Nice	0.097	0.0018	0.503	0.0051	-1.422	0.0803	0.93	01-JAN-70 - 31-DEC-85
	Perpignan	0.077	0.0026	0.483	0.0094	-	-	0.90	01-OCT-80 - 31-DEC-85
	Reims	0.081	0.0014	0.381	0.0062	-0.261	0.0641	0.93	01-JAN-75 - 31-DEC-85
	Rennes	0.081	0.0012	0.415	0.0052	-	-	0.92	01-JAN-70 - 31-DEC-85
	Strasbourg	0.073	0.0014	0.427	0.0061	-0.346	0.0629	0.93	01-AUG-74 - 31-DEC-85
Germany	Braunlage	0.075	0.0014	0.401	0.0056	-0.174	0.0586	0.89	01-JAN-70 - 31-DEC-85
	Braunschweig	0.085	0.0013	0.377	0.0057	-0.478	0.0557	0.90	01-JAN-70 - 31-DEC-85
	Dresden	0.053	0.0014	0.477	0.0060	-0.125	0.0574	0.90	01-AUG-74 - 31-DEC-85
	Fichtelberg	0.057	0.0016	0.547	0.0062	0.266	0.0724	0.87	01-JAN-70 - 31-DEC-85
	Hamburg-S.	0.071	0.0014	0.437	0.0065	-0.613	0.0545	0.91	01-JAN-70 - 31-DEC-85
	Heiligend.	0.045	0.0019	0.637	0.0069	-0.221	0.0695	0.88	01-JAN-70 - 31-DEC-85
	Hohenpeiss.	0.060	0.0014	0.547	0.0050	0.508	0.0701	0.89	01-JAN-70 - 31-DEC-85
	Norderney	0.069	0.0018	0.562	0.0055	-0.240	0.0641	0.89	01-JAN-70 - 31-DEC-85
	Potsdam	0.089	0.0012	0.352	0.0056	-0.663	0.0550	0.92	01-JAN-70 - 03-DEC-85
	Trier-P.	0.085	0.0012	0.378	0.0055	-0.592	0.0574	0.91	01-JAN-70 - 31-DEC-85
	Weihenstephan	0.084	0.0012	0.378	0.0050	-	-	0.92	01-JAN-70 - 31-DEC-85
	Wuerzburg	0.083	0.0012	0.367	0.0052	-0.319	0.0539	0.92	01-JAN-70 - 31-DEC-85
Ireland	Birr	0.067	0.0011	0.546	0.0058	-	-	0.93	01-JAN-71 - 31-DEC-84
	Dublin Airport	0.060	0.0013	0.570	0.0059	-0.448	0.0539	0.94	01-JAN-76 - 31-DEC-85
	Kilkenny	0.062	0.0010	0.578	0.0055	-0.335	0.0481	0.93	01-JAN-70 - 31-DEC-85
	Valentia Obs.	0.072	0.0013	0.599	0.0056	-0.521	0.0559	0.91	01-JAN-70 - 31-DEC-85
Italy	Bologna	0.079	0.0016	0.406	0.0058	-	-	0.93	01-JAN-70 - 31-DEC-85
	Bolzano	0.078	0.0013	0.417	0.0058	-0.630	0.0695	0.92	01-JAN-70 - 31-DEC-85
	Brindisi	0.071	0.0020	0.552	0.0060	1.203	0.1061	0.87	01-JAN-70 - 31-DEC-85
	Cagliari/Elmas	0.078	0.0020	0.463	0.0065	0.938	0.1016	0.88	01-JAN-70 - 31-DEC-85
	Capo Palinuro	0.070	0.0026	0.441	0.0073	1.600	0.1254	0.80	01-JAN-70 - 31-DEC-85
	Crotone	0.062	0.0021	0.475	0.0071	1.569	0.0989	0.88	01-JAN-70 - 31-DEC-85
	Foggia-Ame.	0.090	0.0017	0.400	0.0067	0.407	0.0871	0.90	01-JAN-70 - 31-DEC-85
	Gela	0.063	0.0023	0.578	0.0053	0.633	0.1078	0.90	01-JAN-70 - 31-DEC-85
	Genova/Sestri	0.081	0.0019	0.514	0.0055	-0.293	0.0829	0.91	01-JAN-70 - 31-DEC-85
	Messina	0.092	0.0022	0.494	0.0057	0.706	0.0962	0.89	01-JAN-70 - 31-DEC-85
	Napoli -Cap.	0.087	0.0022	0.429	0.0075	-0.229	0.1100	0.86	01-JAN-70 - 31-DEC-85
	Olbia/Costa S.	0.074	0.0022	0.515	0.0082	-0.411	0.1197	0.90	01-JAN-70 - 31-DEC-85

\- constant c not significant (5% t-test)

Table 6.1. (continued). *Regression coefficients, a_n, b_n, c_n, standard errors* (s.e.), *and coefficient of determination* R^2 *of the regression of daily global radiation according to the proposed method.*

Country	Location	Regression coefficients							Period
		a_n	(s.e.)	b_n	(s.e.)	c_n	(s.e.)	R^2	
Italy	Pantelleria	0.065	0.0049	0.632	0.0147	-	-	0.90	01-JAN-70 - 31-DEC-85
	Pescara	0.081	0.0016	0.460	0.0058	-	-	0.92	01-JAN-70 - 31-DEC-85
	Pisa/S.G.	0.085	0.0015	0.436	0.0057	-0.223	0.0784	0.92	01-JAN-70 - 31-DEC-85
	Roma/Ciamp.	0.095	0.0022	0.422	0.0082	-	-	0.89	01-JAN-70 - 31-DEC-85
	Torino/C.	0.090	0.0018	0.376	0.0066	-0.413	0.0863	0.91	01-JAN-70 - 29-DEC-85
	Trapani/Birgi	0.058	0.0019	0.559	0.0063	1.258	0.1023	0.88	01-JAN-70 - 31-DEC-85
	Trieste	0.080	0.0016	0.492	0.0050	0.184	0.0720	0.92	01-JAN-70 - 31-DEC-85
	Ustica	0.060	0.0023	0.572	0.0060	1.998	0.0930	0.89	01-JAN-70 - 31-DEC-85
	Venezia/T.	0.075	0.0020	0.431	0.0066	-0.417	0.0862	0.90	01-JAN-70 - 31-DEC-85
	Vigna di Valle	0.102	0.0015	0.398	0.0053	-	-	0.92	01-JAN-70 - 31-DEC-85
Spain	Granada-A.	0.086	0.0024	0.280	0.0098	1.924	0.1579	0.89	01-JAN-77 - 31-DEC-82
	Murcia	0.115	0.0012	0.255	0.0062	-	-	0.89	01-AUG-75 - 31-DEC-85
	Mallorca	0.068	0.0016	0.440	0.0076	-	-	0.90	01-MAY-75 - 31-DEC-85
	Salamanca	0.085	0.0022	0.314	0.0097	1.409	0.1221	0.91	01-JAN-76 - 31-DEC-81
Sweden	Froson	0.043	0.0022	0.621	0.0103	-	-	0.93	01-JAN-83 - 31-DEC-89
	Goteborg	0.028	0.0025	0.658	0.0111	-0.655	0.0785	0.91	01-JAN-83 - 31-DEC-89
	Karlstad	0.048	0.0023	0.587	0.0101	-0.187	0.0710	0.93	01-JAN-83 - 31-DEC-89
	Lulea	0.043	0.0026	0.627	0.0107	-0.287	0.1012	0.92	14-JAN-83 - 27-NOV-89
	Lund	0.080	0.0014	0.430	0.0066	-	-	0.94	01-JAN-83 - 31-DEC-89
	Norrkoping	0.050	0.0023	0.542	0.0106	-0.272	0.0729	0.93	01-JAN-83 - 31-DEC-89
	Stockholm	0.066	0.0016	0.467	0.0070	-	-	0.94	01-JAN-83 - 31-DEC-89
	Umea	0.047	0.0019	0.587	0.0094	-	-	0.94	01-JAN-83 - 31-DEC-89
	Vaxjo	0.053	0.0019	0.496	0.0089	-0.138	0.0690	0.93	01-JAN-83 - 31-DEC-89
	Visby	0.037	0.0023	0.649	0.0089	-0.059	0.0746	0.93	01-JAN-83 - 31-DEC-89
Switzerl	Basel	0.087	0.0017	0.364	0.0071	-0.414	0.0906	0.92	01-JAN-81- 31-DEC-86
	Guettingen	0.083	0.0014	0.367	0.0071	-	-	0.92	01-JAN-81- 31-DEC-86
	Neuchatel	0.074	0.0015	0.420	0.0072	-	-	0.92	01-JAN-81- 31-DEC-86
	Lugano	0.074	0.0021	0.436	0.0076	-0.494	0.1020	0.91	01-JAN-81- 31-DEC-86
	Chur	0.080	0.0017	0.371	0.0084	-	-	0.90	01-JAN-81- 31-DEC-86
	Geneve	0.068	0.0021	0.460	0.0091	-0.235	0.1025	0.92	01-JAN-81- 31-DEC-86
	Interlaken	0.087	0.0020	0.351	0.0081	-0.363	0.1095	0.90	01-JAN-81- 31-DEC-86
	Glarus	0.069	0.0019	0.379	0.0074	-0.390	0.0977	0.90	01-JAN-81- 31-DEC-86
UK	Aberporth	0.064	0.0017	0.622	0.0063	-0.577	0.0641	0.90	01-JAN-70 - 19-NOV-85
	Belfast/ A.	0.057	0.0015	0.578	0.0073	-0.584	0.0536	0.90	01-JAN-70 - 08-NOV-85
	Bracknell	0.060	0.0019	0.478	0.0096	-0.256	0.0799	0.90	01-JAN-71 - 31-DEC-85
	Dundee	0.058	0.0019	0.584	0.0091	-0.550	0.0666	0.89	01-JUL-73 - 31-DEC-85
	East Malling	0.068	0.0016	0.436	0.0071	-0.573	0.0650	0.87	01-JAN-70 - 31-DEC-85
	Eskdalemuir	0.047	0.0013	0.560	0.0067	-0.215	0.0512	0.90	01-JAN-70 - 31-DEC-85
	Jersey	0.068	0.0024	0.591	0.0082	-0.384	0.0853	0.90	01-JAN-70 - 31-DEC-85
	Lerwick	0.078	0.0015	0.608	0.0063	-0.542	0.0469	0.91	01-JAN-70 - 31-DEC-85
	London W.	0.061	0.0018	0.477	0.0076	-0.557	0.0621	0.91	01-JAN-70 - 31-DEC-85
	Wallingford	0.057	0.0017	0.472	0.0086	-0.444	0.0675	0.90	01-APR-71 - 31-DEC-85

- constant c not significant (5% t-test)

Table 6.2. *Summary of performance statistics and mean daily measured radiation ($MJ.m^{-2}.d^{-1}$).*

	Location	Mean	Ångström-Prescott		Proposed method		Period
			MBE	RMSE	MBE	RMSE	
Czech Rep	Hradec Kralove	10.55	-0.47	1.59	-0.32	2.28	01-JAN-86-31-DEC-95
	Ostrava Poruba	10.01	0.41	1.65	0.04	2.46	01-JAN-90-31-DEC-95
	Luka	10.44	0.01	1.79	0.09	2.51	01-JAN-90-31-DEC-95
	Svratouch	10.41	0.03	1.57	-0.12	2.46	01-JAN-90-31-DEC-95
	Kucharovice	11.29	0.35	1.47	0.26	2.29	01-JAN-90-31-DEC-95
	Kocelovice	11.06	0.21	1.46	0.42	2.46	01-JAN-90-31-DEC-95
	Praha	10.09	0.12	1.47	-0.11	2.18	01-JAN-90-31-DEC-95
	Tusimice	10.41	0.12	1.61	0.58	2.49	01-JAN-90-31-DEC-95
	Churanov	10.50	0.36	1.91	0.04	2.70	01-JAN-90-31-DEC-95
	Usti Nad Lab.	9.81	-0.01	1.93	0.30	2.63	01-JAN-90-31-DEC-95
Finland	Helsinki-Vantaa	9.34	-0.25	1.38	-0.08	2.24	01-JAN-86 – 31-AUG-96
	Jokioinen	9.07	-0.46	1.48	-0.31	2.27	01-JAN-86 – 31-AUG-96
	Jyvaskyla	8.53	-0.22	1.41	-0.15	2.12	01-JAN-86 – 31-AUG-96
France	Ajaccio	15.24	-0.05	1.36	-0.20	2.25	01-JAN-86 – 31-DEC-89
	La Rochelle	13.11	-0.24	1.41	0.16	2.64	01-JAN-86 – 31-DEC-89
	Nice	14.42	-0.30	1.40	-0.15	2.13	01-JAN-86 – 31-DEC-89
	Perpignan	14.05	-0.15	1.49	-0.12	2.35	01-JAN-86 – 31-DEC-89
	Reims	11.13	0.01	1.53	0.34	2.20	01-JAN-86 – 31-DEC-89
	Rennes	11.22	-0.01	1.40	-0.28	2.11	01-JAN-86 – 31-DEC-89
	Strasbourg	10.63	0.14	1.52	0.00	1.98	01-JAN-86 – 31-DEC-89
Germany	Braunlage	9.72	0.30	1.59	0.35	2.57	01-JAN-86 – 31-DEC-95
	Braunschweig	10.04	-0.11	1.39	0.19	2.28	01-JAN-86 – 31-DEC-95
	Dresden	10.45	0.18	1.67	0.54	2.53	01-JAN-86 – 31-DEC-95
	Fichtelberg	9.94	0.54	1.84	0.29	2.80	01-JAN-86 – 31-DEC-95
	Hamburg-Sasel	9.33	-0.06	1.51	-0.21	2.43	01-JAN-86 – 31-DEC-95
	Heiligendamm	10.36	-0.16	1.75	0.04	2.79	01-JAN-86 – 31-DEC-95
	Hohenpeiss.	11.47	-0.10	1.67	-0.20	2.65	01-JAN-86 – 31-DEC-95
	Norderney	10.33	0.24	1.60	0.14	2.72	01-JAN-86 – 31-DEC-95
	Potsdam	10.09	0.00	1.45	-0.43	2.54	01-JAN-86 – 31-DEC-95
	Trier-Petrisberg	10.56	0.06	1.55	0.12	2.38	01-JAN-86 – 31-DEC-95
	Weihenstephan	11.22	0.02	1.57	-0.35	2.31	01-JAN-86 – 31-DEC-95
	Wuerzburg	10.90	0.04	1.59	0.24	2.26	01-JAN-86 – 31-DEC-95
Ireland	Birr	10.15	-0.50	1.84	-0.61	1.84	01-JAN-85 – 14-OCT-85
	Dublin Airport	8.88	0.11	1.42	0.06	1.66	01-JAN-86 – 31-DEC-88
	Kilkenny	9.67	-0.15	1.68	-0.02	1.74	01-JAN-86 – 31-DEC-88
	Valentia Obs.	9.55	-0.15	1.84	-0.07	1.93	01-JAN-86 – 31-DEC-88
Italy	Bologna	9.46	-2.20	3.32	-3.10	4.27	01-JAN-86 – 01-JUN-89
	Bolzano	11.74	-1.20	2.63	-1.17	2.45	01-JAN-86 – 31-DEC-87
	Brindisi	14.02	-0.65	2.71	-1.23	2.80	01-JAN-86 – 27-DEC-91
	Cagliari/Elmas	15.40	0.09	2.52	-0.17	2.42	01-JAN-86 – 12-AUG-91
	Capo Palinuro	15.63	1.12	3.27	0.74	3.00	01-JAN-86 – 27-DEC-91
	Crotone	15.22	-1.02	2.74	-0.87	2.44	01-JAN-86 – 02-MAY-89
	Foggia-Ame.	14.37	0.60	2.53	0.99	3.03	01-JAN-86 – 29-DEC-91
	Gela	16.78	1.24	4.99	-0.64	2.54	01-JAN-86 – 29-DEC-92
	Genova/Sestri	11.22	-1.07	2.60	-1.42	3.04	01-JAN-86 – 22-JUN-89
	Messina	15.05	0.54	3.12	0.45	3.19	01-JAN-86 – 28-DEC-91
	Milano / Linate	5.24	-0.38	1.72	0.07	1.40	01-JAN-86 – 28-FEB-86
	Napoli -Cap.	14.11	-0.42	2.56	-1.78	3.02	01-JAN-86 – 31-MAY-89

Table 6.2 (continued). *Summary of performance statistics and mean daily measured radiation ($MJ.m^{-2}.d^{-1}$).*

	Location	Mean	Ångström-Prescott		Proposed method		Period
			MBE	RMSE	MBE	RMSE	
Italy	Olbia/Costa S.	15.56	0.00	2.18	-0.84	2.49	01-JAN-86 - 28-APR-88
	Pescara	13.67	-1.56	2.94	-1.45	2.96	01-JAN-86 - 29-OCT-87
	Pisa/S. Giusto	11.82	-0.41	2.62	-0.49	2.74	01-JAN-86 - 20-DEC-91
	Roma/Ciamp.	12.36	-2.59	3.84	-3.24	4.24	01-JAN-86 - 22-DEC-91
	Torino / Caselle	7.28	1.36	3.11	1.77	3.71	02-SEP-89 - 10-DEC-91
	Trapani/Birgi	16.07	0.41	4.46	-0.63	2.67	01-JAN-86 - 29-DEC-92
	Trieste	9.98	-0.77	2.48	-1.32	2.87	01-JAN-86 - 26-DEC-91
	Ustica	15.21	-0.86	2.58	-1.95	3.23	01-JAN-86 - 27-DEC-91
	Venezia/Tess.	11.13	-1.35	3.07	-1.61	2.98	01-JAN-86 - 31-DEC-87
	Vigna di Valle	13.11	0.04	2.24	-0.30	2.27	01-JAN-86 - 22-DEC-91
Spain	Granada - Aero	19.35	0.46	1.54	-0.20	1.77	01-MAY-83 - 31-DEC-83
	Murcia	16.59	0.28	1.50	-0.26	2.30	01-JAN-86 - 31-DEC-87
	Mallorca	15.52	-0.53	1.99	-0.02	2.70	01-JAN-86 - 31-DEC-89
	Salamanca	15.48	0.25	1.59	-0.31	2.24	01-JAN-82 - 31-DEC-82
Sweden	Froson	8.99	-0.03	1.57	0.28	2.24	01-JAN-90 - 31-AUG-96
	Goteborg	9.77	-0.22	1.45	-0.23	2.47	01-JAN-90 - 31-AUG-96
	Karlstad	9.92	-0.31	1.45	-0.04	2.24	01-JAN-90 - 31-AUG-96
	Lulea	10.21	-0.11	1.51	0.09	2.20	14-JAN-90 - 31-AUG-96
	Lund	10.06	-0.33	1.56	-0.20	2.24	01-JAN-90 - 31-AUG-96
	Norrkoping	9.77	-0.29	1.46	-0.18	2.17	01-JAN-90 - 31-AUG-96
	Stockholm	9.61	-0.18	1.39	0.23	2.00	01-JAN-90 - 31-AUG-96
	Umea	9.44	-0.23	1.44	-0.11	2.13	01-JAN-90 - 31-AUG-96
	Vaxjo	9.42	-0.44	1.53	-0.25	2.19	01-JAN-90 - 31-AUG-96
	Visby	10.75	-0.27	1.46	-0.25	2.35	01-JAN-90 - 31-AUG-96
Switserland	Basel	10.79	-0.36	1.71	-0.03	2.16	01-JAN-87 - 31-DEC-95
	Guettingen	10.75	-0.25	1.67	0.19	2.24	01-JAN-87 - 31-DEC-95
	Neuchatel	11.04	-0.60	1.82	0.21	2.29	01-JAN-87 - 31-DEC-95
	Lugano	11.61	0.02	1.75	0.15	2.11	01-JAN-87 - 31-DEC-95
	Chur	11.43	-0.92	1.76	-0.54	2.34	01-JAN-87 - 31-DEC-95
	Geneve	11.70	-1.02	1.93	-0.28	2.28	01-JAN-87 - 31-DEC-95
	Interlaken	11.28	-0.10	1.74	0.11	2.44	01-JAN-87 - 31-DEC-95
	Glarus	10.14	-0.14	1.61	0.10	2.21	01-JAN-87 - 31-DEC-95
UK	Aberporth	10.50	-0.28	1.57	0.07	2.69	04-MAR-86 - 31-JUL-96
	Belfast/ Adergr.	8.83	-0.31	1.45	-0.16	2.12	11-MAR-86 - 31-JUL-96
	Bracknell	9.92	-0.20	1.44	0.16	2.44	01-JAN-86 - 31-AUG-96
	Dundee	8.66	-0.59	2.15	-0.16	2.46	01-JAN-86 - 28-JUN-96
	East Malling	10.01	-0.08	1.47	0.31	2.53	01-JAN-86 - 30-JUN-96
	Eskdalemuir	8.05	-0.24	1.53	-0.05	2.25	01-JAN-86 - 31-AUG-96
	Hemsby	10.66	0.08	1.53	0.35	2.59	01-JAN-90 - 31-JUL-96
	Jersey	11.37	-0.35	1.62	-0.31	2.59	01-JAN-86 - 31-DEC-95
	Lerwick	7.80	-0.34	1.61	-0.33	2.22	01-JAN-86 - 31-JUL-96
	London Weath.	8.93	-0.03	1.36	0.23	2.10	08-JAN-86 - 31-MAR-92
	Wallingford	9.60	0.19	1.87	0.17	2.48	01-JAN-86 - 30-JUN-96

MBEs and RMSEs for Italian stations are higher than for the other stations. The reason for these larger errors could be related to the bimetallic actinographs used. These recorders have only half the accuracy of the thermopile pyranometers in use at most European stations. RMSEs for locations in Northern Europe do not differ very much from those for locations in Southern Europe, indicating that the relative prediction error for the southern locations is lower.

To demonstrate that the proposed model does not systematically over- or underestimate, for various locations monthly values were calculated through summation of daily estimates and compared with observed values. For a selection of stations plots of estimated versus observed monthly totals are presented in Figures 6.1, 6.2, 6.3 and 6.4. For daily estimates the fit may not be perfect, however, for monthly totals the accuracy of the estimate is acceptable and comparable to the accuracy achieved by the Ångström-Prescott method. This was considered as an indication of the applicability of the proposed method.

