2ND INTERNATIONAL POTATO MODELLING CONFERENCE, WAGENINGEN, MAY 1994
PAPER FOR SESSION VII: APPLICATION OF MODELS IN CROP PRODUCTION

Use of a Crop Growth Model Coupled to an Epidemic Model to Forecast Yield and Virus Infection in Seed Potatoes

Thomas Nemecek[1], Jacques O. Derron[1], Andreas Fischlin[2] and Olivier Roth[3]
[1] Federal Agricultural Research Station of Changins, 1260 Nyon, Switzerland
[2] Systems Ecology, Institute of Terrestrial Ecology, Swiss Federal Institute of Technology, Grabenstr. 3, 8952 Schlieren, Switzerland
[3] Widenstr. 3, 8302 Kloten, Switzerland

Abstract

Pathosystems of vector-borne plant viruses consist of the elements viruses, vectors and plants, influenced by man and the natural environment. Most virus epidemic models emphasize the importance of vectors and viruses, but do not consider the role of the plants.

The model "EPOVIR" is the first virus epidemic model coupled to a crop growth submodel, which for his part is coupled to a soil water balance submodel. The two submodels are used in three ways: tuber yield and tuber size are calculated, the physiological age of the leaves and the drought stress are used to calculate the susceptibility to virus infections ("age resistance") and finally, the fraction of soil covered by the canopy is needed to calculate landing rates of the vectors in the potato field. Since the rate of virus spread is a function of plant physiology and phenology as simulated by the crop submodel, the epidemic should react appropriately to changes in plant growth, caused by man or the environment. As an example we show how planting density influences virus infection.

The model EPOVIR is integrated in the decision support system "TUBERPRO", which forecasts tuber yields graded by size and the infection of the tubers by PVY and PLRV. It supports optimization of haulm killing dates in the seed potato production. The system calculates expected seed yield and the probability that virus infection remains below the tolerance limit used in seed certification. The combination of the two factors gives the expected certified seed yield, which can subsequently be optimized.

INTRODUCTION

Pathosystems of vector-borne plant viruses consist of the elements virus, vectors and plants, all influenced by man and the natural environment (ROBINSON, 1976). Most forecasting systems and virus epidemic models focus on vectors and viruses and their relationship (e.g. MARCUS & RACCAH, 1986; KISIMOTO & YAMADA, 1986; MIYAI *et al.*, 1986; MADDEN *et al.*, 1990; KENDALL *et al.*, 1992). The influence of the plants on virus infection and translocation respectively on the vector populations is not included, or at best, described by a few constant parameters or functions (e.g. SIGVALD, 1986; RUESINK & IRWIN, 1986; VAN DER WERF *et al.*, 1989). However, to appropriately describe the effects of plant physiology and phenology on the epidemic process and the influence of the environment on these relationships, a crop growth submodel is necessary. Crop models are used in plant pathology to predict effects of crop growth on fungal epidemics (ROUSE, 1988), but to our knowledge, such models have never been combined with virus epidemic models.

We present a project, where a potato crop submodel has been coupled to a virus epidemic model to predict yield and virus infection in seed potatoes. The crop submodel for his part is coupled to a soil water balance submodel, which accounts for suboptimal water supply conditions. These two submodels influence the epidemic model, but are independent of the latter. The reason is that we are mainly interested in seed potato production, where the yield loss due to viruses is very small. We develop a decision support system for seed potatoes, allowing to forecast virus infection of tubers, respectively the risk that virus infection exceeds the tolerance limits for a certain quality class and to forecast tuber yields graded by size. The system, called "TUBERPRO" (= *Solanum* ***tuber****osum* **pro**gnosis), allows to optimize haulm destruction dates in seed potato production and is now in the test stage (NEMECEK *et al.*, 1994).

The aim of this paper is to show, why and how the crop submodel is used in the virus epidemic model and within "TUBERPRO".

MODEL OUTLINE

The model "EPOVIR" (= epidemiology of **po**tato **vir**uses) forms the core of TUBERPRO. EPOVIR simulates crop growth and virus epidemic from crop emergence to haulm killing in a single field. A detailed description of a first version is given by NEMECEK (1993). It consists of four submodels (Fig. 1):

- An *inoculation submodel*, which calculates vector intensity (after IRWIN & RUESINK, 1986) from vector abundance in the field, vector propensity and vector behaviour. Vector abundance is estimated from suction trap catches. Wingless aphid vectors are considered for PLRV transmission only. The submodel represents the role of the vectors and their relationships to the viruses and the crop.
- An *infection submodel*, which determines the infection of plants and tubers by PVY respectively PLRV, further the fraction of plants serving as infection sources by accounting for the latent period and the age resistance of the plants to virus infections. The submodel represents mainly the role of the viruses and their relationships to the crop.
- A *crop growth submodel*, which calculates the dry mass of leaves, stems, roots, tubers and assimilates, and the physiological state of the canopy.
- A *soil water balance submodel*, which calculates the water content of the soil and the water stress of the potato plants as the ratio of actual and potential transpiration.