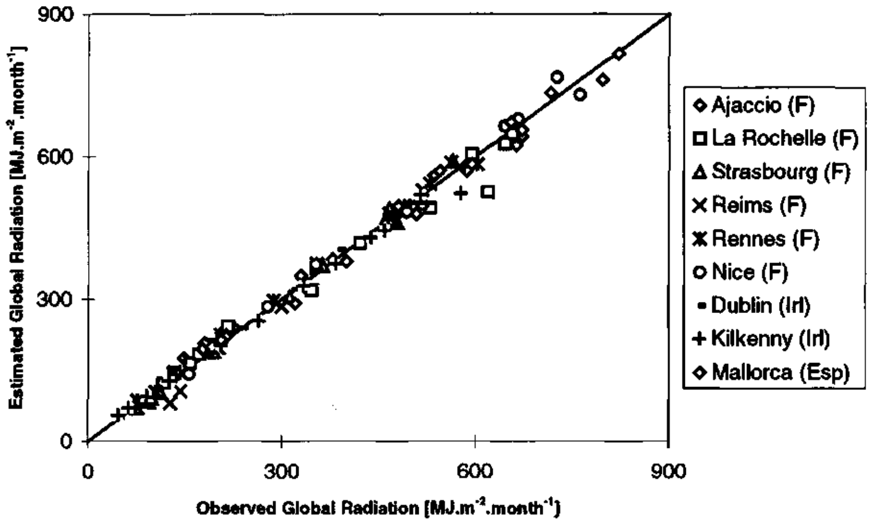

Figure 6.1. *Monthly total values of global radiation, calculated with daily estimates using the proposed method, plotted against observed values for 1987 for various locations in France (F), Ireland (Irl) and for one location in Spain (Esp).*

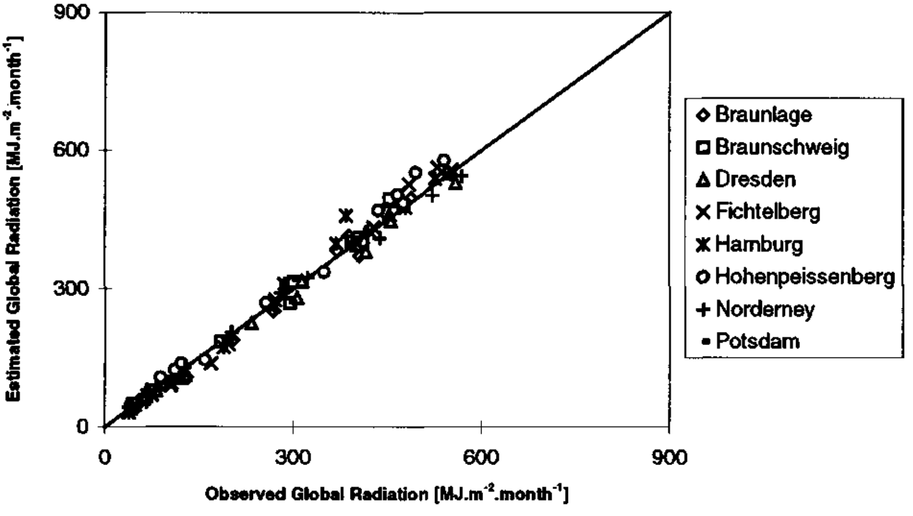

Figure 6.2. *Monthly total values of global radiation, calculated with daily estimates using the proposed method, plotted against observed values for various locations in Germany for 1987*

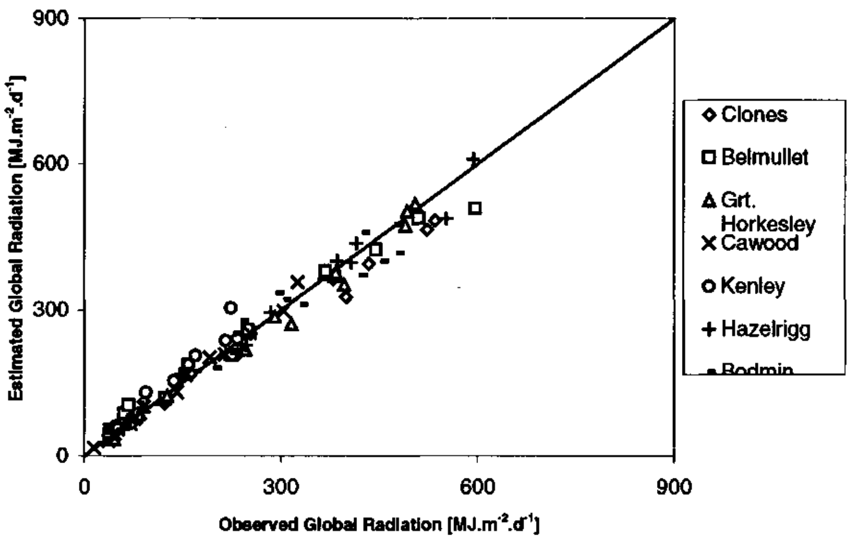

Figure 6.3. *Monthly total values of global radiation, calculated with daily estimates using the proposed method, plotted against observed values for various locations in Great Britain for 1987.*

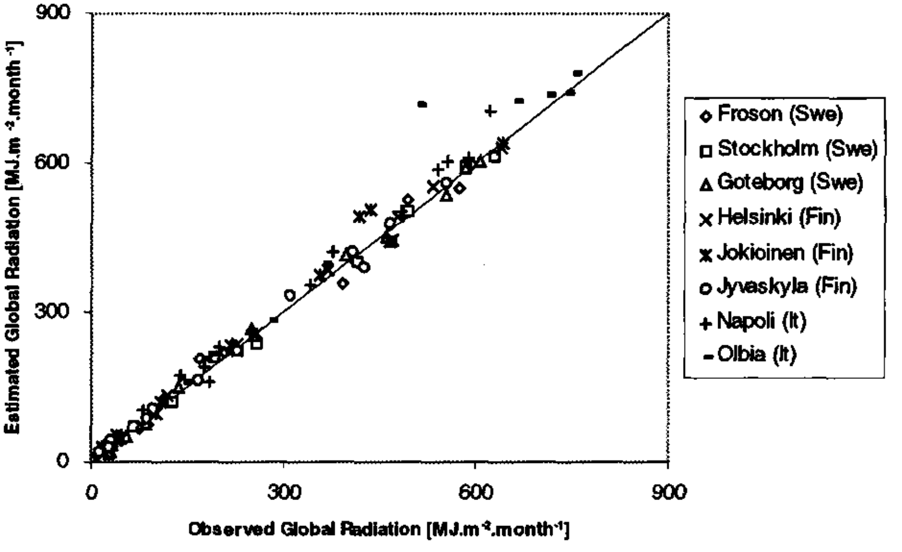

Figure 6.4. *Monthly total values of global radiation, calculated with daily estimates using the proposed method, plotted against observed values for various locations in Finland (Fin), Italy (It) and Sweden (Swe). For Finland and Italy 1987 is considered, for Sweden 1990.*

The regression analysis was repeated; first, monthly regression coefficients were determined and subsequently, daily values were estimated, using independent data. These estimates were summed to monthly totals. The results showed that, although the R^2 values for the winter months were low (for January average R^2 was 0.67), better monthly estimates were obtained for this period when monthly coefficients were used. However, for crop growth simulation applications (e.g. CGMS), where the simulated assimilation is integrated over the length of the growing season, the contribution of the assimilation during winter to the seasonal total is small. For the other months, differences between estimates calculated with monthly and estimates calculated with yearly coefficients were small or negligible.

Figures 6.5, 6.6 and 6.7 show the spatial distribution of the regression constants of the proposed method for the United Kingdom and Ireland. The regression constants show a smooth gradient. The pattern of the isolines of a_n and b_n decrease from west to east. The pattern of variation in the regression constants is similar to that in the annual average global radiation as illustrated in the European Solar Radiation Atlas (Palz & Greif, 1996). Specific well known features of the UK, namely the lower values of global radiation observations in the metropolitan area of greater London and the Midlands (Cowley, 1978) and higher temperatures than the surrounding regions, may possibly be correlated to (i) the strong gradient in a_n values observed in these regions and (ii) lower b_n values for South-East UK in general. These higher temperatures are thought to be the result of a very high population density and a strong degree of industrialization. The lower values of global radiation observations in the metropolitan area of greater London and the Midlands may also be correlated to air pollution. According to Wendisch *et al.* (1996) aerosol concentration is directly linked to the lower transparency of the atmosphere and consequently to lower radiative quantities. According to an anonymous reviewer of this paper, lower global radiation observations in the Midlands may be correlated to the intensified convection over mountainous regions.

For the locations Belmullet (54°14'N, 10°00'W), Clones (54°11', 7°14') in Ireland and Sunderland (54°54'N, 1°23W'), Hazelrigg (54°01'N, 2°45'W), Cawood (51°50'N, 1°08'W), Great Horkesley (51°57'N, 0°53'E) and Kenley (51°18'N, 0°05'W) in the UK, daily values of global radiation were estimated using interpolated regression constants. Monthly values were estimated and plotted against observed values (Figure 6.8). The agreement is good. Table 6.3 shows the interpolated constants and the accuracy obtained for the tested locations. MBE and RMSE values are comparable to those for other locations in Great Britain.

Table 6.3. *Interpolated constants a_n, b_n, c_n, mean daily measured global radiation, mean bias error* (MBE) *and root mean square error* (RMSE) *for estimates of daily global radiation* ($MJ.m^{-2}.d^{-1}$) *for the considered period applying the interpolated constants.*

Location	a_n	b_n	c_n	Mean Obs	MBE	RMSE	Year
Clones	0.062	0.570	-0.360	8.93	0.67	2.72	1985
Belmullet	0.067	0.590	-0.400	8.83	0.07	2.88	1985
Sunderland	0.054	0.550	-0.350	9.38	0.60	1.99	1995
Hazelrigg	0.052	0.580	-0.470	9.21	-0.01	2.47	1990
Cawood	0.054	0.520	-0.330	9.93	-0.21	2.01	1990
Great Horkesly	0.068	0.450	-0.450	10.28	0.36	2.20	1995
Kenley	0.064	0.470	-0.500	7.30	-1.24	2.41	1994

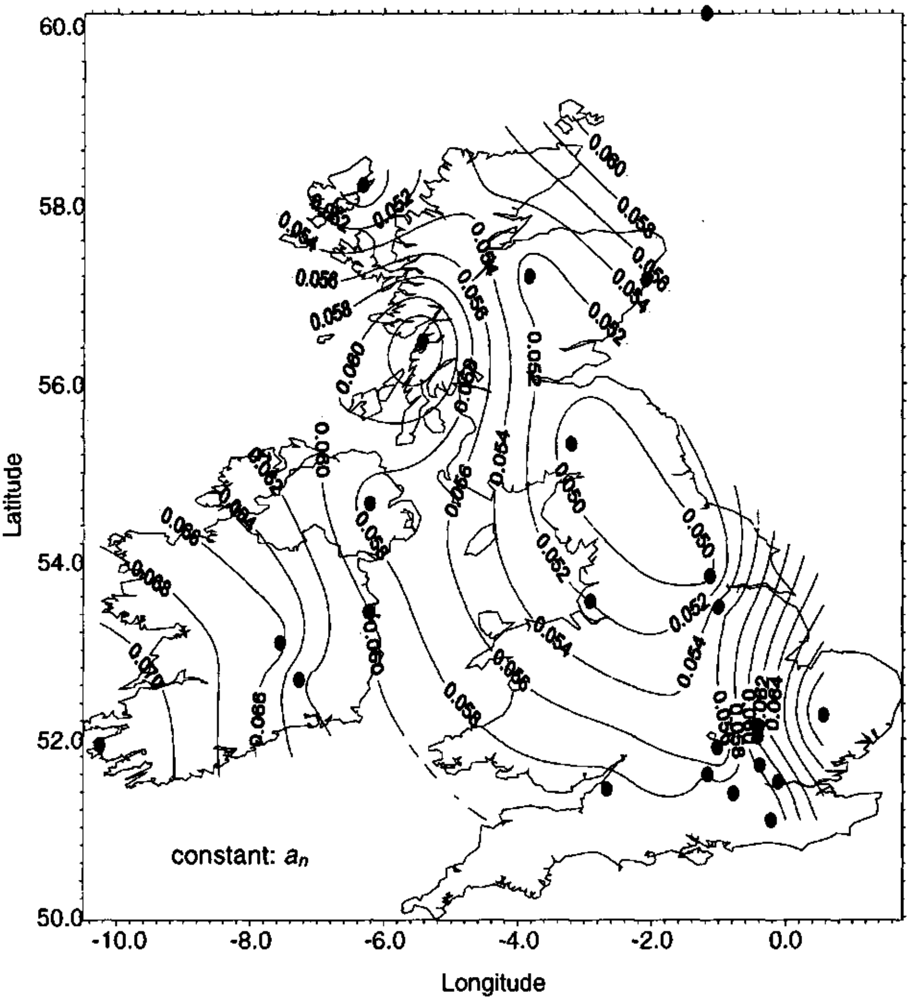

Figure 6.5. *Variation in the constant a_n of the proposed method over Great Britain and Ireland. Black dots indicate the location of the meteorological stations used for interpolation.*

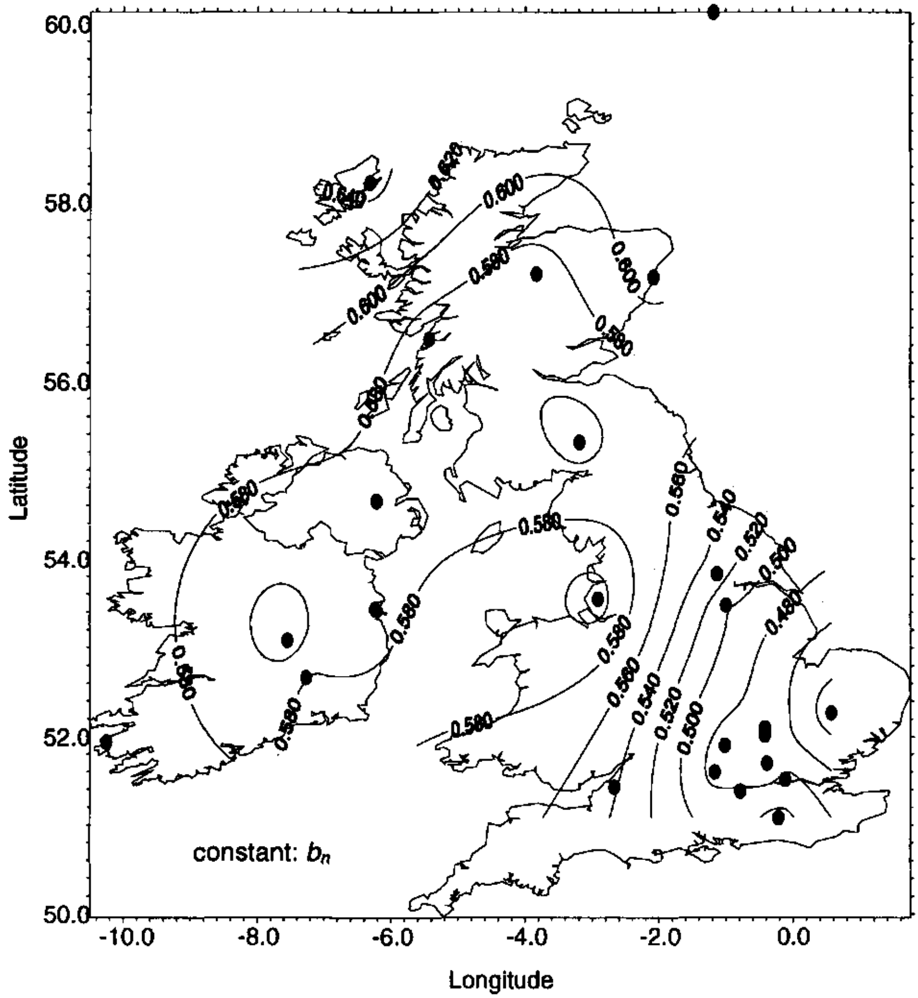

Figure 6.6. *Variation in the constant b_n of the proposed method over Great Britain and Ireland. Black dots indicate the location of the meteorological stations used for interpolation.*

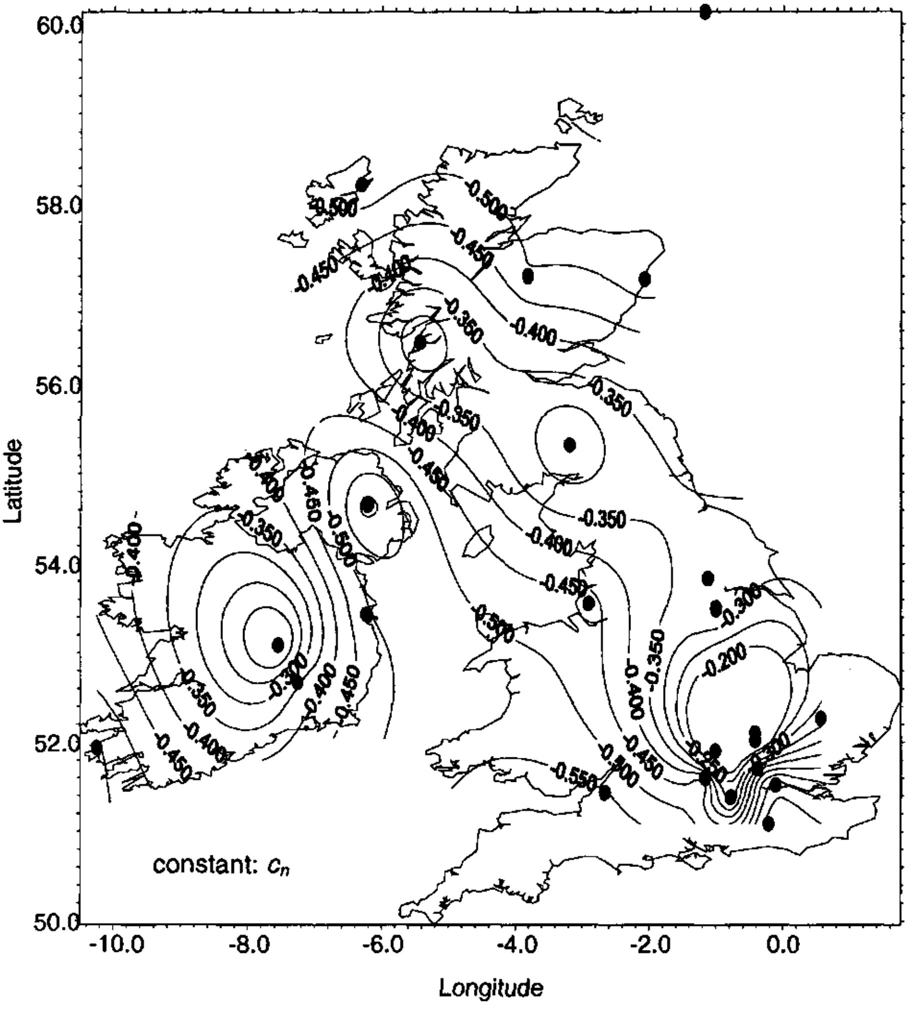

Figure 6.7. *Variation in the constant c of the proposed method over Great Britain and Ireland. Black dots indicate the location of the meteorological stations used for interpolation.*

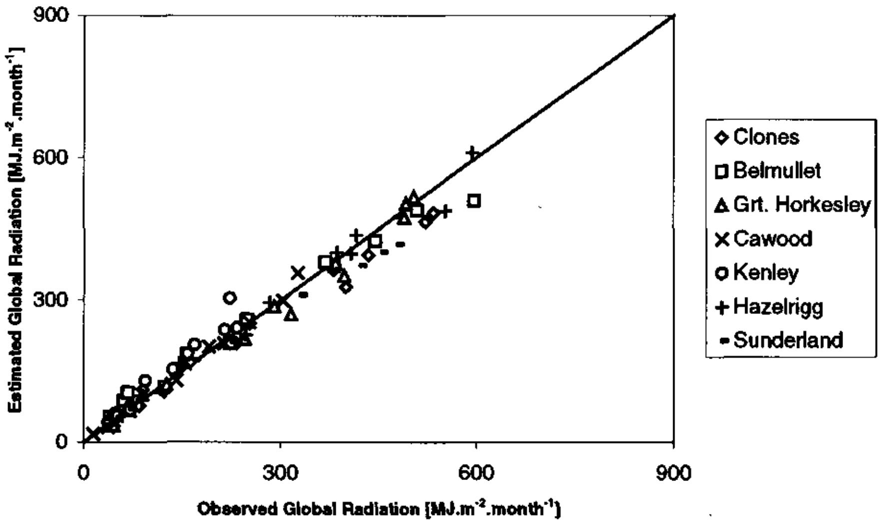

Figure 6.8. *Monthly total values of global radiation, calculated with daily estimates using the proposed method, plotted against observed values for various locations in Great Britain and Ireland. The constants a, b and c are interpolated to the location and subsequently used for the calculation of the radiation estimates.*

6.4 Conclusions

A method for estimating daily global radiation has been developed and tested. Average RMSE and MBE for the comparison between observed and estimated global radiation for the tested locations using the proposed method is 2.48 $MJ.m^{-2}.d^{-1}$ and -0.25 $MJ.m^{-2}.d^{-1}$, respectively. For the Ångström-Prescott method these values are 1.92 $MJ.m^{-2}.d^{-1}$ and -0.22 $MJ.m^{-2}.d^{-1}$. Generally, the Ångström-Prescott method provides better estimates, however, differences with the proposed methods are small.

Although the proposed method may not yield accurate estimates of H at daily level, as input for CGMS these estimates are satisfactory since daily assimilation values, simulated by CGMS, are integrated over the length of the growing season. Generally, the proposed method can be used for those applications for which the Ångström-Prescott method is considered to be adequate.

The following hierarchical method is proposed to introduce global radiation in CGMS, which may also be applicable for other applications where daily global radiation values are required (e.g. drought monitoring, climatology, etc.):

- if observed global radiation is available it should be used,
- if not, but sunshine duration is available, a sunshine duration method (e.g. Ångström-Prescott) should be applied,
- if neither radiation nor sunshine duration observations are available, then the method proposed in this chapter might be applied.

7. Prediction level[6]

7.1 Introduction

Through the Common Agricultural Policy (CAP) the European Union (EU) attempts to regulate the common agricultural market (e.g. set-aside regulations, export subsidies, etc.). Knowledge on crop yield and area planted is essential to evaluate the consequences of the CAP regulations and to estimate the amount of subsidies to be paid at European level (De Winne, 1994). Ecological models, specifically crop growth simulation models, used in combination with agro-economic models may be used as instruments to provide early information on expected production volumes and amount of subsidies to be paid. The SPEL (Sektorales Produktions- und Einkommensmodell der Landwirstschaft der Europäischen Union) model is an example of an agro-economical model which is used in this context (Weber, 1995). CGMS[7] (Crop Growth Monitoring System) is an example of a crop growth simulation model, which is adapted to assess crop growth and yield at European level (Hooijer & van der Wal, 1994; Vossen, 1992; 1990b).

CGMS is currently operational at the Joint Research Centre (JRC) of the EU and is used for early prediction of national yield per unit area and the production volume of various crops for each member state. It combines a crop growth simulation model with a time trend function and a prediction model. Crop growth simulation models integrate weather and soil influences on crop growth and simulate crop variables, such as leaf area index, phenological development stage, etc. A time trend may account for the unmodelled effects of increased fertilizer application, new varieties, improved crop protection techniques, etc. The yield prediction model combines both crop growth simulation results and the time trend function. In this chapter various possible modifications to improve the prediction accuracy of CGMS are evaluated. France was selected as study area.

A wealth of research papers dealing with simulation models as management tools exists. Only a few examples will be given. Abrecht & Robinson (1996) used CERES-Wheat as basis for a decision support system. Littleboy *et al.* (1996) used simulation modelling to determine suitability of agricultural land. Bakema *et al.* (1994) described a simulation system

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[6] Supit, I., Goot, E. van der, 1999. *National wheat yield prediction of France as affected by the prediction level.* Ecological Modelling, 116:203-223.

[7] See Chapter 3

for environmental policy analysis. Jørgensen (1994) discussed the application of ecological models in environmental management practice. Muchow *et al.* (1994) used a crop growth model to assess climatic risks in relation to sowing date for sorghum in a subtropical rainfed environment. Baird *et al.* (1993) developed a rice growth simulation model for scheduling management actions and evaluating consequences of alternative management strategies. Hodges *et al.* (1987) demonstrated that the CERES-Maize model could be applied for maize yield prediction in the Cornbelt of the USA. Williams *et al.* (1984) evaluated erosion effects of cropping practices and tillage using the EPIC model.

In a study to explore land use options using linear programming models, Hijmans & van Ittersum (1996) concluded that much of the spatial variation in the simulation results at a detailed level may be obscured when aggregated into larger administrative units. These authors also concluded that the level of spatial aggregation is very important. The use of aggregated units may lead to considerable errors (cf. de Wit & van Keulen, 1987). Using aggregated simulation for yield prediction may therefore produce less accurate results. The aggregation method applied in CGMS is described in Section 3.4.

In this chapter subregional, regional and national wheat production volumes are predicted (1985-1995). The results at subregional and regional level are summed into predicted national values. The accuracy is examined and the level at which the predictions should preferably be executed is identified.

De Koning *et al.* (1993) and Supit (1997)[8] have used CGMS simulation results in combination with a linear trend for yield and production volume prediction, respectively. Both authors applied an additive prediction model that assumed no dependency between trend and variation in yield per unit area. However, it may be possible that this variation depends on the fertilizer application level and thus on the magnitude of the trend. Furthermore, it may be possible that a nonlinear trend function fits the yield series better. In this chapter these assumptions are applied in a multiplicative prediction model, which uses a nonlinear trend, simulation results and an estimated value for planted area. To evaluate its performance the prediction results are compared with those of an additive model. To justify the use of simulation results and to evaluate its effects on the prediction accuracy, the prediction results are also compared with those of three other trend models. In total five prediction models are examined in this chapter.

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[8]See Chapter 5

Crop growth simulation results are obtained in two different ways. The first method, which is currently operational in CGMS, applies daily global radiation values estimated with the Ångström-Prescott equation (Ångström, 1924; Prescott, 1940). Average values are applied when this method cannot be used. The second method also uses the Ångström-Prescott equation, however, an alternative method to estimate global radiation is used in case the Ångström-Prescott cannot be applied (See Chapter 6).

The objectives of this chapter can be summarized as follows: (i) to investigate the effects of the prediction level on the prediction accuracy of production volume; (ii) to examine a prediction model that uses a nonlinear trend function, simulation results and the area planted to wheat; (iii) to compare two different methods to estimate global radiation and evaluate the prediction results obtained with these estimates.

France is selected as study area since this country has reliable production statistics and is the largest wheat producer in the EU. Production volumes are predicted at subregional, regional and national level. Figure 7.1 shows the NUTS-2 subregions of France.

7.2 Methodology

Currently, the operational version of CGMS aggregates simulation results to NUTS-0 level. Subsequently, these results are used for prediction of the national production volume. In addition to the aggregation to NUTS-0, in this chapter simulation results are aggregated to NUTS-2 and NUTS-1 level and used for prediction of regional and subregional production volumes. Summation of these results yields a prediction of the national production volume. The methodology to estimate national production volume is described in the next section.

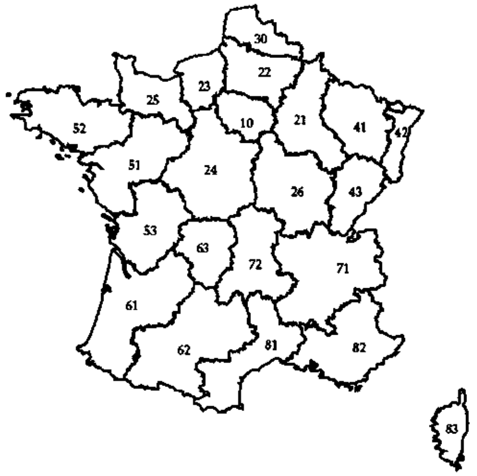

Figure 7.1. *NUTS-2 regions of France. (10) Île de France, (21) Champagne-Ardenne, (22) Picardie, (23) Haute Normandie, (24) Centre, (25) Basse Normandie, (26) Bourgogne, (30) Nord Pas de Calais, (41) Lorraine, (42) Alsace, (43) Franche-Comté, (51) Pays de La Loire, (52) Bretagne, (53) Poitou-Charentes, (61) Aquitaine, (62) Midi-Pyrénées, (63) Limousin, (71) Rhone-Alpes, (72) Auvergne, (81) Languedoc-Roussillon, (82) Provence Alpes Côte D'Azur, (83) Corse.*

7.2.1 Prediction model

Observed national, regional and subregional yields per unit area show a time trend. This trend may be attributed to increased fertilizer application, improved crop management methods, new high yielding varieties, etc. To account for this trend, Vossen (1992, 1990a) proposed a combination of a linear time trend (Palm & Dagnelie, 1993; Swanson & Nyankori, 1979) and crop growth simulation results:

$$\hat{Y}_{Ti} = b_0 + b_1 T + b_2 Y_{Ti} \tag{7.1}$$

where $\hat{Y}_{Ti}$ and Y_{Ti} are estimated yield and simulated yield (ton.ha^{-1}) respectively, at NUTS level i in year T, and b_0, b_1 and b_2 are regression constants. Production volume at NUTS level i, $\hat{P}_{Ti}$ (ton), in year T, can thus be estimated as:

$$\hat{P}_{Ti} = \hat{Y}_{Ti} \hat{A}_{Ti} \tag{7.2}$$

where $\hat{A}_{Ti}$ is the estimated area planted to wheat (ha) at NUTS level i in year T. Equation (7.1) was tested by De Koning *et al.* (1993), using CGMS simulation results. According to these authors the following model performed equally well or sometimes better than equation (7.1):

$$\hat{Y}_{Ti} = c_0 + c_1 T \tag{7.3}$$

where c_0 and c_1 are regression constants. In this chapter, equation (7.3) in combination with equation (7.2) is applied (Model I). Furthermore, the model proposed in Chapter 5 is used (Model IV in this chapter):

$$\hat{P}_{Ti} = b_0 + b_1 T + b_2 \left(Y_{Ti} \hat{A}_{Ti} \right) \tag{7.4}$$

This model is less sensitive to deviations in A then the combined use of equations (7.1) and (7.2). The official observed values for current season's A are available one or two years after the season has ended. Therefore, for operational use, estimates of A have to be applied. The estimation method is described in Subsection 5.2.4.

Equation (7.4) assumes additive effects of weather on yield, i.e. yield variability as a result of weather influences is similar under a high fertilizer input regime and under a low fertilizer input regime. However, according to de Wit & Seligman (1992) fluctuations in yield are larger under improved fertility conditions, suggesting that yield variability, as a consequence of weather influences may depend, amongst others, on the amount of applied fertilizer. According to Russell & Wilson (1994) the trend in yield is mainly a consequence of increased applications of fertilizers, crop protection products and growth regulators, whereas new cultivars have had a limited contribution. Growth regulators made it possible to apply large amounts of fertilizer, without causing lodging.

Radiation interception and conversion of intercepted radiation to dry matter is, amongst others, affected by the fertilizer application. According to van Keulen & Seligman (1987), reduction of the assimilation of a wheat crop as a result of water stress can be assumed to be proportional to the ratio of actual transpiration over potential transpiration. Yield reduction is thus proportionally larger when potential assimilation is larger. This assumption also suggests that the magnitude of the yield reduction as a consequence of water stress may be dependent on the applied fertilizer amount. A multiplicative model may therefore be more appropriate than an additive model.

According to Russell & Wilson (1994), the rate of yield increase started to diminish in various western European countries, amongst others in France, in the middle of the seventies.

A nonlinear trend function may therefore be more appropriate than a linear time trend. The production volume can be described by:

$$\hat{P}_{Ti} = a_0 (T_i)^{a_1} \left(Y_{Ti} \hat{A}_{Ti} \right) \qquad (7.5)$$

where a_0 and a_1 are regression constants and $a_1 < 1$. Equation (7.5) assumes a linear relation between production volume and planted area, suggesting that soil properties which may influence yield, such as hydraulic conductivity, porosity, fertility, nitrogen fixation, etc., are similar for all soil types. Obviously, this assumption is not correct; quality of the exploited soils is not uniform. Weir *et al.* (1984) examined almost 2000 fields of winter wheat in England and Wales. They found that soil series accounted for approximately 20% of the yield variance. According to Russell & Wilson (1994) in the UK and Denmark, and perhaps elsewhere in northwest Europe, over the last twenty years wheat areas have expanded onto sandier soils. In France, in the period 1975-1984, the area planted to wheat increased by 25% (source: EUROSTAT). Buckman & Brady (1964) remarked that sandy soils are: "often too loose and open, and lack the capacity to absorb sufficient moisture and nutrients. They are, as a consequence, likely to be droughty and lacking in fertility." The lower fertility of the sandier soils may be partially counterbalanced through heavy fertilizer applications. However, some soil properties such as hydraulic conductivity, porosity, etc. cannot be compensated through fertilizers and according to Foth (1978), "different soils have different capacities to absorb inputs for profit maximization". This may suggest a nonlinear relation between production volume and planted area and equation (7.5) changes in (Model V):

$$\hat{P}_{Ti} = a_0 (T_i)^{a_1} \left(Y_{Ti} \hat{A}_{Ti} \right)^{a_2} \qquad (7.6)$$

where a_0, a_1 and a_2 are regression constants and $a_2 < 1$. Heterogeneous variability as is assumed by equation (7.6) arises in almost all research fields. In Carroll & Ruppert (1988) various examples of such fields are given, amongst others: pharmacokinetic modelling where the variability depends on time (Bates *et al.*, 1985); enzyme kinetics, where the variability depends on concentration (Currie, 1982; Cressie & Keightley, 1981); fisheries research, where the variability in the production of new fish depends on the size of the spawning population (Ruppert & Carroll, 1985). According to Carroll and Rupert (1984), both sides of equation (7.6) can be modified through logarithmic transformation. Subsequently, linear regression can be used to establish the constants.

Comparison of the prediction results of Model V with those of Model IV may provide support for the multiplicative assumption and for using a nonlinear trend function.

Furthermore, since both Models IV and V apply a trend function as well as simulation results, it would be interesting to know whether these models, as a result of these simulation results, perform better than trend functions alone. Therefore, these models are also compared to:

$$\hat{P}_{Ti} = b_0 + b_1 T \tag{7.7}$$

and

$$\hat{P}_{Ti} = a_0 T^{a_1} \tag{7.8}$$

In this chapter equations (7.7) and (7.8) are called Model II and III, respectively, and can be considered as simplified forms of respectively, Model IV and V. Although not very sophisticated, trend extrapolations have been rather successful in predicting yield per unit area, especially when the trend is driven by technical progress (Weber, 1995). Therefore, to justify the use of more complex models, Models IV and V are also compared with Model I. Table 7.1 presents an overview of the applied prediction models.

The calibration stage, in which the regression constants are estimated, and the applied prediction method are described in Subsection 5.2.4. The prediction criterion is described in Subsection 5.2.5 However, the RMSE and RRMSE do not show whether a prediction model systematically over- or underestimates, moreover, an extreme value may mask the model performance. To evaluate the tested models, additional information on the prediction error is needed. Therefore, the contribution of the systematic error and the random error to the prediction error is analyzed, using the decomposition proposed by Theil (1961) and applied by Allen & Raktoe (1981):

$$\text{MSE} = e_\beta + e_\rho + e_\varepsilon \tag{7.9}$$

where e_β can be considered as a measure of the bias, e_ρ as a linear trend in the error as a function of the magnitude of the observed yield and e_ε as the error due to random disturbances. In a good model the first and second term, the systematic error, should be small and the third term large. Allen & Raktoe (1981) normalized the components of equation (7.9) by dividing each term by the MSE:

$$U^\beta + U^\rho + U^\varepsilon = 1 \tag{7.10}$$

Table 7.1. *Applied models to predict national production volume* $\hat{P}_T$.

	Prediction models applied to predict national production volume $\hat{P}_T$, in year T				
	Time trend			Time trend + crop growth simulation results	
Prediction level:	Model I $\hat{Y}_{Ti} = c_o + c_1 T$	Model II $\hat{P}_{Ti} = b_0 + b_1 T$	Model III $\hat{P}_{Ti} = a_0 (T)^{a_1}$	Model IV $\hat{P}_{Ti} = b_0 + b_1 T + b_2 (Y_{Ti} \hat{A}_{Ti})$	Model V $\hat{P}_{Ti} = a_0 (T)^{a_1} (Y_{Ti} \hat{A}_{Ti})^{a_2}$
NUTS-0	$\hat{P}_T = \hat{Y}_{T0} \hat{A}_{T0}$	$\hat{P}_T = \hat{P}_{T0}$	$\hat{P}_T = \hat{P}_{T0}$	$\hat{P}_T = \hat{P}_{T0}$	$\hat{P}_T = \hat{P}_{T0}$
NUTS-1	$\hat{P}_T = \sum_{l=1}^{o} \hat{Y}_{T1,l} \hat{A}_{T1,l}$	$\hat{P}_T = \sum_{l=1}^{o} \hat{P}_{T1,l}$	$\hat{P}_T = \sum_{l=1}^{o} \hat{P}_{T1,l}$	$\hat{P}_T = \sum_{l=1}^{o} \hat{P}_{T1,l}$	$\hat{P}_T = \sum_{l=1}^{o} \hat{P}_{T1,l}$
NUTS-2	$\hat{P}_T = \sum_{k=1}^{q} \hat{Y}_{T2,k} \hat{A}_{T2,k}$	$\hat{P}_T = \sum_{k=1}^{q} \hat{P}_{T2,k}$	$\hat{P}_T = \sum_{k=1}^{q} \hat{P}_{T2,k}$	$\hat{P}_T = \sum_{k=1}^{q} \hat{P}_{T2,k}$	$\hat{P}_T = \sum_{k=1}^{q} \hat{P}_{T2,k}$

$\hat{Y}_{Ti}$ = predicted yield per unit area (ton.ha^{-1}) at NUTS level *i* in year *T*

$\hat{P}_{Ti}$ = predicted production volume (ton) at NUTS level *i* in year *T*

$\hat{P}_T$ = predicted national production volume (ton) in year *T*

Y_{Ti} = simulated yield (ton.ha^{-1}) at NUTS level *i* in year *T*

$\hat{A}_{Ti}$ = estimated area planted to wheat (ha) at NUTS level *i* in year *T*

o = total number of NUTS-1 regions

q = total number of NUTS-2 subregions

7.3 Data

EUROSTAT provided national crop statistics. In France, yields per unit area are measured for a sample of agricultural holdings from the land use survey which are identified as growing cereals (Bradbury, 1994). Production volumes are calculated from the area and average yield data obtained from the surveys, with some additional "sources at the discretion of the local *département*". Wheat production volumes (ton) and area planted to wheat (ha) at NUTS-2, NUTS-1 and NUTS-0 level for 1975-1995 were obtained. Only at national level do these statistics distinguish between soft and durum wheat. At NUTS-1 and NUTS-2 level no production volume, yield and area information for durum wheat is available.

Daily weather data (i.e. maximum temperature, minimum temperature, rainfall, vapor pressure, wind speed, sunshine duration and cloud cover) for more than 100 weather stations in France are routinely obtained from the Global Telecommunication System (GTS). Daily global radiation is rarely reported, therefore in CGMS the Ångström-Prescott method (equation 6.1) is used to estimate global radiation. In the operational version of CGMS the constants of the Ångström-Prescott equation are estimated using the method proposed by Choisnel *et al.* (1992):

$$\alpha = 0.4885 - 0.0052\,\lambda \qquad (7.11)$$

and

$$\beta = 0.1563 + 0.0074\lambda \qquad (7.12)$$

where λ is the latitude (°). However, tests on received GTS data revealed that 20% of the meteorological stations irregularly report daily sunshine duration observations or not at all. In the operational version of CGMS long-time daily average values of global radiation are applied when no sunshine duration observations are available and consequently the Ångström-Prescott equation cannot be used. According to Nonhebel (1993), however: "Due to the variation in daily and annual global radiation and the nonlinear relation between radiation and photosynthesis, the use of average data (even over short periods) to replace missing data must be avoided." To circumvent the use of average values the method described in Chapter 6 is applied in this chapter: if observed global radiation is reported this information is used; if observed global radiation is not reported, but sunshine duration observations are available, the Ångström-Prescott equation is applied; alternatively equation (6.3) is used. This equation gave good results for France (Supit & van Kappel, 1998)[9].

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[9] See Chapter 6

In contrast to the operational method, in this chapter constants of equation (6.1) and equation (6.3) are either known from an earlier study (Supit, 1994) or obtained through interpolation (van der Goot, 1997) of nearby stations for which these values are known. The prediction results obtained with the operational method and those of the method proposed in Chapter 6 are compared.

Crop growth parameters used in CGMS have been established by Boons-Prins *et al.* (1993) based on research by, amongst others, Falisse (1992), Narisco *et al.* (1992), van Diepen & de Koning (1990), Falisse and Decelle (1990) and van Heemst (1988). Data were also retrieved from field experiments in the UK, Belgium and the Netherlands. Soil information is retrieved from the EU Soils Database (King *et al.*, 1994). The soils database is used in conjunction with the crop knowledge bases to identify areas where a given crop can possibly be grown. Soil properties used to simulate the water-limited situation are derived from the Available Water Capacity Database (King *et al.*, 1995).

7.4 Results and discussion

Table 7.2 presents the RRMSEs and RMSEs of the various prediction methods. Table 7.3 presents the adjusted coefficients of determination, t-values and significance averaged over the number of significant regressions obtained in the calibration stage and Table 7.4 presents the proportions of various error sources to the MSE.

Comparison of the RRMSEs of Model II with those of Model III suggests that the nonlinear time trend (Model III) predicts production volume more accurately than Model II. This may be caused by a better fit of the applied trend function to the production volume series. Regression of the production volume series of 1975-1995 on a linear time trend (Model II) and a power law function of time (Model III) yielded adjusted coefficients of determination, R^2, of 0.76 and 0.88 respectively, suggesting that the nonlinear trend function fits the data better. However, differences in the coefficients of determination of the regressions obtained in the calibration stage are small (Table 7.3); shortness of the applied times series results in comparable coefficients of determination for both models. This does not mean that these models predict equally well (see Table 7.2). The proportion of the systematic error to the MSE, $U^{\beta}+U^{\rho}$, and also the systematic error itself, are higher for Model II than for Model III. The results presented in Table 7.2 and Table 7.3 support the assumption that the nonlinear trend function may be more appropriate for production volume prediction than a linear time trend. For Model III differences in RRMSE and values of $U^\beta+U^\rho$ among the various NUTS levels are small, suggesting that this model predicts equally well at these levels and summation of subregional and regional prediction results has limited influence on the systematic error.

Comparison of the RRMSEs of Model II and III with those of Model IV and V respectively, suggests that including crop growth simulation results in Model II and III improves the prediction accuracy at all aggregation levels. The adjusted coefficients of determination suggest that these better prediction results may be attributed to a better fit of Model IV and V to the production volume series. Of these two models Model V demonstrates the highest prediction accuracy at all NUTS levels. This may be attributed to the nonlinear trend function and to the fact that weather influences on crop growth may also depend on the magnitude of the time trend.

Comparison of the RRMSEs of Model IV with those of Model I, the model which demonstrates the lowest R^2 in the calibration stage, shows that Model IV, the additive model, only provides more accurate results at NUTS-2 level. However, the multiplicative model (Model V) yields lower RRMSEs than Model I at all NUTS levels. The RRMSEs and coefficients of determination of Model I demonstrate that a good fit at the calibration stage does not guarantee more accurate prediction results (Power, 1993).

The prediction models using crop growth simulation results (Models IV and V) yielded the best prediction results when predictions are executed at NUTS-2 level and subsequently summed into national production volume. Furthermore, these models demonstrate the highest values for $U^\beta+U^\rho$ at NUTS-0 level, whereas the lowest values are observed for predictions executed at NUTS-2 level. This phenomenon may be attributed to aggregation of the simulation results and summation of the prediction results. It provides some support for the assumption that local weather effects can be masked when the simulation results are aggregated into larger regions.

Table 7.2. *Relative Root Mean Square Error and Root Mean Square Error (x 1000 ton) of the national production volume predictions, applying various prediction models for different prediction levels and using the proposed and the operational radiation routine.*

	Relative Root Mean Square Error (Root Mean Square Error)						
	Time trend			Time trend +crop growth simulation results Proposed Radiation Routine[I]		Time trend +crop growth simulation results Operational Radiation Routine[II]	
Prediction level:	Model I	Model II	Model III	Model IV	Model V	Model IV	Model V
NUTS-0	0.079 (2393)	0.094 (2850)	0.075 (2269)	0.091 (2764)	0.062 (1892)	0.085 (2585)	0.082 (2494)
NUTS-1	0.071 (2150)	0.092 (2782)	0.075 (2269)	0.081 (2454)	0.064 (1940)	0.085 (2585)	0.070 (2126)
NUTS-2	0.072 (2181)	0.097 (2947)	0.080 (2432)	0.063 (1941)	0.055 (1673)	0.066 (1993)	0.059 (1779)

[I]) Global radiation is estimated using the Ångström-Prescott method. If no sunshine duration is available the cloud cover/temperature range method, equation (6.3), is used. Constants of the radiation estimation methods are interpolated from nearby stations for which these constants are known.

[II]) Global radiation is estimated using the Ångström-Prescott method; constants of this equation are calculated as a function of latitude (Choisnel *et al.*, 1992). Missing data are replaced by long time daily average.

Table 7.3. *Adjusted coefficients of determination* (R^2)*, t-values* (t_t, t_c) *and significance* (sig.) *averaged over the number of significant regressions*

	Time trend									Time trend +crop growth simulation results Proposed Radiation Routine[I]								Time trend +crop growth simulation results Operational Radiation Routine[II]							
	Model I			Model II			Model III			Model IV				Model V				Model IV				Model V			
	R^2	t_t	sig.	R^2	t_t	sig.	R^2	t_t	sig.	R^2	t_t	t_c	sig.	R^2	t_t	t_c	sig.	R^2	t_t	t_c	sig.	R^2	t_t	t_c	sig.
NUTS-0	0.52	3.44	0.018	0.56	4.01	0.015	0.60	4.27	0.012	0.77	5.24	6.30	0.004	0.79	3.23	6.73	0.005	0.79	3.47	5.53	0.004	0.77	3.81	5.65	0.005
NUTS-1	0.52	3.53	0.020	0.60	4.25	0.011	0.61	4.26	0.010	0.72	4.01	4.83	0.006	0.71	3.92	4.84	0.007	0.70	4.01	4.26	0.008	0.72	3.85	4.51	0.007
NUTS-2	0.50	3.38	0.021	0.59	4.29	0.014	0.61	4.28	0.012	0.73	4.22	5.17	0.006	0.73	4.18	5.35	0.007	0.72	4.19	4.80	0.007	0.73	4.26	5.17	0.006

t_t = t-value of trend
t_c = t-value of simulation result
[I]) See Table 7.2
[II]) See Table 7.2

Table 7.4. *Proportions of the various components of the Mean Square Error.*

	Time trend									Time trend +crop growth simulation results Proposed Radiation Routine[I]						Time trend +crop growth simulation results Operational Radiation Routine[II]					
Prediction	Model I			Model II			Model III			Model IV			Model V			Model IV			Model V		
Level	U^β	U^ρ	U^ε	U^β	U^ρ	U^ε	U^β	U^ρ	U^ε	U^β	U^ρ	U^ε	U^β	U^ρ	U^ε	U^β	U^ρ	U^ε	U^β	U^ρ	U^ε
NUTS-0	0.154	0.094	0.752	0.343	0.022	0.635	0.130	0.043	0.827	0.018	0.424	0.558	0.188	0.222	0.590	0.003	0.358	0.639	0.004	0.340	0.656
NUTS-1	0.105	0.026	0.869	0.333	0.012	0.655	0.120	0.043	0.836	0.010	0.233	0.757	0.000	0.112	0.887	0.013	0.284	0.703	0.014	0.147	0.839
NUTS-2	0.071	0.031	0.898	0.200	0.147	0.653	0.063	0.099	0.837	0.004	0.055	0.940	0.080	0.009	0.911	0.081	0.000	0.919	0.009	0.023	0.969

U^β = proportion of the Mean Square Error due to the bias in the prediction procedure
U^ρ = proportion of the Mean Square Error due to the error in the regression
U^ε = proportion of the Mean Square Error due to random disturbances
[I]) See Table 7.2
[II]) See Table 7.2

Weather affects crop growth differently at various stages of crop development. It is clear that different weather patterns in various (sub)regions are experienced, especially when distances between these (sub)regions are large. Aggregation averages out local weather patterns and it is obvious that these patterns cannot be accounted for by one single simulation value. In southern France, water shortage may for example be the growth-limiting factor and in the north this may the intercepted radiation. As a consequence, aggregated values may account for a smaller proportion of the variation in production volume and larger prediction errors may occur. However, the regression results presented in Table 7.3 do not provide strong support for this hypothesis. The adjusted coefficients of determination do not demonstrate a better fit to the production volume series at NUTS-1 or NUTS-2 level. This may suggest that summation of the individual NUTS-2 prediction results may also reduce the error in the production volume due to error compensation. The MBE decomposition presented in Table 7.4 furthermore suggest that, although the RRMSE of the predictions executed at NUTS-0 level for Model V is slightly lower than the one executed at NUTS-1 level, preference should be given to predictions executed at NUTS-1 or NUTS-2 level.

Aggregation of the observed yield per unit area, and summation of the production volume and planted area from NUTS-2 to NUTS-1 and subsequently to NUTS-0 may mask the spatial variation in the trend in these variables. Predictions executed at subregional or regional level, using the trend models (Models I, II and III) may therefore provide more accurate results than predictions executed at national level, since the trend in yield per unit area, production volume and planted area for each individual subregion or region can be accounted for. However, the RRMSEs and the coefficients of determination observed in the calibration stage do not provide strong evidence to support this assumption. The RRMSEs for predictions executed at NUTS-1 level are slightly lower than or comparable to those executed at NUTS-0 level, while the RRMSEs for predictions at NUTS-2 level are slightly higher than those at NUTS-1 level. Only the error decomposition for Model I shows lower values for the systematic error for predictions executed at NUTS-1 and NUTS-2 level, respectively.

Comparison of the prediction results of Model I with those of Model II, suggests that if only linear trend models are used, better prediction results can be obtained if production volume is decomposed in an area component and a yield per unit area part which are estimated separately and then multiplied. Combining these two components and predicting production volume using a trend function may mask the variation or trend in either one of them.

For Model IV and V slightly better prediction results are obtained using the proposed radiation method instead of the operational method (except for Model IV, for predictions executed at NUTS-0 level). This improvement could be attributed to: (i) the method applied to assign values to the constants of the Ångström-Prescott equation or (ii) the alternative method to estimate global radiation when no sunshine duration observations are available. Analyses of the data received via GTS demonstrate that observed global radiation values are never reported and consequently cannot account for the improvement. The coefficients of determination for Model IV and V as observed in the calibration stage (Table 7.3) do not demonstrate a better fit to the production volume series when the proposed radiation routine is used instead of the operational routine. Only a slight increase in the t-values of the simulation results can be seen, which suggests that the crop growth simulation results calculated with the proposed radiation routine may account for a slightly higher proportion of variation in production volume in comparison to those established with the operational radiation routine. The proposed radiation routine may have a noticeable effect on the crop growth simulation results, however, the prediction accuracy increase is small. Larger accuracy increase can be obtained through selection of the appropriate prediction level.

The effect of area estimates on the production volume predictions is analyzed. Figure 7.2 demonstrates the estimates of the total area planted to wheat. The RRMSEs of the estimates are 0.048, 0.042 en 0.044 for estimates at NUTS-0, NUTS-1 and NUTS-2 level respectively. Differences among the NUTS levels are small. In 1993 a large error is observed, which can be attributed to a change in the CAP regulations which came into effect in 1992 and was aimed at a reduction of the planted area. Table 7.5 shows the RRMSEs of the prediction using official values for planted area. Model I demonstrates the lowest RRMSEs, differences in these values among various prediction levels are small. Model IV demonstrates the highest RRMSEs at all NUTS levels.

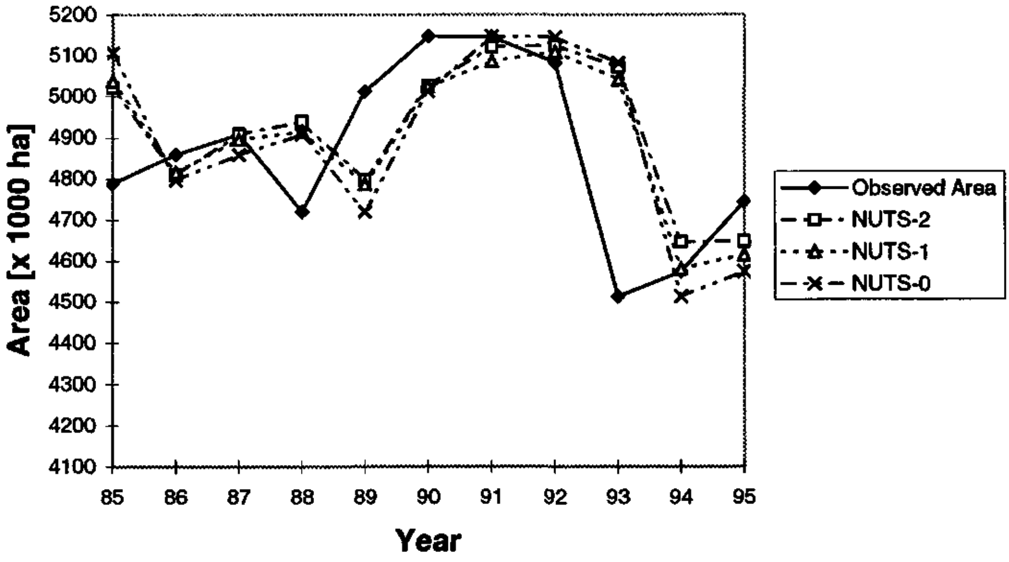

Figure 7.2. *Observed and estimated values of the total area planted to wheat at national level. The estimates are executed at various NUTS levels.*

At NUTS-0 level Model V performs far worse than Model I, however the results at the other NUTS levels are comparable, demonstrating that the use of simulation results aggregated to NUTS-0 level should be avoided. Comparison of these results with those presented in Table 7.2 demonstrates the sensitivity to uncertainty in the area estimates. For Model IV and V the sensitivity to these uncertainties is much less than for Model I. This comparison also suggests that the low RRMSE for Model V for predictions at NUTS-0 level, using estimated area, may be attributed to chance.

Table 7.5 *Relative Root Mean Square Error and Root Mean Square Error (x 1000 ton) of the production volume predictions, applying various prediction models at different prediction levels, using the proposed radiation routine[1] and observed values of planted area.*

Prediction	Relative Root Mean Square Error (Root Mean Square Error)		
Level	Model I	Model IV	Model V
NUTS-0	0.059 (1756)	0.109 (3301)	0.101 (3059)
NUTS-1	0.057 (1718)	0.074 (2244)	0.056 (1691)
NUTS-2	0.055 (1672)	0.062 (1888)	0.057 (1729)

[1]) See Table 7.2

In Figures 7.3, 7.4 and 7.5 values for the observed and predicted production volumes at the three prediction levels are presented. As a result of the area over-estimation in 1993 the trend models (Model I, II and III) show a large prediction error at all NUTS levels. The prediction results of Model IV and V at NUTS-1 and NUTS-2 level do not demonstrate such an error in that year, however, at NUTS-0 level these two models underestimate the production volume.

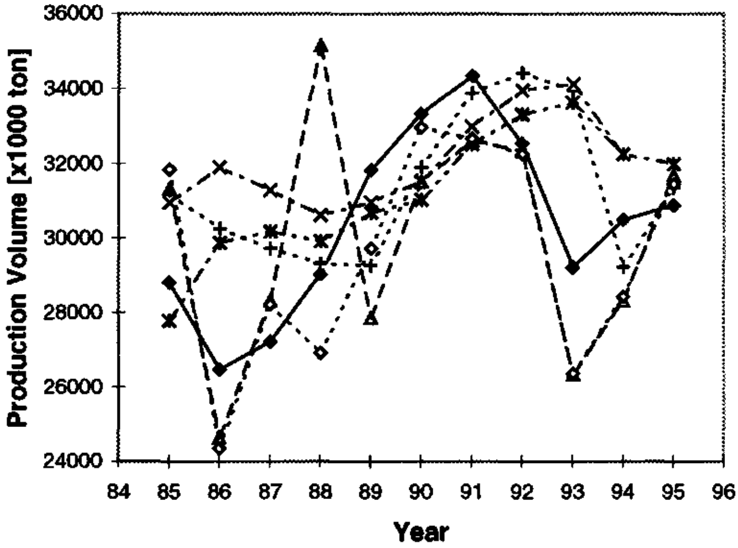

Figure 7.3. *Observed (♦) and predicted production volumes (x1000 ton) using Model I (+), Model II (x), Model III (*), Model IV (Δ) and Model V (◊). Predictions apply to NUTS-0 level and are executed with the proposed radiation routine (see Chapter 6).*

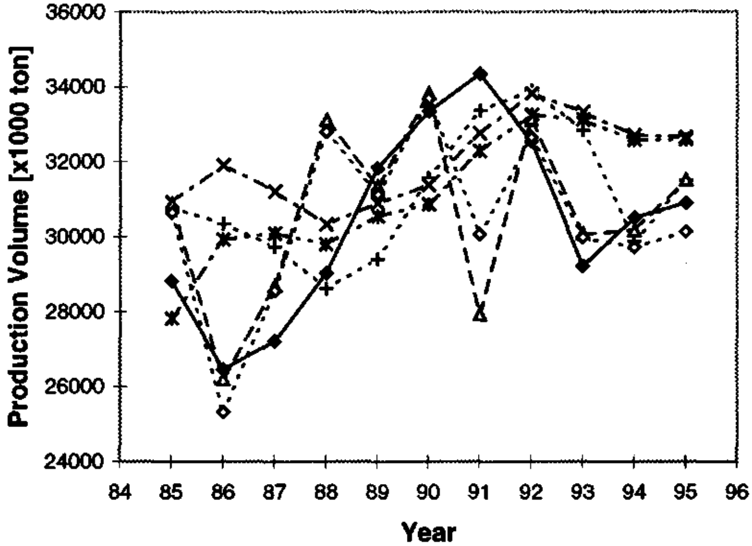

Figure 7.4. *Observed (♦) and predicted production volumes (x1000 ton) using Model I (+), Model II (X), Model III (*), Model IV (Δ) and Model V (◊). Predictions apply to NUTS-1 level and are executed with the proposed radiation routine (see Chapter 6).*

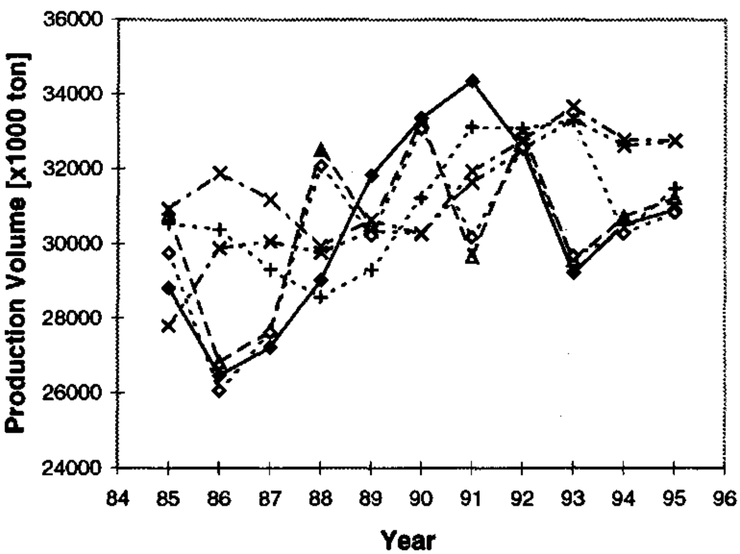

Figure 7.5. *Observed (♦) and predicted production volumes (x1000 ton) using Model I (+), Model II (X), Model III (*), Model IV (Δ) and Model V (◊). Predictions apply to NUTS-2 level and are executed with the proposed radiation routine (see Chapter 6).*

The better results at NUTS-1 and NUTS-2 level for Model IV and V in 1993 may be attributed to aggregation of the simulation results and summation of the predictions. They may also be attributed to the selection of potential biomass as predictor: as a consequence of weather, lower values for the simulated potential biomass are observed in 1993, resulting in lower predicted production volumes.

The difference in observed and predicted production volume in 1991 cannot be explained. Very high yields per unit area are observed for NUTS number 10, 21 and 22. These yields were respectively, 8.1, 8.0 and 7.9 $ton.ha^{-1}$. The simulated potential yields were respectively, 7.5, 7.6 and 7.8 $ton.ha^{-1}$. Observed yields in the surrounding subregions are lower. Further study should elucidate whether this discrepancy between observed and predicted yield is related to the model itself, or a reaction to modifications of the CAP rules or whether it could be related to other sources.

Figures 7.6 and 7.7 show the percentage of the number of cases each predictor is selected. Water-limited grain yield and water-limited biomass are rarely chosen: the predictor selection procedure gives preference to potential yield and potential biomass.

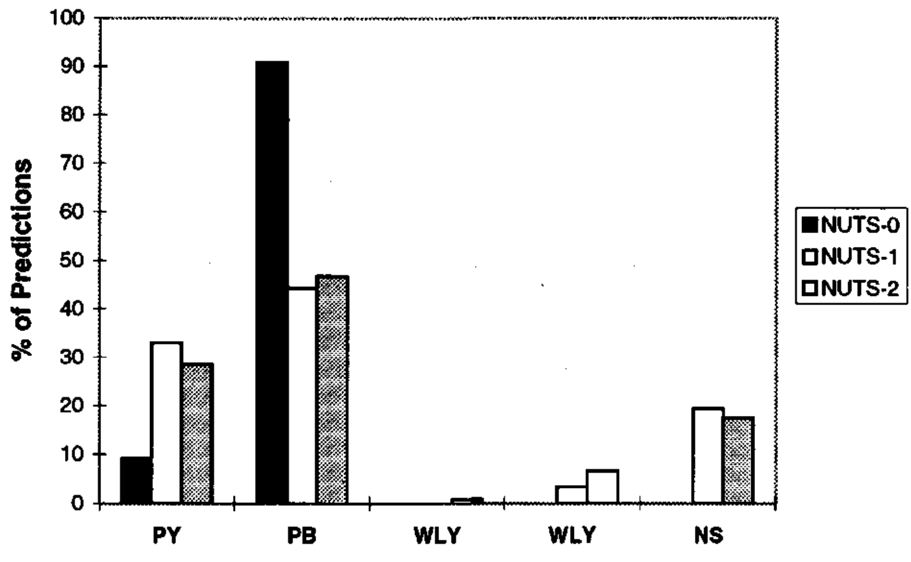

Figure 7.6. *Percentage of the number of cases each predictor is selected at NUTS-0, NUTS-1 and NUTS-2 level, applying Model IV as prediction model, using the proposed radiation routine.* **PY** *= potential yield,* **PB** *= potential biomass,* **WLY** *= water-limited yield,* **WLB** *= water-limited biomass,* **NS** *= crop simulations not significant (5% t-test).*

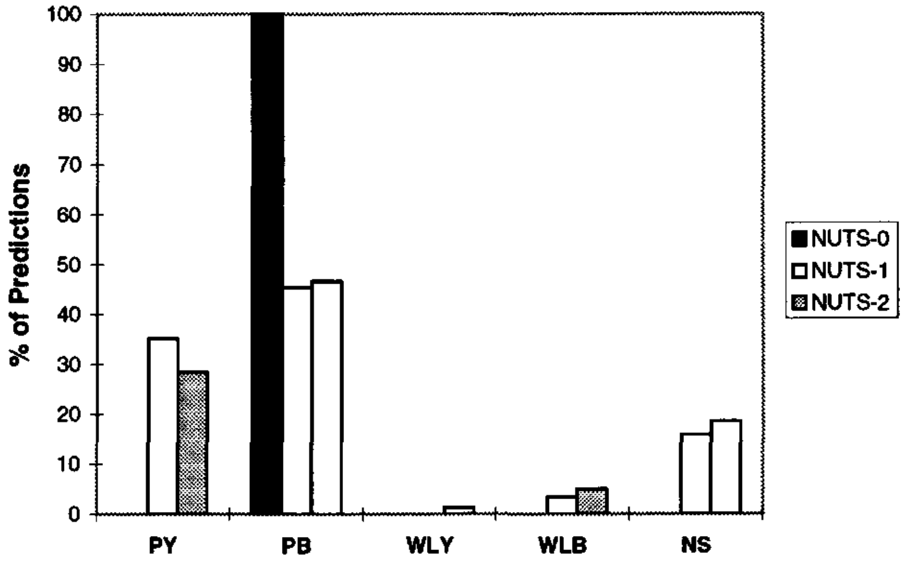

Figure 7.7. *Percentage of the number of cases each predictor is selected at NUTS-0, NUTS-1 and NUTS-2 level, applying Model V as prediction model, using the proposed radiation routine.* **PY** *= potential yield,* **PB** *= potential biomass,* **WLY** *= water-limited yield,* **WLB** *= water-limited biomass,* **NS** *= crop simulations not significant (5% t-test).*

Results obtained in Chapter 5 demonstrated that a linear time trend in combination with simulation results (Model IV) predicted the national wheat production volume of France better than a linear time-trend and/or average (Model II). For soft wheat RRMSEs were 0.099 and 0.094 for Models II and IV, respectively, and for durum wheat the RRMSEs were 0.486 and 0. 328, respectively. These values were obtained for predictions at NUTS-0 level. Different values for RRMSEs for Models II and IV are obtained in this chapter (see Table 7.3, operational radiation routine). These differences are mainly caused by grouping information on yields and planted area for both wheat types together in this chapter. Detailed information on yields and planted area for soft and durum wheat was not available at NUTS-1 and NUTS-2 level.

Caution should be observed: only one country was analyzed and only 11 years of production volume values are predicted. The results of this study may not be transferable to other EU member states. Trend and simulation results are regressed on official production volume figures and the regression constants are subsequently used for prediction. Uncertainty in the official yield statistics may result in large prediction errors. For countries with less reliable regional or subregional yield statistics, summation of yield predictions, executed at regional or subregional level, may not yield more accurate results than predictions executed at national level directly. Further research should indicate for each EU member state at which NUTS level the prediction should be executed and which prediction model should be used to obtain the most accurate prediction of the production volume.

Caution should also be observed concerning the use of the nonlinear trend function as applied in this study. This trend function is sensitive to values attributed to T. In this study for year 1975 T=1, for 1976 T=2, etc. is chosen. Attribution of other values, as demonstrated in Table 7.6, gave less accurate prediction results. The best results are obtained when for 1975 T is set to 1. This may suggest, that similar to the UK, in France in the middle of the seventies the yield increase started to diminish (Russell & Wilson, 1994).

7.5 Conclusions

Production volumes are predicted at three different levels: at subregional, regional and at national level. Prediction results at subregional and regional level are summed to national production volume. In total five prediction models are used. Three models are combinations of trend functions and averages. The other two, an additive and a multiplicative model, apply crop growth simulation results in combination with a trend function. Similar to the models that apply trend and simulation results, one of the three trend models also applies a value for planted area. At the time production volumes have to be predicted (i.e. end of the season), official values for current season's planted area are not available and have to be estimated. The crop growth simulation results were established with two different radiation routines.

In general, the results suggest that better prediction results of national production volume can be obtained using predictions executed at regional or subregional level and subsequently sum these results into national values. This suggests that local variation in weather and consequently local variation in simulation results and also in yield may be obscured as a result of aggregation of these variables into larger administrative regions. Another explanation may be that summation of individual regional and subregional prediction results may reduce the prediction error in national production volume due to error compensation.

Of the applied models, the multiplicative model performs best at subregional and regional level. The higher prediction accuracy may be attributed to the applied nonlinear trend function in combination with the multiplicative character of this model. This result may also support the assumption that weather effects on crop growth also depend on the magnitude of the time trend.

For the trend models differences in prediction accuracy among the prediction levels are small. The trend model, which predicts yield per unit area and is subsequently multiplied with an area estimate, performs better than the other two trend models. This model also performs slightly better than the multiplicative model when observed values for planted area are used. However, observed values for planted area are never available at the time production volume have to predicted (i.e. at the end of the growing season). Therefore, the multiplicative model may be preferred since this model is less sensitive to uncertainty in the area estimates. The prediction accuracy improves slightly when the improved radiation routine is applied.

Caution is needed: France has reliable regional statistics; other countries may have less accurate statistics and prediction at regional or subregional level may not lead to more accurate results

Table 7.6. *Relative Root Mean Square Error of the production volume predictions. A multiplicative prediction model is applied at respectively, NUTS-0, NUTS-1 and NUTS-2 level, using various initial values for year 1975. The prediction results are subsequently summed to production volume.*

Relative Root Mean Square Error of the production volume predictions						
Initial Values of *T* for year 1975	Prediction level					
	NUTS0		NUTS1		NUTS2	
	Model III	Model V	Model III	Model V	Model III	Model V
1	0.075	0.062	0.075	0.064	0.080	0.055
3	0.080	0.063	0.079	0.064	0.085	0.056
5	0.084	0.062	0.083	0.065	0.088	0.059
7	0.087	0.062	0.086	0.068	0.091	0.061
9	0.090	0.062	0.089	0.069	0.093	0.061

8. Sowing dates[10]

8.1 Introduction

Worldwide agricultural market prices are impacted by information pertinent to the supply or consumption of foodstuffs (Marcus & Heitkemper, 1994). According to these authors, international market price adjustments or change in agricultural supplies in one area of the world often causes price adjustments in markets far distant. The European Union (EU), through its Common Agricultural Policy (CAP), attempts to regulate the common agricultural market (e.g. set-aside regulations, export subsidies, etc.). The Directorate General for Agriculture (DG VI) is responsible for the implementation and control of the CAP regulations. To assist DG VI in its tasks, a project "Monitoring Agriculture with Remote Sensing (MARS)"[11] was initiated. The objectives of this project are to evaluate changes in land use as a reaction to the modifications of the CAP rules (De Winne, 1994) and to estimate crop yields, using amongst others remote sensing techniques, a crop growth simulation model and field surveys. The Joint Research Centre (JRC) of the EU is executing the MARS project.

In the framework of this project data on sowing dates, area sown, yields, etc. are collected. These data provide information on land use changes and give an indication on the amount of subsidies to be paid. Furthermore, they may be used as input in agro-economic and agro-meteorological models that are applied as management tools to assist in the evaluation of the CAP regulations.

In view of possible collaboration between the EU and various northern African countries in the Mediterranean region in the domain of crop growth monitoring, a study was initiated with the aim to investigate sowing and flowering date variation and its consequences for winter cereals yields, grown under rainfed conditions in semi-arid regions. Data collected for the subproject that evaluated land use changes were used in this chapter. The conclusions may, amongst others, provide a better understanding of sowing strategies of winter cereals and the consequences of sowing date variation in the studied area.

According to Cooper *et al.* (1987), winter cereals are the predominant rainfed crop in semi-arid environments. For Spain information on sowing dates, area sown, etc., for winter

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[10] Supit, I., Wagner, W., 1998. *Analysis of yield, sowing and flowering dates of barley of field survey results in Spain.* Agricultural Systems, 59:107-122.
[11] See Chapter 2

cereals was readily available, therefore this chapter concentrated on this country. Barley (*Hordeum vulgare L.*) is selected, since it is the predominant rainfed winter cereal grown in Spain. It accounts for more than 50% of the national annual cereal production (source: EUROSTAT). According to Cantero-Martinez *et al.* (1995a,b) in northeastern Spain rainfed cropping systems have continuously used barley as a single crop for the last thirty years. Available soil water is the main limitation to rainfed production, and irrigation is often not economically feasible.

The sowing date per field depends on suitability of the soil for cultivation, harvest date of the preceding crop, soil temperature and farmer's priorities for sowing. Actual and expected rainfall may influence the timing of sowing. According to Russell (1990), sowing in the winter months is normal in Mediterranean regions and a wide range of sowing dates can be observed. According to van Keulen & Seligman (1987), sowing in semi-arid regions is often delayed until an effective rain event has made the soil sufficiently wet to minimize the risk of germination failure. In dryland agricultural systems of semi-arid regions, sowing takes place in autumn or winter once 25 mm of rain has fallen at the start of the wet season (Russell, 1990). This amount of rainfall has been found to be sufficient to allow emergence.

The consequences of sowing date variation on yield have been studied for various cereals. According to Aufhammer *et al.* (1992), it can be inferred from general agronomic knowledge that, for winter crops, earlier sowing dates in summer will result in improved canopy development and increased nitrogen uptake. Early autumn and winter sowings tend to give higher yields than spring sowings and are especially advantageous in areas with summer droughts. Van Keulen & Seligman (1987), using a simulation model, concluded that lower wheat yields are to be expected when sowing is delayed. Aggarwal & Kalra (1994) found similar results for wheat yields in India. Petrini *et al.* (1993) investigated the influence of sowing date on yield of two sorghum cultivars in Italy. Their results suggest that early sowing is only marginally beneficial to yield, even if this allows changing the temporal extension of the growing season.

Three basic strategies should be considered when water supply is limiting (Loomis, 1983): (i) synchronization between crop phenology, water supply and water use; (ii) maximization of water use in transpiration; (iii) maximization of yield per unit transpiration. Synchronization between crop phenology and seasonal water supply can be achieved by selection of appropriate cultivars with respect to time of flowering and drought resistance, and by the timing of sowing.

To examine whether the sowing date coincides with the expected or with the actual onset of the rainy season, historical rainfall data are analyzed. Historical rainfall recordings may provide information on the expected start of the rainy season. Actual rainfall data may give an indication of the soil moisture conditions at sowing time. In many semi-arid regions, however, the density of recording stations is low and historical and actual meteorological data are scarce. Substantial spatial variability of precipitation in semi-arid regions, even over short distances, results in a serious problem for the analysis of rainfall regimes (Stroosnijder & Koné, 1982; Shanan *et al.*, 1967). Generally, where possible, spatial interpolation of rainfall data should be avoided. Anonymous (1995) obtained large errors in the interpolation of daily rain occurrences. Hulme *et al.* (1995) obtained a value of the relative root mean square error of 35% interpolating mean monthly precipitation values for 800 stations.

Alternatively, satellites may provide information about precipitation and soil moisture. For example, the standard GOES Precipitation Index (GPI) method may provide accurate estimates of the number of rainy hours (Iehlé *et al.*, 1997). Wagner *et al.* (1999, in press) presented a method to estimate the relative soil moisture content as a fraction of saturation of the soil surface layer from scatterometer measurements of the European Remote Sensing (ERS) satellites. The advantage of this remote sensing method is that a spatial picture of moisture conditions in the surface soil layer over large regions can be presented. Unfortunately, the temporal resolution is low. The revisit time of the ERS satellites is three to four days and the ERS scatterometer cannot work in parallel with the Synthetic Aperture Radar (SAR) which is also flown on board these satellites. Over Europe preference is given to SAR observations and therefore, only a few ERS scatterometer measurements per 10-day period or even per month are available.

Rainfall recordings from meteorological stations provide temporal information, however, the spatial validity is limited. Additional spatial information may be provided by soil moisture estimates from scatterometer data.

8.2 Methodology

In agricultural research the effects of factors influencing crop yield, such as quantity of fertilizers, weed management intensity, etc. are studied and can be quantified. However, it is impossible to collect information on these factors for all farms in the EU as a basis for monitoring national and total European crop production. In the framework of the MARS project the following strategy is applied to circumvent this problem: a limited number of yield and production volume influencing factors is analyzed, using a large population of sampling plots, spread over a large area under the assumption that the non-considered factors do not vary much in time.

Data collected for the MARS subproject "Rapid estimates of acreage and potential yields" are used. The main objective of this subproject is to evaluate changes in land use within the EU. It operates 60 test sites (40 x 40 km) in 13 countries. Ten of these test sites are located in Spain (Figure 8.1). To facilitate agricultural classification using satellite images, the locations of the test sites are chosen in such a way that they coincide with a complete image of the SPOT satellite. Within each test site, 16 segments (1.4 x 1.4 km) are selected. Segment size and shape are standard and their location does not change over time. In the ideal situation the segments are regularly distributed over the sites and the distance between the segments is 10 km (Figure 8.2). However, if a substantial part of the segment consisted of non-arable land it was relocated or if relocation was not possible it was omitted.

A study on 206 segments in France (Carfagna *et al.*, 1994) demonstrated that segments of 49 ha were sufficient for regional area estimates, although larger segments performed better. Depending on crop type and sampling costs, optimum segment size ranged from 140 to 200 ha. For the "Rapid estimates" subproject a segment size of 196 ha is chosen. Within each segment, 32 sampling points (20 x 20 m) regularly distributed over the segment, are selected (Figure 8.2). The location of these sample points does not change over time and their exact geographical position is marked on aerial photos to facilitate land use observations in the subsequent years. For each sampling point crop type is established. The yield of the field in which the sample plot is located is estimated and attributed to the sample plot. Yield is estimated by visual estimation by members of a panel consisting of agronomists, agricultural technicians and a selected group of farmers, not necessarily owner of the plots. Furthermore, according to M. Zalba (in charge of the field surveys in Spain), yield information is provided by an independent organization dealing with agricultural insurance and responsible for arbitrating compensation claims in case of a natural disaster (pers. comm.). Additional yield information is provided by agricultural organizations in the region and by the national meteorological service. From 1993 onwards, for each sampling point, sowing date, flowering date, harvest date and data on fertilizer application are collected. To reduce the cost of surveying, only 16 points per segment are sampled from 1994 onwards.

Figure 8.1. *Location of the sample sites in Spain*

This chapter concentrates on test sites where barley is the predominant cereal: Albacete, Badajoz, Ciudad Real, Guadalajara, Lerida, Teruel and Valladolid. Within these test sites only sample plots where barley was cultivated are considered; plots with other crops are omitted. For each site, per 10-day period, the number of sampling points sown to barley is determined and the collected data analyzed. Per test site yield variance analyses are executed. Yield values are grouped by sowing and flowering date and the yield differences among these dates are examined. Furthermore, it is investigated whether variation in rainfall amount or relative soil moisture is associated with variation in the number of sample plots sown per 10-day period.

To investigate whether sowing coincides with the expected onset of the rainy season or with the actual onset, the actual and historical rainfall data are analyzed. For Lerida and Valladolid 10-day rainfall totals were collected from records of nearby meteorological stations. For the other test sites only interpolated rainfall data were available. Missing data were replaced by interpolated values from the grid weather tables as applied in CGMS (See Subsection 3.2.1). This system is based on the crop growth simulation model WOFOST (Supit *et al.*, 1994; van Diepen *et al.* 1989; 1988; Keulen & Wolf, 1986). It operates on grid cells of 50 x 50 km. For each grid cell the required inputs are daily weather data as obtained by interpolation of observations from the existing network of meteorological stations (van der Voet *et al.*, 1993; Beek *et al.*, 1992), soil characteristics and management practices (i.e. sowing date, sowing density, etc.).

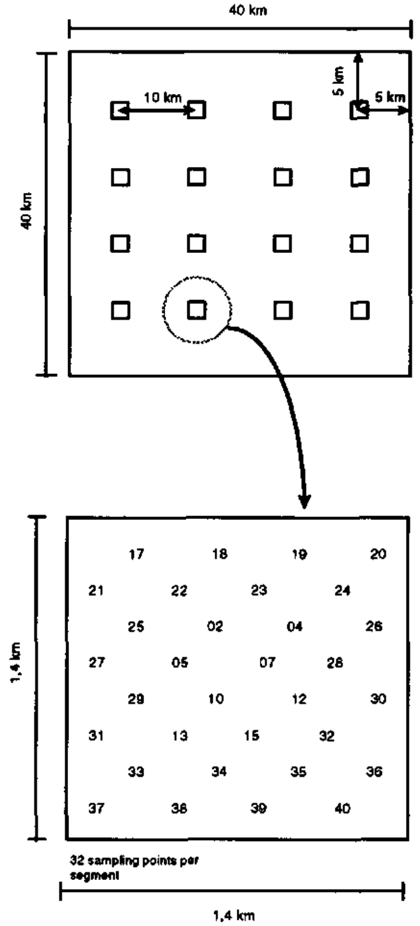

Figure 8.2. *Sampling sites, segments and identification numbers of the sampling points.*

Historical observed precipitation data from Lerida and Valladolid and historical interpolated data for the other test sites have been analyzed for the period 1975-1990. For each 10-day period total precipitation was calculated and for various probability levels the theoretical amount of rainfall, R_g, was determined:

$$P(R_o \leq R_g) = \int_0^{R_g} f(u)\,du \quad \text{and} \tag{8.1}$$

$$0 \leq \int_0^{R_g} f(u)\,du \leq 1 \tag{8.2}$$

where R_o is observed 10-day period rainfall and $f(u)$ the probability density function. Since most rainfall amounts are small, except for a few occasional heavy rains, rainfall distribution tends to be positively skewed and a gamma distribution can be applied (Buishand, 1978). The probability density function of the gamma distribution is given by:

$$f(u) = \frac{\beta^{\alpha}}{\Gamma(u)} u^{\alpha-1} e^{-\beta u} \tag{8.3}$$

where $\Gamma(u)$ is the gamma function and α and β are constants; α x β is the mean and α x β^2 is the variance of the distribution. Alternative distribution functions, such as the exponential distribution (Todorovic & Woolisher, 1974) or the three-parameter mixed exponential distribution (Woolisher & Pegram, 1979) can also be used. However, determination of the most appropriate distribution function falls beyond the scope of this chapter.

Estimation of the values α and β can be difficult when α is small. Estimates based on the maximum likelihood and methods of moments are not stable when α is less than 1. Several methods have been proposed to estimate α for this situation. In this chapter the method of Greenwood & Durand (1960), also described by Johnson & Kotz (1970), has been applied:

$$\alpha = (0.5000876 + 0.16488552Y - 0.0544274Y^2)/Y \quad \text{for } 0 < Y < 0.5772 \tag{8.4}$$

or:

$$\alpha = (8.898919 + 9.059950Y + 0.9775373Y^2)/Y(17.79728 + 11.968477Y + Y^2) \quad \text{for } 0.5772 \leq Y < 17 \tag{8.5}$$

where $\beta = \overline{X}/\alpha$ and $Y = \ln(\overline{X}/G)$, $\overline{X}$ = the arithmetic mean and G = geometric mean. The goodness of fit was tested with the Kolmogorov test (Genstat, 1994).

A spatial picture of the soil moisture conditions was inferred from ERS scatterometer measurements. The ERS scatterometer is a radar, operating at a frequency of 5.3 GHz (C-Band) and can acquire imagery independent of cloud cover and sunlight conditions (Attema, 1991). It is flown on board the ERS-1 and ERS-2 satellites and provides global coverage since 1991. The spatial resolution is 50 km and an overview over large regions can be given. The recorded signal is sensitive to vegetation (Frison & Mougin, 1996) and soil moisture

(Magagi & Kerr, 1997; Pulliainen *et al.*, 1996). The employed soil moisture retrieval algorithm accounts for effects of heterogeneous land cover and seasonal vegetation development and provides estimates of the relative soil moisture content as a fraction of saturation of the soil surface layer (Wagner *et al.*, 1999; in press). The thickness of the surface layer is about 5 to 10 cm corresponding to the penetration depth of C-band microwaves into the soil (Ulaby *et al.*, 1986). However, according to Jackson (1986), useful information about soil moisture to a depth of approximately 40 cm can be extracted. Ragab (1992) investigated the relation between surface layer soil moisture and soil moisture storage in the root zone for crops with a fully developed root system. He concluded that a high correlation existed between soil moisture in the surface layer and soil moisture in the deeper layers.

8.3 Results and discussion

8.3.1 Rainfall and soil moisture

According to Cantero-Martínez *et al.* (1995b), the rainy season in Spain generally starts in autumn and continues until spring. A more detailed analysis of historical rainfall data (1975-1990) reveals that for all sites, except Lerida, the rainy season starts around the second 10-day period of October. In Lerida the rainy season starts around the last 10-day period of September. Table 8.1 presents the theoretical rainfall quantities, R_g, for the 10-day periods from October-February for probability levels of $P(0 \leq R_o \leq R_g)$ = 0.3, 0.5 and 0.7, respectively, where R_o is observed rainfall. In Table 8.2 observed and interpolated 10-day period rainfall totals for the seasons 93-94, 94-95 and 95-96, as well the cumulative rainfall for the growing seasons are given. For all sites, except Lerida, the season 94-95 was drier than the other two seasons. For Ciudad Real the seasons 93-94 and 94-95 were both drier than 95-96. Comparing the seasons 93-94 and 94-95 cumulative rainfall values with historical values demonstrate that these two seasons can be considered as dry. The season 94-95 was extremely dry. The cumulative rainfall values for this season for Albacete, Ciudad Real and Teruel were lower than the lowest values in the historical series. The cumulative values for the other test sites were also low, but not to the same extent. According to Picatoste (Sección de Meteorología Hidrológica, Instituto Nacional de Meteorología) in the period 1991-1995 many regions suffered from drought (pers. comm.).

Figure 8.3 compares soil moisture time series derived from ERS scatterometer of the test site Sevilla with rainfall observations of a nearby synoptic station. Peaks in soil moisture estimates occur during or shortly after rainfall events. Some rainfall events are not reflected in the moisture series because of lack of satellite data. The summer months are generally dry resulting in low soil moisture values. The very low soil moisture values between February and October 1995 reflect the severe drought conditions in that year. It can also be seen that soil moisture values decrease approximately exponentially when a rainfall event is followed by a dry period (e.g. in January and November 1994, November 1995) which can be explained by the redistribution of water from the wetted surface layer into the relatively dry deeper layers (Hillel, 1980).

Spatial variability of rainfall in semi-arid regions is large and the use of interpolated rainfall data may introduce large errors in the analysis of rainfall regimes and their influence on sowing. To gain insight in the relation between rainfall and planting strategy, maps demonstrating the spatial and temporal distribution of rainfall over Spain should be made.

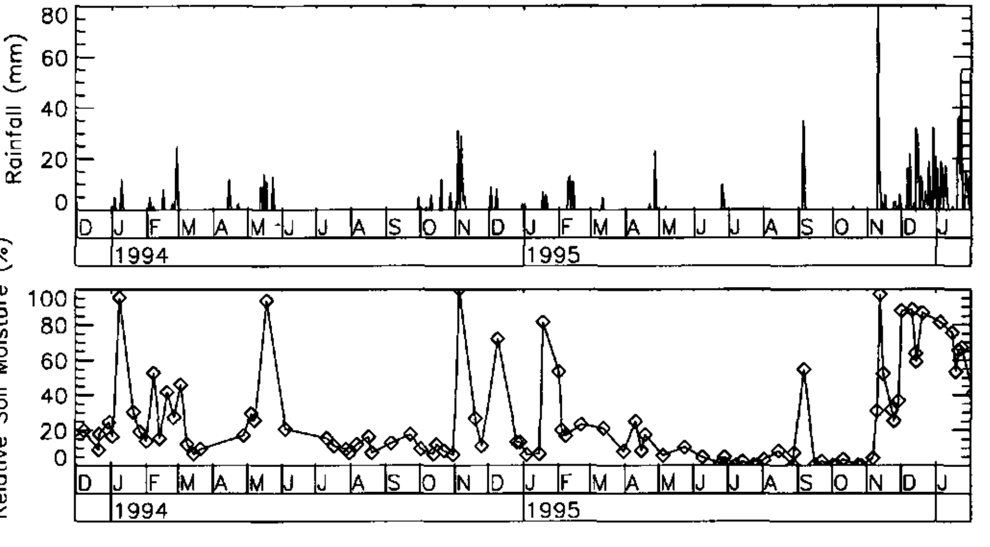

Figure 8.3. *Time series of rainfall (top) and relative surface soil moisture content derived from ERS scatterometer data (bottom) over Sevilla (5.88°W, 37.42°N) for the period from December 1993 to January 1996.*

Table 8.1. *Probability $P(R_o \leq R_g)$ that observed and interpolated 10-day period rainfall R_o (mm) is less than or equal to R_g (mm) calculated with the incomplete Gamma function.*

		10-day period rainfall R_g (mm)														
Location	$P(R_o \leq R_g)$	October			November			December			January			February		
		I	II	III	I	II	III	I	II	III	I	II	III	I	II	III
	0.3	0.0	1.7	0.3	0.5	5.1	0.0	1.4	1.6	2.3	3.0	0.0	0.0	1.9	3.1	3.4
Albacete	0.5	2.4	10.9	5.2	5.4	11.5	5.1	4.9	5.6	7.3	8.2	7.1	4.6	6.5	7.8	6.8
	0.7	8.1	25.3	16.4	15.0	21.3	15.1	11.2	12.0	14.8	15.3	13.5	12.9	14.6	15.6	11.4
	0.3	1.1	7.5	2.7	4.7	5.1	0.0	4.5	7.7	0.3	4.0	1.9	3.4	5.7	4.6	3.3
Badajoz	0.5	6.3	19.3	11.9	19.7	14.7	5.4	12.1	18.3	7.4	10.2	7.7	11.4	13.3	11.9	8.8
	0.7	17.1	37.5	24.0	39.3	32.1	16.7	25.4	35.6	28.2	18.4	17.7	23.6	25.2	23.2	17.7
	0.3	0.0	6.3	0.5	4.2	2.9	0.0	4.3	3.2	1.5	3.8	1.9	2.7	5.1	4.6	3.8
Ciudad Real	0.5	2.1	15.8	6.0	12.8	8.9	5.0	11.3	9.0	8.4	8.5	8.6	10.5	11.9	10.9	9.0
	0.7	7.8	30.0	17.1	27.6	19.0	15.2	20.8	18.5	22.6	14.9	17.9	20.2	21.8	21.0	16.7
	0.3	0.0	4.6	1.2	1.3	2.1	1.1	1.5	3.1	1.4	1.6	1.5	2.3	6.3	7.1	3.2
Guadalajara	0.5	3.0	13.0	5.1	7.9	6.7	5.0	5.4	8.3	7.9	5.4	6.7	9.7	11.7	13.2	7.3
	0.7	13.1	26.5	12.1	21.9	14.6	11.9	12.8	16.6	21.3	11.4	16.2	19.5	19.4	20.0	13.6
	0.3	12.2	8.4	7.9	4.4	8.8	8.7	13.0	11.8	9.4	8.3	8.9	12.6	11.5	10.2	8.8
Lerida	0.5	19.5	19.0	19.6	11.7	19.4	17.5	19.8	24.8	17.4	17.2	19.7	25.3	22.7	17.8	17.3
	0.7	29.3	34.1	37.4	24.1	34.2	30.3	28.7	45.7	28.7	31.3	36.4	45.2	37.4	28.6	28.6
	0.3	1.4	4.4	4.4	3.1	3.3	3.0	1.8	5.3	4.6	1.9	3.3	3.2	4.7	3.4	5.3
Teruel	0.5	5.8	10.3	12.4	9.0	7.8	7.0	4.7	11.0	9.2	5.7	8.3	9.7	9.5	8.9	10.0
	0.7	13.1	19.6	25.6	18.6	15.1	12.0	9.8	18.8	15.8	12.2	14.9	19.1	16.6	18.5	16.5
	0.3	2.9	6.1	4.5	5.3	5.1	1.0	4.3	5.6	2.3	3.3	3.5	3.3	6.3	3.4	5.4
Valladolid	0.5	8.8	14.0	10.7	12.8	14.0	4.7	10.3	13.8	9.5	7.2	9.0	10.4	12.6	9.0	10.5
	0.7	17.2	25.5	18.5	23.7	28.3	12.5	19.9	27.3	22.0	13.4	18.3	22.9	21.9	18.0	18.0

Table 8.2. *Observed and interpolated 10-day period rainfall R_o (mm) for three seasons*

Location	Season	10-day period rainfall R_o (mm)															
		October			November			December			January			February			Oct.-July
		I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	
Albacete	93-94	13.5	7.3	47.4	31.3	8.0	3.7	0.0	7.0	0.0	4.0	6.8	3.7	66.4	15.8	5.3	220.4
	94-95	15.0	28.4	3.0	14.5	3.0	0.0	0.6	2.6	0.0	10.0	0.0	0.0	5.8	24.0	3.0	151.3
	95-96	5.0	0.0	0.2	3.7	10.8	23.2	23.1	10.6	20.9	0.0	3.0	0.0	0.0	6.0	0.0	263.5
Badajoz	93-94	46.1	51.8	19.0	74.4	0.9	11.2	0.3	3.0	0.5	0.0	0.0	8.1	20.0	2.0	0.0	441.5
	94-95	9.6	11.6	28.1	79.2	1.1	1.0	13.0	0.1	13.4	20.9	2.0	0.0	14.2	17.3	32.6	360.6
	95-96	0.9	0.0	7.2	17.0	55.9	15.0	25.7	8.9	145.6	0.0	14.9	12.3	15.7	49.0	0.0	683.7
Ciudad Real	93-94	27.8	18.1	31.0	17.4	0.1	8.5	0.0	5.1	0.0	0.0	0.0	0.2	2.4	2.0	0.0	192.5
	94-95	4.2	39.6	12.0	40.0	1.0	0.0	7.1	0.0	0.4	17.6	0.9	0.0	10.6	9.9	5.4	197.2
	95-96	0.0	1.0	3.0	7.3	60.2	3.2	5.4	28.2	93.4	0.0	8.7	5.7	6.2	5.1	0.1	414.9
Guadalajara	93-94	39.8	19.4	19.1	13.5	0.0	3.6	0.0	0.5	0.0	0.0	0.1	0.0	3.2	7.5	0.0	361.0
	94-95	1.9	5.7	5.7	15.1	1.0	0.0	2.1	0.5	2.0	7.3	0.0	0.0	3.8	2.1	9.5	259.1
	95-96	0.0	2.0	1.7	3.5	20.5	8.6	4.0	11.2	34.1	0.0	3.7	1.0	2.0	17.2	0.5	404.8
Lerida	93-94	33.1	12.0	28.4	23.1	3.6	9.3	3.2	4.3	42.1	1.7	0.0	0.6	49.3	3.1	2.5	790.8
	94-95	13.7	19.7	22.6	43.5	11.5	0.5	3.5	9.8	27.8	13.1	12.4	3.4	29.8	29.9	15.3	757.5
	95-96	8.8	12.1	0.5	2.0	17.7	16.7	65.1	6.5	21.6	46.8	24.3	10.9	7.6	12.3	18.7	807.8
Teruel	93-94	25.7	24.1	33.4	22.8	5.3	12.5	0.3	5.0	2.1	0.1	0.2	0.0	57.1	1.7	11.1	276.3
	94-95	14.0	29.0	12.1	32.3	5.2	0.0	5.0	2.1	2.2	14.2	0.6	0.2	8.6	17.8	10.1	225.5
	95-96	4.0	1.3	2.2	5.5	16.8	20.4	21.2	8.0	33.8	0.8	5.0	0.6	4.6	6.1	3.9	301.8
Valladolid	93-94	75.9	53.1	7.2	9.4	0.0	11.5	0.6	2.2	1.6	0.5	0.9	0.2	2.0	0.9	0.9	363.0
	94-95	5.0	20.8	31.6	46.4	3.2	0.7	7.4	3.4	22.5	34.6	5.3	0.0	9.7	2.8	26.7	271.6
	95-96	8.0	2.5	9.5	19.1	72.0	22.2	2.6	1.2	101.3	12.6	12.3	10.6	6.5	32.4	3.2	544.2

However, with the available rainfall data no accurate maps could be produced. Therefore, as an alternative, maps presenting the spatial variation in the relative soil moisture estimates averaged over the number of scatterometer data acquisitions per 10-day period were made (see Figure 8.4). These maps demonstrate for each 10-day period how soil moisture within the test sites relates to soil moisture in the surrounding areas. They also provide an indication of the soil moisture conditions at the time of sowing and show soil moisture variations over time as well as occurrences and extent of drought periods. For some 10-day periods no data were available. In 1993 and 1994, only the first 10-day period of November demonstrated areas with a relative soil moisture content exceeding 75%. The drought ended in November 1995 when high rainfall amounts quickly saturated the soil.

8.3.2 Sowing dates, rainfall and sowing conditions

In season 94-95 more sampling points were sown to barley than in the seasons 93-94 and 95-96 (Table 8.3), suggesting that the area sown to barley was highest in that season. This is confirmed by the official area estimates of EUROSTAT: areas sown to barley were: 3539.5 10^6 ha, 3556.0 10^6 ha and 3529.9 10^6 ha for the seasons 93-94, 94-95 and 95-96, respectively. Reduction in the area in 95-96 compared to 94-95 could be the result of new subsidies on industrial crops such as sunflower and flax, causing an increase in the area sown to these crops.

Table 8.3. *Number of sampling points per test site sown to barley*

Site	Year		
	1994	1995	1996
Albacete	52	54	64
Badajoz	25	45	45
Ciudad Real	100	89	106
Guadalajara	79	100	51
Lerida	105	114	114
Teruel	70	64	76
Valladolid	96	71	61
Total	527	537	517

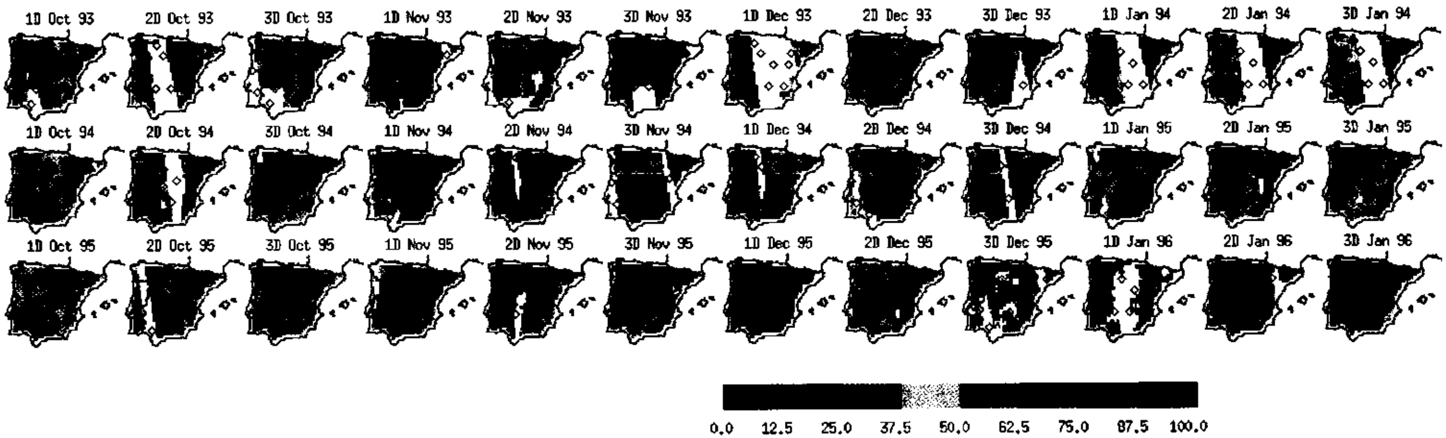

Figure 8.4. *Estimated average 10-day period surface soil moisture content expressed in percent of saturation for the months October to January of the seasons 93-94, 94-95, and 95-96. Estimates are based on ERS scatterometer measurements. Pixels are white if either no data were available or did not pass quality control procedures.*

Table 8.4 shows the number of sample plots sown per 10-day period. Although for several plots the sowing date was not available, generally for more than 85 % of the sampling points sowing dates could be obtained. About 80% of the sowings occurred during the first six 10-day periods of the rainy season. The number of sample plots sown during this period is significantly higher (F-test 5%) than in the other 10-day periods. The exception is Guadalajara, where the majority of the plots is sown in December. The reason for this phenomenon is not known.

For all sites, the probability of receiving 25 mm or more rain in a 10-day period, the amount found to be sufficient to allow emergence, is less than 50% (Table 8.1). Little evidence could be found that farmers wait until 25 mm of rain has fallen before sowing. Sowing in the studied seasons often took place under low soil moisture conditions. Similar practices were also observed in the central Ebro valley by Cantero-Martínez *et al.* (1995b). These authors recorded that in three out of the four studied seasons the amount of soil moisture at sowing was very low. The impression exists that farmers base their sowing not only on a certain threshold amount of rain but also on knowledge about historical rainfall. For example, in Lerida in 1995, sowing took place in October, as in the years 1994 and 1993. In contrast to the years 1993 and 1994, sowing in 1995 took place under dry soil moisture conditions as can be seen in Table 8.2 and Figure 8.4. However, the sampling plot yields were of the same order of magnitude as the preceding seasons, indicating that suboptimal sowing conditions, as a result of low soil moisture conditions, may be compensated later in the season. A similar situation was observed in Guadalajara for the seasons 93-94 and 94-95, where sowing took place in December and January under dry conditions (Table 8.2 and Figure 8.4).

Analysis of the sowing dates showed that about 80% of the sample plots were sown within a period of six 10-day periods. The hypothesis that variation in rainfall or soil moisture is associated with variation in sowing dates was tested. For all test sites, except Guadalajara, the analyzed period was the first 10-day period of October until the third 10-day period of November. For Guadalajara the period from the third 10-day period of November till the second 10-day period of January was chosen. The following models were tested:

$$Q_T = aT + c \qquad (8.6)$$

$$Q_T = aT + bV_T + c \qquad (8.7)$$

$$Q_T = aT + bV_{T-1} + c \qquad (8.8)$$

$$Q_T = bV_T + c \qquad (8.9)$$

where Q_T is the accumulated number of sample plots sown in 10-day period T, expressed as a fraction of the total number of sample plots; V_T is either rainfall or soil moisture derived from the ERS scatterometer averaged over the number of available observations in 10-day period T and a, b and c are regression coefficients.

Regressions were established per site and per season and subsequently pooled for the three seasons. The correlation coefficient, r, for the regression of Q_T on T, for all test sites per season and for the three seasons pooled was higher than 0.90. V_T and V_{T-1} were not significant (t-test 5%). Although rainfall and soil moisture may influence the timing of sowing, significant variation in sowing date as a result of variation in precipitation or soil moisture could not be demonstrated.

Sowing for all test sites, except Guadalajara, may be correlated to the expected onset of the rainy season. The need to synchronize between phenology of the selected barley cultivars and the expected water supply during the growing season may limit the possibilities to postpone sowing. According to van Keulen & Seligman (1987) postponement of sowing can result in logistic problems and a late start of growth. These authors investigated the consequences of different sowing dates on yields and growth of wheat in Israel. They concluded that lower total dry matter and lower grain yields are to be expected when sowing is postponed in a season where early rains occur. It may thus be profitable for the Spanish farmers to sow early at the beginning of the expected rainy season, even though the soil moisture conditions are suboptimal. Enough rainfall may fall in the days after sowing to ensure germination, emergence and canopy development. Moreover, if enough rain falls in the course of the season, the crop may profit from early development, and higher yields can be expected than in dry years when sowing is delayed. On the other hand, if the season is dry, consequences of early sowing for yield are small or not noticeable, as was found in this chapter (see next section). Sowing in dry soil may hamper germination and emergence, however, the water availability after emergence is the most important yield-limiting factor in semi-arid regions and sufficient rainfall after this stage may compensate the effects of water stress at emergence.

Table 8.4. *Number of sampling plots per test site sown to barley per 10-day period in 93-94, 94-95 and 95-96 in Spain*

		Number of sampling plots sown															
Location	Season	October			November			December			January			February			Total
		I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	
	93-94	1	4	10	19	5	-	1	-	-	2	-	-	-	1	-	43
Albacete	94-95	-	1	13	23	14	-	-	-	-	-	-	-	-	-	-	51
	95-96	-	8	2	7	27	7	-	-	-	4	-	-	-	-	-	55
	93-94	7	4	-	8	-	-	1	-	-	-	-	-	-	-	-	20
Badajoz	94-95	7	9	2	12	9	3	-	-	1	-	-	-	-	-	-	43
	95-96	1	2	6	12	1	-	-	-	-	-	1	-	-	-	-	23
	93-94	2	2	5	22	32	10	3	10	2	1	-	-	-	2	-	91
Ciudad Real	94-95	3	4	18	15	30	1	-	-	-	3	-	-	-	-	-	74
	95-96	-	13	26	6	20	22	2	1	1	2	-	6	-	-	-	99
	93-94	-	-	-	3	3	4	8	12	12	16	10	8	1	-	-	77
Guadalajara	94-95	3	-	-	3	3	2	17	15	10	30	14	1	1	-	-	99
	95-96	-	3	-	-	4	-	3	1	3	11	6	7	9	1	-	48
	93-94	2	22	30	24	8	9	-	-	-	-	-	-	-	-	-	95
Lerida	94-95	2	21	59	21	-	4	2	-	2	-	-	-	-	-	-	111
	95-96	17	32	38	18	4	-	-	-	-	-	-	-	-	-	-	109
	93-94	1	1	5	28	17	5	8	1	-	-	-	-	-	-	-	66
Teruel	94-95	1	1	8	31	14	5	2	-	-	-	-	-	-	-	-	62
	95-96	-	5	5	36	12	8	1	1	-	1	-	-	1	-	-	70
	93-94	-	-	6	20	33	6	2	3	3	1	2	3	12	2	-	93
Valladolid	94-95	1	-	2	8	32	14	3	3	-	1	3	2	2	-	-	71
	95-96	-	2	9	9	21	-	9	1	2	2	1	-	1	1	-	58

- no sowing was observed

8.3.3 Yield, sowing date and flowering date

Table 8.5 presents the number of plots where flowering has been observed. Generally, flowering occurred between the second 10-day period of April and the second 10-day period of May. Within this period, the highest percentage of flowering plots was observed in the first 10-day period of May (F-test 5%). Comparison of Table 8.5 with Table 8.4 shows that for a number of plots for which sowing dates were available flowering date could not be obtained. In the season 94-95 this was caused by drought; crop failure occurred before flowering.

Table 8.6 presents average yields of the sampling plots grouped by sowing date. The growing season 94-95 was very dry and consequently yields for all test sites, except Lerida, were low. For some sample plots complete crop failure was recorded. Analysis of the yield, grouped by sowing date, demonstrated a significant difference among the seasons for all sites (F-test 5%), which can be explained by the difference in rainfall among the seasons, rainfall distribution and duration of the droughts.

Within the seasons, except for Albacete seasons 93-94 and 95-96, Lerida season 94-95 and Badajoz season 93-94, no significant effect of sowing date on yield could be demonstrated. In the case of Albacete a few sample plots were observed with an average yield more than twice as high as in the other plots. This may suggest that these plots were irrigated. These plots were sown in the same 10-day period and located in the same segment. For wheat, early autumn sowings tend to give the highest yields (Russell & Wilson, 1994). For barley, grown without water limitations, this may also be true. However, in this chapter, significant variation in yield as a result of variation in sowing date could not convincingly be demonstrated (F-test 5%). Factors such as water stress, terminal drought, diseases, etc., could mask the effects of the initial growing conditions.

Yield variance analysis, grouping yield by flowering date, gave similar results: yield differences among the plots as a result of flowering date variation were not significant (F-test 5%).

Table 8.5. *Number of sampling plots where flowering is observed, grouped per 10-day period in 93-94, 94-95 and 95-96 in Spain.*

		Number of sample plots												
Location	Season	March			April			May			June			Total
		I	II	III	I	II	III	I	II	III	I	II	III	
	93-94	-	-	-	2	18	12	6	5	-	-	-	-	43
Albacete	94-95	-	-	-	2	9	2	19	9	1	-	-	-	42
	95-96	-	-	-	-	-	27	28	-	-	-	-	-	55
	93-94	1	3	-	8	6	-	2	-	-	-	-	-	20
Badajoz	94-95	5	8	11	11	4	1	-	-	-	-	-	-	40
	95-96	-	-	-	8	12	3	-	-	-	-	-	-	23
	93-94	8	-	-	7	26	29	9	11	-	-	1	-	91
Ciudad Real	94-95	-	1	-	19	7	3	8	2	-	-	-		40
	95-96	-	-	-	4	15	40	32	8	-	-	-	-	99
	93-94	-	-	-	-	1	9	24	32	3	1	-	-	70
Guadalajara	94-95	-	-	-	-	-	2	62	29	6	-	-	-	99
	95-96	-	-	-	-	2	6	30	6	4	-	-	-	48
	93-94	-	-	17	37	12	13	7	8	-	-	-	-	94
Lerida	94-95	-	-	4	3	44	29	10	17	2	-	-	-	109
	95-96	-	-	-	5	59	42	2	1	-	-	-	-	109
	93-94	-	-	-	-	-	-	35	14	8	2	-	-	59
Teruel	94-95	-	-	-	1	2	6	17	31	2	2	-	-	61
	95-96	-	-	-	-	-	5	47	13	2	3	-	-	70
	93-94	-	-	-	2	11	8	46	21	1	4	-	-	93
Valladolid	94-95	-	-	-	5	1	5	17	30	12	1	-	-	71
	95-96	-	-	-	-	13	10	13	15	7	-	-	-	58

- no flowering observed

The influence of rainfall on crops in semi-arid regions has been extensively studied (e.g. Vossen, 1990a; van Keulen & Seligman, 1987; Dennett *et al.*, 1981; Doorenbos & Kassam, 1979), and a variety of approaches to assess the effects of water availability or water stress on yield exists. The simplest approach is to relate total seasonal rainfall to yields measured at a given site or region (e.g. Le Houérou *et al.*, 1988; Le Houérou & Hoste, 1977; Breman, 1975). In this chapter the mean test site yield was correlated to accumulated rainfall over the months October to May and to the mean relative soil moisture content established for the same period. The correlation coefficient, r, was 0.59 ($p < 0.03$) and 0.71 ($p < 0.01$) for the regression of yield on accumulated rainfall and mean soil moisture content, respectively. Villar (1989), as cited by Cantero-Martínez *et al.* (1995b), analyzed 30 years of barley yield records. He found a similar correlation coefficient ($r = 0.56$) for the correlation between yield and the cumulative rainfall for the months October to May. The higher correlation for the mean relative soil moisture content may suggest that a part of the accumulated rainfall does not infiltrate and consequently cannot account for crop growth. According to van Keulen & Seligman (1992), in many semi-arid regions runoff occurs on a large scale and precipitation is transported far from its original "impact site".

Table 8.6. *Average barley yields grouping the sampling plots by sowing date.*

		Yield (ton/ha)														
Location	Season	October			November			December			January			February		
		I	II	III	I	II	III	I	II	III	I	II	III	I	II	III
	93-94	0.8	1.2	1.1	1.5	1.7	-	1.2	-	-	4.8	-	-	-	-	-
Albacete	94-95	-	0.0	0.1	0.3	0.8	-	-	-	0.0	-	-	-	-	-	-
	95-96	-	2.0	1.9	1.6	1.9	2.5	-	-	-	5.0	-	-	-	-	-
	93-94	1.4	1.6		0.8			1.5	-	-	-	-	-	-	-	-
Badajoz	94-95	0.3	0.0	0.1	0.1	0.3	0.1	-	-	0.0	-		-	-	-	-
	95-96	0.3	0.7	1.7	1.9	1.8	-	-	-	-	-	0.5	-	-	-	-
	93-94	0.1	0.2	0.8	0.5	0.6	0.3	1.8	1.3	0.2	0.3	-	-	-	-	-
Ciud.Real	94-95	0.0	0.2	0.2	0.1	0.2	0.0			0.0	1.8	-	-	-	-	-
	95-96	-	1.7	1.6	2.1	2.4	2.1	1.7	2.0	1.5	1.9	-	2.1	-	-	-
	93-94	-	-	-	2.1	3.3	2.9	2.1	2.4	2.6	2.6	2.5	2.6	2.4		-
Guadalajara	94-95	-	-	-	0.8	1.9	1.0	0.7	0.7	1.1	1.9	1.4	0.6	2.0		-
	95-96	-	1.8	-	-	3.2	-	3.5	3.0	1.9	2.9	3.2	3.1	3.1	3.0	-
	93-94	2.5	2.2	2.5	2.3	1.8	2.3	-	-	1.9	-	-	-	-	-	-
Lerida	94-95	2.7	2.6	2.3	2.9	-	1.8	1.7	-	0.0	-	-	-	-	-	-
	95-96	3.4	3.5	3.5	3.2	2.6	-	-	-	-	-	-	-	-	-	-
	93-94	1.2	1.8	0.6	0.8	0.7	0.5	1.0	1.2	-	-	-	-		-	-
Teruel	94-95	2.0	1.5	1.6	1.2	1.1	1.7	1.3		0.0	-	-	-		-	-
	95-96	-	1.9	2.5	2.0	2.1	2.5	2.7	1.6		2.0	-	-	3.8	-	-
	93-94	-	-	2.6	2.6	2.5	2.6	3.5	2.5	2.6	2.2	2.5	3.0	2.1	2.0	-
Valladolid	94-95	0.8	-	1.8	1.8	1.5	1.2	1.6	1.5		1.0	2.1	2.0	2.0	-	-
	95-96	-	2.4	3.3	3.2	3.3	3.2	3.0	2.5	3.2	3.2	-	2.8	3.5	-	-

- no sowing occurred

These regression results are not conclusive: yield observations within the seasons are not independent, and the test only suggests that soil moisture estimates, derived from ERS scatterometer data, may be associated with the yield variation. More research on the use of scatterometer estimates as input in agro-meteorological models is needed to fully appreciate its usefulness for agricultural monitoring.

8.4 Conclusions

In the period 1993-1996, the majority of the barley sowings took place at the expected start of the rainy season. Delay of the onset of the rainy season resulted in sowing under dry, suboptimal conditions. Variation in sowing date associated with variation in rainfall could not be convincingly demonstrated. Farmers may base their sowing strategy on the assumption that sowing at the expected beginning of the rainy season in combination with sufficient rainfall during the growing season will result in higher yields than when sowing is delayed. In dry years, when available water is the main limiting factor, effects of sowing date variation on yield cannot be demonstrated. The need to synchronize between phenology of the selected barley cultivars and seasonal rainfall may also limit the possibilities to postpone sowing. Yields in Lerida and Guadalajara show that favourable soil moisture conditions in later stages of the crop cycle may compensate for poor initial growth conditions. Furthermore, no significant effect of variation in flowering date on yield could be demonstrated. Provided that effects of sowing date variation and crop responses to water stress are correctly modelled, it may be assumed that, at least for Spain under the prevailing farming methodologies, one single sowing date per region may be sufficient as input for a crop growth monitoring system, to assess yield and crop status.

9. General conclusions

9.1 Summary

As described in **Chapter 1**, the European Union (EU), through its Common Agricultural Policy (CAP), attempts to regulate the common agricultural market to, among others, secure food supplies and provide consumers with food at reasonable prices. Implementation and control of these CAP regulations is executed by the Directorate General for Agriculture (DG VI) of the EU. To manage this common market, to evaluate the consequences of these regulations and to estimate the subsidies to be paid, DG VI requires detailed information on planted area, crop yield and production volume (De Winne, 1994).

Information on land use, interannual land use changes and yields is routinely collected by the national statistical services, which convey this information to the statistical office of the European Commission, EUROSTAT. Collection and compilation of these agricultural statistics however, is time consuming and laborious; it often takes up to one or two years before this information is available in the EUROSTAT databases. At this late stage, these statistics are of limited use for evaluating policy or to estimate the amount of subsidies to be paid. Hence, more timely and accurate information is needed. To assist DG VI and EUROSTAT to collect this information, the MARS project was initiated, with the aim to develop methods to produce timely statistics on land use, planted area and production volumes for various crops within the EU. The CAP and the MARS project are described in **Chapter 2**.

The MARS project applies remote sensing imagery and ground surveys to estimate the planted area. Since no proven methods to relate satellite imagery to quantitative crop yields were available at the beginning of the MARS project, a crop growth monitoring system (CGMS) based on a crop growth simulation model was developed. CGMS and the operational method currently applied in the MARS project to predict production volumes of various crops, are described in **Chapter 3**.

The basic assumption in CGMS is that the crop growth model takes into account the variation in yield caused by meteorological factors, whereas a time trend takes into account the yield increase resulting from use of improved varieties, new techniques, etc. (Vossen, 1990a; 1992). De Koning *et al.* (1993) tested this system and concluded that adding crop growth simulation results to a linear time trend did not convincingly improve the prediction accuracy.

Simple time trend functions are easy to use and Palm & Dagnelie (1993) reported that adding meteorological variables to these functions, to account for weather influences, did not demonstrably improve the prediction accuracy. A disadvantage of mere trend functions however, remains that they do not account for weather variations, breaks in the trend in yield and production volume series as a result of changes in the CAP regulations, changing fertilizer prices, etc. In this thesis several variants of the current operational version of CGMS are explored.

The research of de Koning *et al.* (1993) and Palm & Dagnelie (1993), implicitly assumed that yield per unit area and planted area are independent of each other. In **Chapter 4,** total production volume instead of yield per unit area is considered, hypothesizing that the annually planted area and the yield per unit area are mutually dependent and should therefore be analyzed simultaneously. It is assumed that weather and economic factors affect production volume variation. For two of the major wheat producing countries the analysis fails to demonstrate a relation between the soft wheat production volume and selling or intervention price. Intervention and selling price are also not significantly associated with the durum wheat production volume (5% t-test). Furthermore, for soft wheat, for 5 out of the 10 investigated countries, and for durum wheat, for 3 out of the 4 investigated countries, the expenditure on crop protection agents is not significantly associated with the production volume. Although these results suggest that prices and the expenditure on crop protection in some cases may be associated with production volume, these parameters are not generally applicable to describe production volume and should therefore not substitute the linear time trend in the applied prediction model. As an alternative to economic factors, the fertilizer application per unit area is examined. The analysis shows that this factor can account for the trend and production volume variation.

In **Chapter 5**, production volumes of soft and durum wheat are predicted. Two types of prediction models were examined. The first type included the planted area in the prediction model, and production volume was predicted in one step. The second type predicted the production volume in two steps: first, yield per unit area was predicted and subsequently, this value was multiplied by an estimate for the planted area. Furthermore, two functions to describe the trend in yield and production volume series were tested: a linear function of time and a linear function of the fertilizer application. A hypothetical and an operational situation were studied. The hypothetical situation assumes that current year's information on planted area and fertilizer consumption is available, whereas the operational situation assumes that these two variables are not available and consequently have to be estimated.

Comparison of the results from the one-step model with those from the two-step model demonstrates that in the operational situation in 14 out of 16 crop-country combinations the one-step model predicted more accurately when a linear time trend was applied. When fertilizer application was applied the one-step model in 10 out of 16 crop-country combinations provided more accurate results. Furthermore, when two-step prediction models were applied, crop simulation results were significant in approximately 30% of the cases (5% t-test). However, when models of the one-step type were used, this number increased to more than 80%.

Although these results cannot be viewed as a proof that one-step models are really superior, they still give an indication and provide a direction for further research. It corroborates the assumption that variation in planted area and yield per unit area are not independent and therefore variation in production volume should be analyzed using models of the one-step type.

Comparison among the one-step model results in the operational situation shows that in 50% of the investigated crop-country combinations the model that applied simulation results plus either a linear time trend or fertilizer application, predicted more accurately than the model that did not apply simulation results.

In the hypothetical situation the two-step model that uses the fertilizer application provided the most accurate results. However, analysis also demonstrates that in the operational situation this model yielded the least accurate results. In this situation, the one-step models provided the most accurate results since they are less sensitive to errors in the planted area estimates.

Although the prediction results obtained with simulation results are not always more accurate when compared to results derived from trend extrapolations or simple averages, the use of simulation results in combination with a trend function certainly holds a promise for further improvement.

In **Chapter 6**, a method to estimate daily global radiation was developed and tested. This method uses cloud cover and the temperature range as input. It provides less accurate results than the Ångström-Prescott equation, but the differences are small. This method may be used as an alternative for the Ångström-Prescott method when sunshine duration observations are not available. A hierarchical method is proposed to introduce global radiation in CGMS. If observed global radiation is available it will be used, if only sunshine duration is available the Ångström-Prescott method will be used, if neither radiation nor sunshine is available, the method developed here may be applied.

In **Chapter 7**, an additive and a multiplicative model are compared. An additive model assumes that variation in production volume as a result of weather variation is similar under high production systems and low production systems. The multiplicative model assumes that variation in production volume over the years is proportional to the mean production level. Wheat production volumes for France were predicted at subregional, regional and national level. The predictions at subregional and regional level were aggregated to national values.

The results suggest that more accurate predictions of total national production volume can be obtained when predictions executed at regional or subregional level are aggregated into a national value instead of estimating this value in one step. This may be the result of the applied aggregation procedure (see Section 3.4). Presumably, local weather effects are obscured in the aggregated values. Another explanation could be that errors in the production volumes of the individual regions or subregions compensate each other when summed to a total national value.

The results in this chapter also provide some evidence that aggregated predictions derived from the multiplicative model are more accurate than those derived from the additive model, suggesting that effects of weather on crop growth depend on the magnitude of the annual mean yield (Valdez-Cepeda, 1993). Furthermore, predictions obtained with the proposed method (Chapter 6) to calculate and introduce global radiation values into CGMS, are slightly more accurate than the results obtained with the operational version of CGMS.

Caution should be exercised: prediction of production volumes at lower administrative levels applying the CGMS prediction routine may not be feasible for all EU member states. Official yield and production volume statistics on these levels, required as input for the prediction routine, may not be available or may contain large errors.

Field surveys as executed in the framework of the MARS project may provide information on farming practices, which may help adapting the currently applied prediction model. In **Chapter 8** these data are analyzed with the aim to increase insight in sowing strategies of rainfed barley in semi-arid regions. The hypothesis is that in CGMS sowing date variation should be accounted for: CGMS assumes per crop and per region one sowing and one flowering date, hypothesizing that sowing and flowering date variation have limited effects on the regional production volume. The results obtained in this chapter, at least for barley grown under rainfed conditions, support this hypothesis: no association could be demonstrated between (i) sowing date variation and yield per unit area; (ii) sowing date variation and the precipitation amount; (iii) flowering date variation and yield per unit area. Farmers may base their sowing strategy on the fact that sowing at the presumed beginning of the rainy season will give higher yields than when sowing is delayed, provided rainfall during the growing season is sufficient. In dry years, when available water is the main yield-limiting factor, effects of sowing date variation on yield are not noticeable. The need to synchronize seasonal rainfall and phenology of the selected barley cultivars may also limit the possibilities to postpone sowing.

9.2 Evaluation and further research

The principal objective of this study was to explore possibilities to improve CGMS in such a way that it may be applied for quantitative yield prediction for all EU member states. Various options have been explored. Although some interesting results have been obtained, only two concrete suggestions for such an improvement can be given: (i) predictions should be executed at lower administrative level and subsequently aggregated to national values, (ii) planted area should be included in the analysis and prediction model. More research is needed to identify tangible points for improvements in CGMS.

Generally, to judge the acceptability of a model in an application mode, statistical criteria in comparing model predictions to a sample of observations are appropriate (Sinclair & Seligman, 1996). In this thesis, prediction results were compared to official yield and production statistics. However, according to the results of Bradbury (1994) the error in those statistics is not known for most EU member states and the methods to generate these data differ from country to country (see Subsection 3.2.5). To evaluate CGMS and the prediction results, accurate methods to collect yield, production and land use statistics should be developed, preferably at national, regional, and subregional level. Moreover, these methods should be consistent for all EU member states and efforts should be made to assess their accuracy. Evaluation can only take place when the accuracy of the official yield and production statistics is known. In the present situation of uncertainty about accuracy of official statistics, and in the absence of supplementary field data, one cannot even investigate whether the CGMS predictions are better or worse than the official statistics. Therefore, in the context of CGMS, it is quite hard to conclusively prove statistically that one prediction method is superior to another. For a true statistical proof, data from a new series of years, not used while exploring all kinds of predictive models, are needed. Nevertheless, one may use statistics to explore why one prediction method is better than another or to understand why a prediction method does not perform as expected.

The results demonstrated that where accurate regional or subregional statistics were available, national production volume is better predicted through aggregation of predictions at regional or subregional level than through direct estimation of the national value (Chapter 7). This may be related to the fact that in the former situation local environmental conditions are better taken into account. However, differences in prediction accuracy among the applied models at these levels are small in absolute sense. Also, the prediction accuracy improvement using the radiation routine proposed in Chapter 6 was small. The question may be asked whether the effort necessary to compile the input data for CGMS justifies the use of such a model if the gains are limited. More research to obtain insight in the prediction capability plus analysis of the costs and benefits is needed. Also, accurate methods to estimate the planted area at regional and subregional level have to be developed. (The method applied in the MARS project is operational since the beginning of the 90's; it only estimates the planted area at country level and not all countries are considered.)

Another question might be whether one single model should be applied for crop growth simulation and prediction for all EU member states. According to Sinclair & Seligman (1996), models developed for specific environmental conditions may fail when applied in other environments. Further research might indicate whether more accurate results could be obtained when for various climatic zones or soil type classes different models are included in CGMS. The system has to be tested for the whole of the EU, using a large number of annual observations that have not been used for development and selection of an appropriate model to be included in the prediction system.

Caution is also needed when extending CGMS with submodels that may account for various crop growth processes not yet included in the system. According to, amongst others, Sinclair & Seligman (1996), Passioura (1996), Colson *et al.* (1995), Bell & Fisher (1994), Assare *et al.* (1992) and Spitters (1990), increasing crop model complexity is not likely to improve the predictions. Each new submodel introduces new errors.

CGMS assumes that a crop growth model accounts for variation in yield due to meteorological factors, whereas a time trend accounts for the yield increase as a result of improved varieties, new techniques, etc. The yield and production volume series applied in this thesis demonstrate a substantial trend in time that cannot be explained by the applied crop growth simulation model. A more accurate prediction model may be developed when more insight is gained in factors that cause this trend. A potential factor to be investigated is the regional fertilizer consumption and its variation over time as a result of economic influences.

New techniques, introduction of growth regulators, improved varieties, etc. made increased fertilizer applications possible (e.g. Foulkes *et al.*, 1998; Russel & Wilson, 1994; Hough, 1990) and it may well be that current wheat growing systems, as Porter (1993) observed, are more sensitive to soil nitrogen than to soil water level. Hence, a model combining fertilizer application and crop growth simulation results may offer perspectives, especially for those regions where high production volumes are observed. Another option could be the application of simple fertilizer yield response functions (Weber, 1995; Buresh & Baanante, 1993; Cerrato & Blackmer, 1990; Nelson *et al.*, 1985). However, as discussed by Sinclair & Park (1993), the limiting-factor paradigm that plant growth is constrained by one single resource whose availability is so low that it solely determines growth rate may not be true. Crop growth may be limited by a number of resources that influence each other (e.g. Nielsen & Halvorson, 1991)

As a rule, information on fertilizer application and planted area is not available when the final predictions have to be made and these values should be estimated (Chapter 5). According to Young *et al.* (1994), Christen & Hanus (1993) and Knowles *et al.* (1991), introduction of innovations in agriculture may be driven by agricultural policies, implemented by local authorities, or by the EU through market prices and subsidies. An agro-economic model may predict farmers' management decisions and estimate changes in fertilizer and crop protection agent applications (e.g. Oude Lansink & Peerlings, 1996) as well as planted area. A bio-economic model should be developed, that integrates agro-ecological and socio-economic model parameters, similar to those applied for policy analysis of sustainable land use (e.g. Kruseman & Bade, 1998; Ruben *et al.*, 1998), with the aim to reduce the unexplained part in production volume variation. In this context, the SPEL model (Henrichsmeyer, 1994) and the ECAM model (Folmer *et al.*, 1993), should be investigated for possible integration with CGMS. These models operate at country level and are developed as supporting tools to evaluate the EU policy for the agricultural sector of the whole of the EU. SPEL is currently used by EUROSTAT to analyze trends in yield and production volume and land use changes in all EU member states.

Economic factors however, may only partly account for the trend in production volume (de Hoogh, 1990), and according to Oskam & Stefanou (1997) it seems probable that the CAP has stimulated productivity growth in the agricultural sector, although this conclusion is very weak. As with all other proposed changes to CGMS, further research should demonstrate that including agro-economic models in CGMS improves the prediction accuracy.

The merits of the soil moisture submodel should also be evaluated. The procedure that selected the simulation results as input for the prediction routine rarely selected the water-limited simulation results. Preference was given to potential situation simulation results, suggesting that the water-limited calculations are a source of additional error to the predictions. This may be related to the averaging of spatially highly variable soil properties, such as hydraulic conductivity. According to Addiscott (1995), if one moves from field level to higher spatial scales, soil variation is likely to increase in importance. Moreover, if a model applies nonlinear mathematical functions to simulate soil processes, the model mean may not be equal to the function of the mean input parameters (de Wit & van Keulen, 1987). Also, the assumption of the constant rate of vertical root extension as applied in CGMS may be inaccurate and may add an additional source of uncertainty to the simulations. More research concerning root extension and the influence of droughts on allocation of assimilates to the root system is needed. Another reason for the inaccuracy of the water-limited simulation results may be the spatial interpolation of rainfall. Kuittinen *et al.* (1998) tested the interpolation routine as applied in CGMS under Finnish conditions. These authors found that spatial interpolation of daily rainfall based on rain gauge data is difficult, due to high spatial variability in precipitation and large errors were observed. They proposed the use of the weather radar network in the Nordic countries that provides adequate temporal and spatial coverage of precipitation events and estimates of rainfall amounts. This suggestion should be investigated. The method applied in Chapter 8, to extract soil moisture information from the backscatter signal of ERS satellites, could provide an alternative for the soil moisture calculations. This may be especially useful for semi-arid regions where vegetation is scarce and crop yield is limited by water availability.

9.3 The MARS project

In the period 1994-1998 the methodologies incorporated in CGMS had to be improved. Improvements anticipated were, amongst others, the use of satellite-derived data as input for CGMS, assuming that land use and crop growth and development as well as stress situations can be detected through remote sensing. Other anticipated modifications were improved techniques for interpolation of rainfall data using information from satellites. However, at the time of writing of this thesis, the operational methodology to forecast yield and production volume is still as described in Section 3.7: a panel of analysts assesses the state of the crops using the information sources described in Figure 3.8. Based on these assessments, yield and production volume are predicted. Remote sensing derived information and field survey data are not incorporated in CGMS.

In the framework of the MARS project, research is carried out to include remote sensing information in CGMS. Radar satellite images were examined to test whether it was possible to distinguish various crops and determine the planted area. However, the results were not convincing. The report by Synoptics (1997) concludes that winter cereal crops can be identified "with over 60% certainty". Moreover, it appeared to be difficult to distinguish various types of winter cereals. According to a report by Scot Conseil (1994) it was difficult to differentiate various crop types with only high-resolution optical imagery (SPOT or Landsat TM). However, promising results were obtained through the fusion of radar and optical imagery (Lemoine & Kidd, 1998). Other studies aimed at the estimation of the leaf area index from remote sensing data. This information might be used as a forcing function in CGMS or any other crop growth simulation model as demonstrated by Bouman (1995). Kuittinen *et al.* (1998) demonstrated large errors when in Finland leaf area index was estimated from NOAA imagery. However, promising results were obtained with high-resolution optical imagery.

The main objective of the MARS project was to develop methods for improving agricultural statistics within the EU using remote sensing techniques, to estimate land use and planted area, and a crop growth simulation model for yield and production volume prediction (see Subsection 2.3.1). However, remote sensing did not provide accurate information on either land use or planted area and, although some promising results have been obtained in this study, so far it has not been convincingly demonstrated that applying a crop growth simulation model provides more accurate predictions than simple time-trend models. The final conclusion is that more research is needed to reach the main objective of the MARS project.

10. References

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11. Appendix

Table A1. *Mean soft wheat selling prices in Euro/100kg*

Year	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93
B	11.57	13.22	15.13	16.33	16.55	16.58	16.78	17.87	18.43	19.71	18.18	17.62	17.97	18.28	17.21	16.66	15.52	15.47	15.59	13.64
D	18.40	17.50	19.30	20.10	19.20	20.10	19.10	18.10	18.90	19.40	20.30	19.40	20.60	18.80	20.90	20.60	19.80	18.50	19.00	19.20
DK	11.34	11.78	14.13	14.55	15.54	15.54	16.52	17.65	18.55	20.50	19.51	19.01	18.51	17.78	16.67	16.92	15.69	16.19	16.78	14.55
ESP	11.64	13.41	14.50	13.76	14.37	16.76	16.80	17.88	18.85	17.25	18.77	20.09	20.76	19.59	19.67	19.87	19.76	21.52	20.19	17.95
IRL	9.32	12.00	12.93	14.28	13.92	13.18	13.76	15.36	15.78	18.28	16.45	12.65	14.37	15.41	15.97	15.53	14.87	14.94	14.35	13.70
UK	12.06	10.12	11.65	12.85	13.15	14.99	16.76	20.00	20.43	21.44	19.31	18.95	16.52	15.89	16.20	16.24	15.84	16.63	16.50	14.58
NL	11.87	12.87	15.06	15.88	16.18	16.19	16.29	17.55	19.44	20.51	19.19	18.19	18.69	17.53	16.95	16.47	15.31	15.64	15.76	13.68
ITL	13.26	13.44	15.68	16.61	17.09	17.55	18.85	20.87	21.19	22.26	23.03	21.62	23.22	21.75	21.05	21.36	19.58	21.15	19.69	19.47
F	10.30	11.19	12.92	13.30	13.87	14.16	15.02	16.17	17.03	17.42	16.68	16.30	17.09	16.15	15.09	15.69	14.89	15.29	14.58	13.48
GR	11.57	11.75	13.62	15.20	14.54	15.32	16.10	19.72	20.52	20.07	19.89	18.41	15.81	14.31	16.18	18.07	17.85	17.70	16.95	15.98

Source: EUROSTAT

Table A2. *Mean durum wheat selling prices in Euro/100kg*

Year	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93
E	12.64	15.09	16.90	16.18	16.83	19.69	19.59	20.61	21.76	19.47	20.67	21.37	22.05	21.35	22.19	23.47	22.83	22.07	21.49	20.75
F	24.35	20.61	18.32	20.21	19.55	19.20	22.49	23.12	23.52	26.61	25.27	23.89	25.59	23.35	19.62	23.19	21.92	19.26	18.34	19.62
GR	13.72	15.80	18.20	19.89	19.32	20.50	22.42	26.97	29.60	31.67	32.50	31.56	26.78	24.94	24.25	26.55	25.78	24.12	23.65	21.70
ITL	25.25	20.46	19.65	22.80	22.18	23.03	25.47	33.77	34.84	34.93	39.41	36.93	34.58	34.91	36.68	37.77	32.42	32.95	32.09	37.71

Source: EUROSTAT

Table A3. *Common wheat intervention prices in Euro/100kg*

Year	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94
Soft wheat	11.55	12.59	13.10	12.01	14.70	14.92	15.59	16.52	17.93	18.46	18.27	17.94	17.94	17.37	17.94	17.41	16.86	16.86	16.35	11.55	10.66
Durum wheat	17.58	19.05	20.20	20.30	24.54	24.91	23.29	25.18	29.84	31.21	31.21	31.21	29.96	21.98	22.19	21.58	21.27	22.77	22.09	11.55	10.66

Source: EUROSTAT

12. Acronyms

ARIS	Agriculture and Regional Information System
CAP	Common Agricultural Policy
CERES	Crop Environment Resource Synthesis
DG VI	Directorate General for Agriculture
EAGGF	European Agricultural Guarantee Guideline Fund
ECAM	European Community Agricultural Model
EMU	Elementary Mapping Unit
EPIC	Erosion Productivity Impact Calculator
ERS	European Remote Sensing
EU	European Union
EUROCARE	European Centre for Agricultural, Regional and Environmental Policy Research
EUROSTAT	Statistical Office of the European Communities
FAO	Food and Agricultural Organization
CGMS	Crop Growth Monitoring System
GIS	Geographic Information System
GLP	Gemeenschappelijke Landbouw Politiek
GTS	Global Telecommunication System
JRC	Joint Research Centre
MARS	Monitoring Agriculture with Remote Sensing
MBE	Mean Bias Error
NGDC	National Geophysical Data Center
NOAA	National Oceanic and Atmospheric Administration
NUTS	Nomenclatures des Unités Territoriales Statistiques
RMSE	Root Mean Square Error
RRMSE	Relative Root Mean Square Error
TM	Thematic Mapper
SAI	Space Applications Institute
SAR	Synthetic Aperture Radar
SMU	Soil Mapping Unit
SPEL	Sektorales Produktions- und Einkommensmodell der Landwirtschaft der Europäischen Union
SPOT	Satellite pour l'Observation de la Terre
STU	Soil Typological Unit
WMO	World Meteorological Organisation
WOFOST	World Food Studies

13. Samenvatting

De Europese Unie (EU) tracht door middel van de Gemeenschappelijke Landbouw Politiek (GLP) de Europese landbouwmarkt te sturen met als doel de voedselproductie veilig te stellen en de consument tegen redelijke prijzen van voedsel te voorzien. Het Directoraat Generaal voor de Landbouw (DG VI) van de Europese Commissie draagt zorg voor de implementatie en controle van de GLP maatregelen.

Tot de verantwoordelijkheden van DG VI behoren o.a. het beheer van de gemeenschappelijke markt, het schatten van opbrengsten, het schatten van te betalen subsidies en, op korte en langere termijn, het evalueren van de gevolgen van de GLP regelingen. Hiervoor is informatie over landgebruik, jaarlijkse veranderingen in landgebruik en opbrengsten van de te velde staande gewassen nodig. Deze informatie wordt door nationale overheden verzameld, die deze vervolgens doorgeeft aan de statistische dienst van de Europese Commissie, EUROSTAT. Het verzamelen en verwerken van deze gegevensbestanden is tijdrovend en arbeidsintensief; gewoonlijk duurt het een jaar, soms zelfs twee jaar, voordat deze informatie beschikbaar is in de gegevensbanken van EUROSTAT. Het gevolg is dat deze gedateerde informatie slechts een bescheiden bijdrage levert aan de evaluatie van de GLP regelingen en de schattingen van te betalen subsidies. Om DG VI en EUROSTAT te ondersteunen bij het verzamelen van informatie is het *Monitoring Agriculture with Remote Sensing* (MARS) project in het leven geroepen (1988). Hoofddoel van het MARS project is het ontwikkelen van methoden om genoemde informatie sneller te beschikbaar te krijgen. De GLP en het MARS project worden in **Hoofdstuk 2** beschreven.

De geplande duur van het MARS project was 10 jaar (1989-1999), onderverdeeld in 2 fases van 5 jaar. Tijdens de eerste fase lag de nadruk op het ontwikkelen van twee methodologieën: één om m.b.v. teledetectiemethoden en veldwaarnemingen het geplante areaal te schatten; de tweede om de gemiddelde opbrengst per hectare en vervolgens de productie per land te voorspellen. Dit proefschrift is nauw gerelateerd aan deze tweede methodologie. Gewasopbrengsten worden in deze methodologie voorspeld m.b.v. het WOFOST simulatiemodel, dat gekoppeld is aan een Geografisch Informatie Systeem (GIS) en aan een opbrengstvoorspellingsroutine. Deze drie modules vormen samen het *Crop Growth Monitoring System* (CGMS). Kwalitatieve voorspellingen van gewasopbrengsten worden met behulp van dit CGMS iedere tien dagen gegenereerd, geanalyseerd en iedere maand samengevat in het MARS bulletin. Zowel CGMS als de ontwikkelde operationele methode om gewasopbrengsten te schatten worden in **Hoofdstuk 3** beschreven.

In de tweede fase was het de bedoeling teledetectietechnieken en veldwaarnemingen met CGMS te integreren en het systeem geschikt te maken voor kwantitatieve opbrengstvoorspellingen. Het onderzoek beschreven in dit proefschrift is gestart in de tweede fase van het MARS project en had als doel om methoden te onderzoeken waarmee deze doelstelling bereikt zou kunnen worden.

De vooronderstellingen waarop CGMS gebaseerd is, zijn: (i) een gewasgroeisimulatiemodel kan de jaarlijkse schommelingen in gewasopbrengst per hectare als gevolg van weersinvloeden verklaren, (ii) de jaarlijkse stijging van de opbrengst per hectare, als gevolg van nieuwe variëteiten, nieuwe technieken, etc. kan door een lineaire trendfunctie beschreven worden (Vossen, 1990a; 1992).

De Koning *et al.* (1993) hebben onderzoek gedaan naar de CGMS opbrengstvoorspellingen en concludeerden dat even nauwkeurige, en soms betere resultaten werden bereikt, wanneer alleen de trendfunctie werd toegepast. Simpele trendfuncties zijn makkelijk hanteerbaar voor gewasopbrengstvoorspellingen; een nadeel blijft echter dat zij geen weersinvloeden, of effecten van veranderingen in GLP- regelgeving of kunstmestprijzen kunnen verklaren. Ook het toevoegen van meteorologische variabelen aan deze functies om weersinvloeden te kunnen verklaren, verbeterde de voorspellingsnauwkeurigheid niet aantoonbaar (Palm & Dagnelie, 1993).

In het onderzoek van de Koning *et al.* (1993) en Palm & Dagnelie (1993) werd impliciet aangenomen dat het geplante areaal en de opbrengst per hectare wederzijds onafhankelijk zijn. In **Hoofdstuk 4** wordt het totale tarweproductievolume geanalyseerd, aannemend dat het geplante areaal en de opbrengst per hectare wederzijds afhankelijk zijn en derhalve gelijktijdig geanalyseerd moeten worden.

Omdat trendfuncties geen trendbreuk in de opbrengstcijfers en/of gevolgen van veranderingen in de GLP regelgeving of kunstmestprijs kunnen verklaren, is onderzocht of simulatieresultaten in combinatie met economische factoren schommelingen in het productievolume kunnen beschrijven. De onderzochte economische factoren hebben alle betrekking op tarwe en zijn: (i) de gemiddelde marktprijs per jaar, (ii) de interventieprijs en (iii) de uitgaven aan gewasbeschermingsmiddelen. De resultaten laten zien dat er voor bepaalde landen een verband tussen de onderzochte factoren en de opbrengstschommelingen bestaat. De gevonden relaties zijn echter niet algemeen toepasbaar. Eveneens is de kunstmestgift per hectare onderzocht, er vanuit gaande dat de hoogte van de kunstmestgiften mede bepaald wordt door de opbrengst- en winstverwachtingen van de boer. De resultaten laten zien dat de kunstmestgiften per hectare de jaarlijkse schommelingen in het productievolume kunnen verklaren.

In **Hoofdstuk 5** worden productievolumes van tarwe voorspeld m.b.v. twee typen voorspellingsmodellen. Bij het eerste type maakt het geplante areaal onderdeel uit van het model (één-stap type). Bij het tweede type wordt eerst de opbrengst per hectare geschat en vervolgens wordt het resultaat met het geplante areaal vermenigvuldigd (twee-stap type). Verder worden twee manieren vergeleken om de trend in de opbrengst per hectare en het productievolume te beschrijven. De eerste manier gaat uit van een lineaire tijdtrend en de andere van de gemiddelde kunstmestgift per hectare. Verder worden een hypothetische en een operationele situatie beschouwd. De hypothetische situatie veronderstelt dat het geplante areaal en de gemiddelde kunstmestgift per hectare bekend zijn op het moment dat de definitieve voorspelling gemaakt moet worden (i.e. aan het eind van het groeiseizoen). De operationele situatie gaat er vanuit dat deze waarden niet beschikbaar zijn en dus geschat moeten worden.

In de hypothetische situatie levert het twee-stap model, dat alleen de kunstmestgift als invoer gebruikt, de nauwkeurigste resultaten op. Vergelijking van de operationele en de hypothetische situatie toont echter aan dat, alhoewel modellen van het twee-stap type in de hypothetische situatie over het algemeen nauwkeuriger voorspellen dan de modellen van het één-stap type, het laatst genoemde modeltype in de operationele situatie minder gevoelig is voor onnauwkeurigheden in het geplante areaal en de kunstmestgegevens en dientengevolge in deze situatie nauwkeuriger resultaten oplevert.

De vergelijking van de resultaten verkregen in de operationele situatie m.b.v. de tijdtrendfunctie laat zien dat in 14 van de 16 gewas-land combinaties het één-stap model type nauwkeuriger resultaten oplevert dan het twee-stap type. Wanneer de gemiddelde kunstmestgift voor voorspelling wordt gebruikt, dan levert het één-stap model type in 10 van de 16 gewas-land combinaties nauwkeuriger voorspellingen op. Verder tonen de regressieresultaten aan dat de uitkomsten van het simulatiemodel slechts in 30% van de gevallen significant (5% t-test) waren, wanneer predictiemodellen van het twee-stap type gebruikt werden. Wanneer echter modellen van het één-stap type gebruikt werden, nam het aantal gevallen waarin de simulatieresultaten significant waren toe tot 80%. Alhoewel deze uitkomsten geen bewijs zijn, ondersteunen ze de veronderstelling dat het geplante areaal en de opbrengst per hectare niet onafhankelijk zijn en dat het productievolume met behulp van modellen van het eerste type onderzocht moet worden.

De resultaten van het één-stap type in de operationele situatie tonen ook aan dat in 50% van de geteste gewas-land combinaties, een voorspellingsmodel bestaande uit een trendfunctie en simulatieresultaten, nauwkeuriger voorspellingen oplevert dan modellen die alleen een beschrijvende trendfunctie toepassen.
Alhoewel dit geen sluitend bewijs is dat het gebruik van gewasgroeisimulatiemodellen nauwkeuriger voorspellingen oplevert, suggereren de resultaten wel dat weersinvloeden: (i) een rol spelen bij schommelingen in productievolume en (ii) in de voorspellingen verdisconteerd kunnen worden. Er dient echter vermeld te worden dat de verschillen tussen modellen die gewasgroeisimulatieresultaten toepassen en de modellen die alleen een beschrijvende trendfunctie bevatten, niet altijd groot zijn.

In **Hoofdstuk 6** wordt een alternatieve methode ontwikkeld om globale straling te schatten. Deze methode gebruikt de bewolkingsgraad en het verschil tussen dagelijkse maximum- en minimumtemperatuur als invoergegevens. De resultaten van deze methode zijn minder nauwkeurig dan die met de Ångström-Prescott vergelijking verkregen worden. De verschillen zijn echter niet groot. Deze methode kan als alternatief voor de Ångström-Prescott vergelijking dienen, als geen waarnemingen van zonneschijnduur beschikbaar zijn. Verder wordt in dit hoofdstuk een hiërarchische methode om globale straling in CGMS in te voeren voorgesteld: indien gegevens van globale straling beschikbaar zijn worden deze gebruikt; als alleen gegevens van zonneschijnduur beschikbaar zijn wordt de Ångström-Prescott vergelijking gebruikt; als gemeten straling noch zonneschijnduur beschikbaar zijn wordt de in dit hoofdstuk besproken methode gebruikt.

In **Hoofdstuk 7** worden nationale, regionale en sub-regionale productievolumes van tarwe in Frankrijk met behulp van een additief en een multiplicatief model geschat. Een additief model veronderstelt dat de jaarlijkse schommelingen in het productievolume als gevolg van weersinvloeden in een laag- en in een hoog-productief systeem even groot zijn. Een multiplicatief model neemt aan dat deze schommelingen evenredig zijn aan het opbrengstniveau. De regionale en de sub-regionale voorspellingen zijn opgeteld tot nationale waarden.

De resultaten suggereren dat voorspellingen van het nationale productievolume nauwkeuriger zijn wanneer de voorspellingen op regionaal en sub-regionaal worden uitgevoerd en vervolgens opgeteld worden tot nationale waarden, dan wanneer deze direct geschat worden. Dit zou kunnen samenhangen met de gebruikte aggregatiemethode. CGMS houdt namelijk geen rekening met het werkelijke landgebruik: alleen de bodemgeschiktheid voor een bepaald gewas wordt beschouwd, d.w.z. gewasgroeisimulaties worden uitgevoerd wanneer de bodem geschikt geacht wordt voor een bepaald gewas, ongeacht of dit gewas in werkelijkheid verbouwd wordt of niet. De aldus verkregen simulatieresultaten worden vervolgens naar *Elementary Mapping Units* (EMU), sub-regionale, regionale en nationale waarden geaggregeerd.

Het is dus mogelijk dat lokale weersinvloeden in het geaggregeerde eindresultaat overschaduwd worden door die van het weer in gebieden waar het gewas niet verbouwd wordt. Wanneer men de voorspellingen op sub-regionaal of regionaal niveau uitvoert kunnen lokale weersinvloeden beter in de analyse meegenomen worden. Het zou ook kunnen dat de fouten in de voorspellingen van de verschillende (sub-)regio's elkaar compenseren, wanneer deze waarden naar nationaal niveau opgeteld worden.

De in dit hoofdstuk gepresenteerde resultaten suggereren verder dat: (i) het multiplicatieve model iets nauwkeuriger voorspellingen oplevert dan het additieve model, hetgeen de hypothese versterkt dat de schommelingen in de opbrengsten per hectare over de tijd proportioneel zijn aan de gemiddelde opbrengst (Valdez-Cepeda, 1993), en (ii) de hiërarchische methode om straling in CGMS in te voeren, zoals in Hoofdstuk 6 voorgesteld, iets nauwkeuriger voorspellingen oplevert dan de operationele CGMS versie.
Een waarschuwing met betrekking tot het voorspellen op (sub-)regionaal niveau is op zijn plaats: de meeste EU lidstaten hebben op lagere administratieve niveaus geen betrouwbare landbouwstatistieken en de CGMS methode kan dan beter niet gebruikt worden voor het voorspellen van (sub-)regionale gewasopbrengsten.

In **Hoofdstuk 8** worden de veldwaarnemingen van een MARS sub-project geanalyseerd met als doel meer inzicht te krijgen in de zaaistrategie en in de effecten van variatie in zaai- en bloeidatum op de opbrengst van niet-geïrrigeerde wintergranen in semi-aride gebieden. De achterliggende hypothese is dat in CGMS rekening gehouden zou moeten worden met verschillen in zaaidata om nauwkeuriger voorspellingen te krijgen. In CGMS wordt namelijk per gewas en per regio slechts één zaaidatum en één bloeidatum verondersteld, er vanuit gaande dat variatie in zaaidatum en bloeidatum een geringe invloed heeft op het regionale productievolume.

De in dit hoofdstuk beschreven resultaten ondersteunen deze veronderstelling voor gerst verbouwd in semi-aride gebieden zonder irrigatie: er is geen verband aangetoond tussen (i) zaaidatum en opbrengst per hectare, (ii) de hoeveelheid regenval en de werkelijke zaaidatum en (iii) bloeidatum en opbrengst per hectare. Boeren zouden mogelijkerwijs hun beslissing om te zaaien kunnen laten afhangen van de verwachte aanvang van het regenseizoen, met als achterliggende gedachte dat bij voldoende regenval uitstel van zaaien lagere opbrengsten oplevert. Wanneer echter het beschikbare water tijdens het groeiseizoen de limiterende factor is, zijn effecten van variatie in zaaidatum niet aantoonbaar, en maakt het niet uit of men vroeg of laat in het seizoen zaait. De noodzaak om de keuze van gerstvariëteiten af te stemmen op de te verwachten seizoensneerslag zou de effecten van de variatie in zaaidata ook kunnen beperken.

In **Hoofdstuk 9** worden naast een samenvatting, tevens de conclusies en aanbevelingen tot verder onderzoek gepresenteerd. Verschillende manieren om CGMS geschikt te maken voor kwantitatieve opbrengstvoorspellingen zijn onderzocht. Hoewel er enkele interessante resultaten verkregen zijn waarop verder geborduurd kan worden, kunnen er slechts twee concrete aanbevelingen gegeven worden: (i) het is mogelijk het nationale productievolume nauwkeuriger te voorspellen door de predicties uitgevoerd op (sub-) regionaal niveau op te tellen tot nationaal waarden, (ii) het geplante areaal zou onderdeel moeten uitmaken van de analyse en het voorspellen van het productievolume.
Om goede schattingen te kunnen maken van de nauwkeurigheid van de voorspellingen is het noodzakelijk accurate methoden te ontwikkelen om productievolume- en landgebruikstatistieken te verzamelen, op nationaal en liefst ook op regionaal en sub-regionaal niveau. Deze methoden behoren consistent in alle EU lidstaten te worden toegepast en de nauwkeurigheid moet getest worden. In dit proefschrift zijn enkele voorspellingsmodellen onderzocht en de resultaten zijn vergeleken met officiële EUROSTAT productievolumestatistieken, aannemend dat deze correct zijn. Brady (1994) concludeert echter dat deze hypothese niet klopt: (i) de nauwkeurigheid van deze statistieken is voor meeste EU landen niet bekend, (ii) de methode om deze informatie te verzamelen is per land verschillend en (iii) men maakt veelvuldig gebruik van subjectieve schattingen. Zinvolle vergelijking van voorspellingsmethoden kan alleen plaatsvinden wanneer de nauwkeurigheid van officiële opbrengst- en productiestatistieken bekend is. Wanneer dit, zoals op dit moment, niet het geval is, en wanneer geen additionele veldwaarnemingen beschikbaar zijn, kan niet onderzocht worden of en in welke mate de CGMS voorspellingen beter of slechter zijn dan de officiële statistieken en of de ene voorspellingsmethode nauwkeuriger is dan de andere. Voor een echt statistisch bewijs zijn onafhankelijke gegevens nodig, d.w.z. data die niet gebruikt zijn voor het ontwikkelen, onderzoeken en testen van diverse modellen. Desalniettemin kan men statistiek gebruiken om aanwijzingen te vinden voor de kwaliteit van

voorspellingsmethoden of om inzicht te verkrijgen in factoren die het functioneren van een voorspellingsmethode negatief beïnvloeden.

Verder onderzoek zou zich ook moeten richten op het verklaren van de trend in opbrengst per hectare en in productievolume. Agro-economische modellen zouden hierbij nuttig kunnen zijn. Zij zouden veranderingen in het kunstmest- en bestrijdingsmiddelengebruik en het geplante areaal, op nationale, regionale en/of sub-regionale schaal, samenhangend met veranderingen in de GLP regelingen en veranderende markt- en kunstmestprijzen, etc. moeten kunnen voorspellen en daarmee gepaard gaande schommelingen in productievolume kunnen verklaren.

14. Publications

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Supit, I., Wagner, W., 1999. Analysis of yield, sowing and flowering dates of barley of field survey results in Spain. Agricultural Systems, 59:102-122.

15. Curriculum Vitae

Iwan Supit werd op 25 februari 1959 in Eindhoven geboren. In 1970 legde hij in Nieuw Nickerie, Suriname, het toelatingsexamen voor de HBS af. In 1976 behaalde hij het VWO diploma aan het van der Putt College te Eindhoven. Vervolgens ging hij aan de Landbouwuniversiteit te Wageningen studeren. In 1982 legde hij met goed gevolg het examen Nederlandse taal, cultuur en inburgering af. In 1984 behaalde hij het ingenieursdiploma Tropische Cultuurtechiek, met als hoofdvakken Meteorologie en Hydrogeologie. In 1986 vertrok hij als assistent deskundige voor de *World Meteorological Organisation* (WMO) naar Niger, waar hij twee jaar verbleef. Vervolgens werd hij door dezelfde organisatie in 1988 naar Ecuador uitgezonden, waar hij drie jaar verbleef. In 1991 vertrok hij voor een periode van 2,5 jaar naar Bangladesh waar hij als bestuurslid van de "Banani School of Hope", een school voor kinderen uit de slums, actief was. Gedurende deze periode verrichtte hij ook consultancies voor de *Food and Agricultural Organization* (FAO), WMO en het *Joint Research Centre* (JRC) van de Europese Unie (EU), Ispra, Italië. In 1994 kreeg hij een driejarige EU onderzoeksbeurs bij het JRC. De resultaten van het daar verrichte onderzoek zijn in dit proefschrift vastgelegd. Na deze beurs was hij tot februari 1999 als *auxiliary agent* bij het JRC werkzaam. Tegenwoordig is hij mede-eigenaar van PRIVATEERS N.V.

Table II *Regression coefficients belonging to Table 5.3 averaged over the number of significant regressions.*

	Country	Model I			Model II			Model III			Model IV		
		Complete		Trend Only	Complete		Trend Only	Complete		Trend only	Complete		Trend only
		b_t	B_c	b_t	b_t	b_c	b_t	b_t	b_c	b_t	b_t	b_c	b_t
Soft wheat	B	41.67	-	41.67	5.41	0.26	5.41	0.21	-	0.21	0.02	0.29	0.02
	D	337.67	0.41	474.75	55.90	0.31	82.27	0.18	-	0.18	0.03	-	0.03
	DK	0.06	0.56	0.08	10.34	0.29	24.09	0.45	0.66	0.21	0.02	0.12	0.02
	F	633.72	0.46	1125.97	92.43	0.28	114.00	0.17	0.48	0.16	0.02	0.22	0.02
	E	283.90	0.19	-200.56	50.80	0.11	38.24	0.14	0.33	0.11	0.02	0.12	0.02
	GR	118.10	0.18	-109.94	9.45	0.13	-	-	0.12	-	0.03	0.10	0.03
	I	156.42	0.13	-139.09	26.66	0.16	-	0.08	-	0.08	0.02	-	0.02
	IRL	16.71	0.76	29.22	1.11	0.75	2.12	0.26	0.95	0.30	0.02	0.91	0.02
	L	1.62	0.31	1.72	0.17	0.18	0.19	0.21	0.32	0.22	0.02	0.25	0.02
	NL	35.97	0.59	42.00	2.91	0.60	3.92	0.21	-	0.22	0.02	-	0.02
	P	31.66	0.11	22.82	6.26	0.10	4.61	0.08	-	0.08	0.02	-	0.02
	UK	433.48	0.85	768.65	53.78	0.78	60.37	0.25	0.74	0.14	0.02	0.67	0.02
Durum wheat	F	16.77	0.29	131.33	3.39	0.20	15.74	0.13	0.47	0.14	0.02	0.19	0.02
	E	21.89	0.30	62.46	4.27	0.10	3.75	0.18	0.37	-0.04	0.02	0.11	0.02
	I	107.08	0.19	168.99	47.45	0.12	60.96	0.09	0.18	0.05	0.03	0.12	0.03
	GR	59.55	0.17	95.90	7.59	0.13	14.53	-	0.18	-	0.02	0.15	0.02
	Eur12	246.86	0.38	113.08	26.25	0.26	34.05	0.16	0.27	0.15	0.02	0.26	0.02

(-) not significant (5% t-test)

ANNEX

Table I *Regression constants of the regression according to the equations (4.1), (4.2) and (4.3) respectively. As wheat price the intervention price and the selling price are considered. Period 1975-1991.*

		equation (4.1)				*equation (4.2)*		*equation (4.3)*	
		Intervention Prices		Selling Prices					
	Country	b_z	b_2	b_z	b_2	b_E	b_2	b_F	b_2
soft wheat	B	49.30	0.3027	43.00	0.3969	7.88	0.143	4.436	0.0854
	D	354.80	0.4066	223.00	0.4712	41.70	0.361	47.1	0.2763
	DK	1.40	0.7735	4.60	0.7712	1.32	0.761	10.09	0.2548
	E[1]	-	-	145.20	0.1398	-	-	50.92	0.1008
	F	756.00	0.3970	114.00	0.5390	106.90	0.356	79.38	0.2676
	GR	67.70	0.1564	53.40	0.1447	-13.55	0.165	11.83	0.1257
	I	148.00	0.1288	108.80	0.1280	74513.00	0.068	24.53	0.1551
	IRL	21.71	0.7750	22.70	0.8210	8.80	0.632	0.926	0.6498
	NL	41.82	0.5170	37.10	0.5020	5.85	0.663	2.199	0.5701
	UK	221.00	0.8290	61.90	0.9178	-10.10	1.025	24.8	0.628
durum wheat	E[1]	-	-	10.74	0.1559	20.90	0.152	3.422	0.11541
	F	10.47	0.2657	-4.60	0.2633	5.23	0.212	3.169	0.2094
	GR	10.43	0.1736	8.04	0.1676	-5.50	0.150	12.23	0.13128
	I	33.20	0.1581	31.80	0.1532	51678.00	0.152	13.49	0.1345

([1]) Spain joined the E.U. in 1986. The system of price intervention was not applicable before this year.
(-) not significant (5% t-test)

Table III *Areas planted to wheat (x 1000 ha) and wheat yields (ton.ha^{-1}) for various EU member states (source EUROSTAT).*

	Year	B	D	DK	E	F	GR	I	IRL	L	NL	P	UK	E	F	GR	I
Area	75	183.4	1569.2	101.8	2555.0	3592.8	743.4	1992.5	44.6	8.6	106.9	447.2	1034.6	106.2	283.1	182.4	1552.0
	76	204.7	1631.6	126.5	2675.6	4066.6	730.9	1872.8	50.4	8.8	130.5	512.5	1231.0	96.5	207.7	199.8	1671.3
	77	185.5	1598.8	116.0	2622.2	4008.2	734.2	1524.6	48.4	8.3	126.4	251.4	1076.0	92.7	100.4	204.8	1271.8
	78	187.4	1619.3	121.9	2663.4	4072.3	773.8	1799.8	50.3	8.1	120.7	341.5	1257.0	88.6	94.3	220.4	1672.2
	79	190.7	1627.5	114.3	2461.7	3987.0	786.1	1790.8	50.3	8.1	140.7	271.3	1370.8	89.4	100.0	204.4	1661.5
	80	187.5	1668.2	139.3	2601.6	4473.9	770.0	1695.1	53.0	8.9	142.2	336.9	1440.9	97.1	116.1	241.9	1713.0
	81	173.0	1631.5	150.2	2531.7	4618.1	792.5	1574.5	49.3	7.0	131.6	326.3	1491.1	103.7	124.2	272.1	1684.7
	82	176.8	1577.7	180.9	2535.8	4727.8	749.1	1625.3	57.1	6.2	130.9	338.2	1662.8	126.3	115.1	306.7	1701.4
	83	197.0	1655.2	241.8	2431.2	4713.3	682.1	1576.1	59.5	6.2	148.2	317.4	1695.1	172.4	111.9	301.7	1756.9
	84	186.0	1634.2	332.3	2154.4	4975.7	553.1	1475.6	77.2	8.3	143.5	270.3	1939.0	151.3	130.9	314.2	1798.3
	85	188.1	1623.7	340.0	1910.7	4632.4	469.0	1295.2	77.7	6.4	128.1	261.7	1902.0	132.7	165.0	425.8	1741.1
	86	189.5	1648.1	354.0	1995.9	4594.9	426.0	1270.8	74.6	7.0	117.6	293.4	1997.4	118.3	264.1	487.0	1861.4
	87	194.0	1671.4	399.0	2115.8	4597.0	400.0	1191.8	56.1	7.5	110.8	298.3	1993.9	105.5	311.5	488.1	1895.1
	88	214.5	1743.4	309.0	2229.4	4433.2	384.0	1093.0	58.6	7.6	114.5	256.5	1885.7	109.4	287.9	507.5	1782.0
	89	210.9	1776.9	446.0	2186.7	4701.8	381.0	1143.5	60.7	8.4	137.8	289.5	2082.6	131.3	311.1	535.9	1800.1
	90	213.1	1670.9	535.0	1816.7	4751.6	327.0	1061.1	70.1	8.6	140.6	186.7	2013.1	189.9	395.4	675.5	1701.9
	91	207.0	2453.3	520.9	1764.4	4653.3	293.0	1002.6	85.7	8.0	123.2	274.0	1980.6	459.1	491.6	713.9	1680.4
	92	208.6	2598.5	582.5	1612.8	4658.3	332.3	987.8	90.6	8.2	126.9	254.0	2066.2	630.3	423.7	615.9	1529.7
	93	203.6	2394.6	619.4	1379.0	4291.7	328.9	889.1	79.2	8.4	118.0	238.0	1759.0	651.5	222.4	583.1	1410.1
	94	202.9	2434.9	573.6	1378.0	4345.2	277.4	844.9	74.1	9.0	121.5	214.0	1811.0	610.1	234.9	594.0	1544.0
	95	210.4	2587.3	614.0	1459.3	4514.0	252.3	853.4	71.2	9.4	134.7	226.0	1855.2	633.8	230.0	572.7	1601.0
Yield	75	3.8	4.5	5.1	1.6	4.0	2.4	3.1	4.4	2.5	4.9	1.3	4.3	1.3	2.9	1.9	2.2
	76	4.5	4.1	4.7	1.6	3.8	2.7	3.3	4.0	1.8	5.4	1.3	3.9	1.3	2.6	2.1	1.8
	77	4.2	4.5	5.2	1.5	4.3	2.0	2.8	5.1	3.0	5.2	0.9	4.9	1.6	2.6	1.4	1.6
	78	5.3	5.0	5.3	1.7	5.1	2.8	3.2	5.0	3.6	6.6	0.7	5.3	2.0	3.3	2.3	2.1
	79	5.2	5.0	5.2	1.6	4.8	2.6	3.1	5.0	3.6	5.9	0.9	5.2	1.8	3.4	1.9	2.0
	80	4.7	4.9	4.7	2.2	5.2	3.0	3.2	5.2	3.2	6.2	1.2	5.9	2.5	3.7	2.8	2.1
	81	5.2	5.1	5.6	1.3	4.8	2.8	3.4	5.8	3.4	6.7	0.9	5.8	1.1	3.3	2.8	2.0
	82	5.9	5.5	6.7	1.6	5.3	3.0	3.7	7.0	4.2	7.4	1.2	6.2	2.2	3.2	2.6	1.7
	83	5.3	5.4	6.4	1.6	5.2	2.2	3.6	6.5	3.5	7.0	1.0	6.4	1.5	3.6	1.9	1.7
	84	7.0	6.3	7.4	2.6	6.5	2.6	3.7	7.7	5.3	7.9	1.6	7.7	3.3	4.4	2.7	2.6
	85	6.3	6.1	5.8	2.6	6.1	2.2	3.6	6.4	5.0	6.6	1.4	6.3	2.8	4.4	1.9	2.2
	86	6.8	6.3	6.2	2.1	5.5	2.6	3.7	5.5	4.9	8.0	1.6	7.0	2.4	3.9	2.7	2.4
	87	5.6	5.9	5.7	2.6	5.6	2.6	4.1	6.9	5.0	6.9	1.7	6.0	2.8	4.5	2.7	2.4
	88	6.0	6.8	6.7	2.8	6.3	2.7	3.7	7.8	4.8	7.2	1.4	6.2	3.1	4.0	2.8	2.2
	89	6.8	6.2	7.2	2.3	6.5	2.9	3.8	7.6	4.6	7.6	1.9	6.7	2.8	4.5	3.1	1.7
	90	6.1	6.6	7.4	2.3	6.6	2.2	4.2	8.5	5.0	7.7	1.4	7.0	2.8	5.0	1.8	2.2
	91	6.8	6.8	7.0	2.4	6.8	3.2	4.3	7.9	5.6	7.7	2.1	7.3	2.8	5.2	3.1	3.1
	92	7.8	6.0	6.2	1.9	6.6	2.7	4.7	7.9	5.7	8.0	1.3	6.8	2.0	4.5	2.3	2.8
	93	7.2	6.6	7.0	3.0	6.6	2.6	4.6	6.8	5.8	8.8	1.7	7.3	1.2	4.0	1.9	2.9
	94	7.0	6.8	6.5	2.4	6.6	3.0	4.6	7.7	5.0	8.1	2.0	7.4	1.6	4.4	2.7	2.7
	95	7.0	6.9	7.5	1.8	6.6	2.9	4.7	8.3	5.7	8.7	1.4	7.7	0.6	4.5	2.4	2.5

Table IV *Simulation results (ton.ha^{-1}) obtained with the proposed radiation routine and the Operational Radiation routine.*

	Proposed Radiation Routine[I]				Operational Radiation Routine[II]			
Year	**PB**	**PY**	**WLB**	**WLY**	**PB**	**PY**	**WLB**	**WLY**
75	20.1	8.9	20.1	7.9	19.0	9.1	20.5	7.4
76	18.8	6.3	18.8	2.1	13.6	6.4	19.0	1.5
77	20.7	8.5	20.7	8.2	20.4	8.7	21.3	8.2
78	21.3	9.3	21.3	8.9	20.9	9.5	21.8	8.9
79	21.0	8.9	21.0	7.9	19.9	9.0	21.4	7.5
80	21.8	8.7	21.8	8.3	21.2	9.0	22.4	8.1
81	19.9	8.9	19.9	8.7	19.7	9.1	20.4	8.7
82	20.3	8.1	20.3	6.2	18.0	8.2	20.6	5.4
83	20.3	8.0	20.3	7.4	19.7	8.1	20.8	7.3
84	21.2	9.0	21.2	7.8	20.0	9.1	21.6	7.4
85	21.4	9.0	21.4	8.2	20.6	9.1	21.8	8.0
86	20.1	7.6	20.1	5.3	17.6	7.7	20.5	4.8
87	21.2	7.5	21.2	6.9	20.3	7.6	21.6	6.9
88	20.6	9.5	20.6	9.1	20.2	9.6	20.9	9.2
89	21.6	9.1	21.6	6.7	19.1	9.2	21.8	6.6
90	21.5	9.7	21.5	8.6	20.4	9.8	21.7	8.5
91	21.3	7.9	21.3	7.0	20.1	8.0	21.5	7.0
92	21.1	8.6	21.1	7.9	20.3	8.2	20.3	7.6
93	19.2	8.5	19.2	8.2	18.9	8.5	19.1	8.1
94	20.8	9.0	20.8	8.3	20.1	9.0	20.9	8.4
95	20.6	8.7	20.6	7.8	19.6	8.8	21.0	7.7

PB = potential biomass , **PY** = potential yield, **WLB** = water-limited biomass, **WLY** = water-limited yield

I) Global radiation is estimated using the Ångström-Prescott method. If no sunshine duration is available the cloud cover/ temperature range method, equation (6.3), is used. Constants of the radiation estimation methods are interpolated from nearby stations for which these constants are known.

II) Global radiation is estimated using the Ångström-Prescott method; constants of this equation are calculated as a function of latitude (Choisnel *et al.*, 1992). Missing data are replaced by long time daily average.