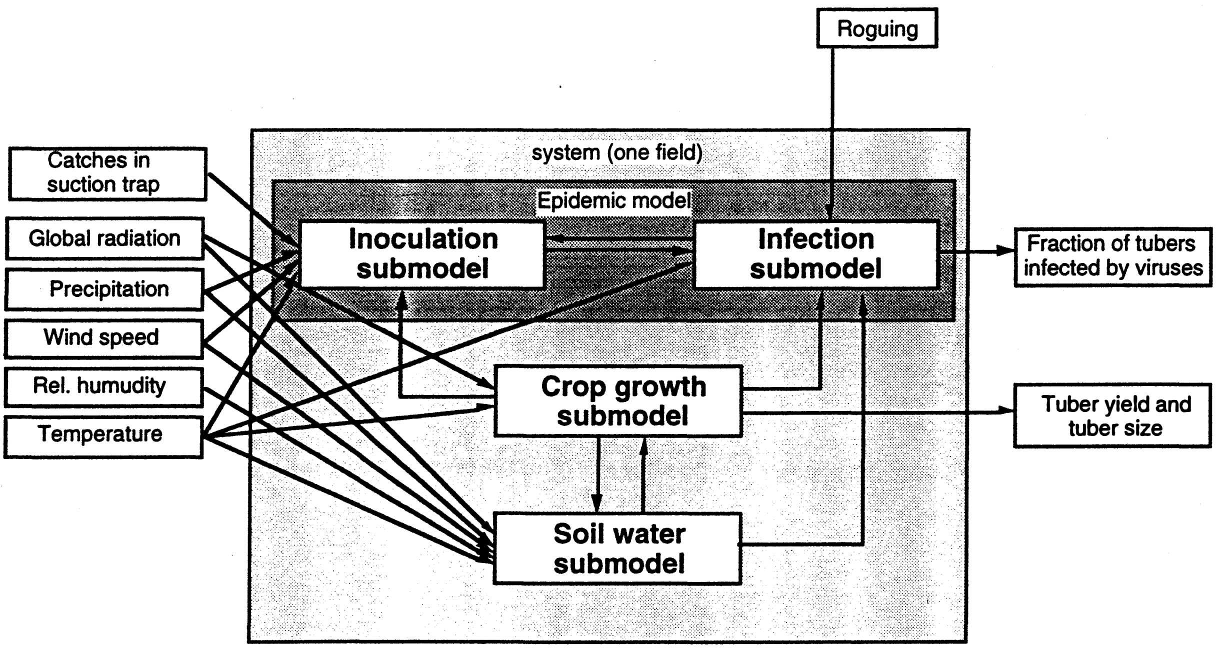

Fig. 1: Structure of the model EPOVIR (= epidemiology of **po**tato **vir**uses).

The crop model has been developed by JOHNSON *et al.* (1986 & 1987). The original model used measurements of soil moisture, which were not available in our experiments. Hence we replaced these measurements by a soil water balance submodel, based on work of VAN KEULEN & WOLF (1986). A complete description as well as validation results of the coupled crop growth-soil water balance submodels for cv. Maris Piper is given by ROTH *et al.* (in press). The crop submodel was adapted to varieties cultivated in Switzerland and extended by a tuber size submodel. These changes and the corresponding validation results are given by NEMECEK & DERRON (1994). The crop model was capable of reproducing experimental data collected under wet and dry conditions with sufficient reliability.

EPOVIR is implemented in the programming language Modula-2 (WIRTH, 1985) by using the simulation environment ModelWorks (FISCHLIN *et al.*, 1990) on Apple™ Macintosh™ computers.

USE OF THE CROP GROWTH SUBMODEL

According the above definition of a plant-vector-virus pathosystem, the submodels for crop growth and soil water balance are used in three ways in the model EPOVIR: to calculate yield, to describe the influence of plant physiology on virus multiplication and translocation in plants and to describe the effect of plant phenology on vector behaviour.

Plants

Forecasting tuber yield and tuber size are of course highly important in the decision support system. The crop submodel calculates total tuber yield and the fraction being between arbitrarily chosen size limits. Fig. 4 gives an example of such a forecast.

Plant-Virus Interaction

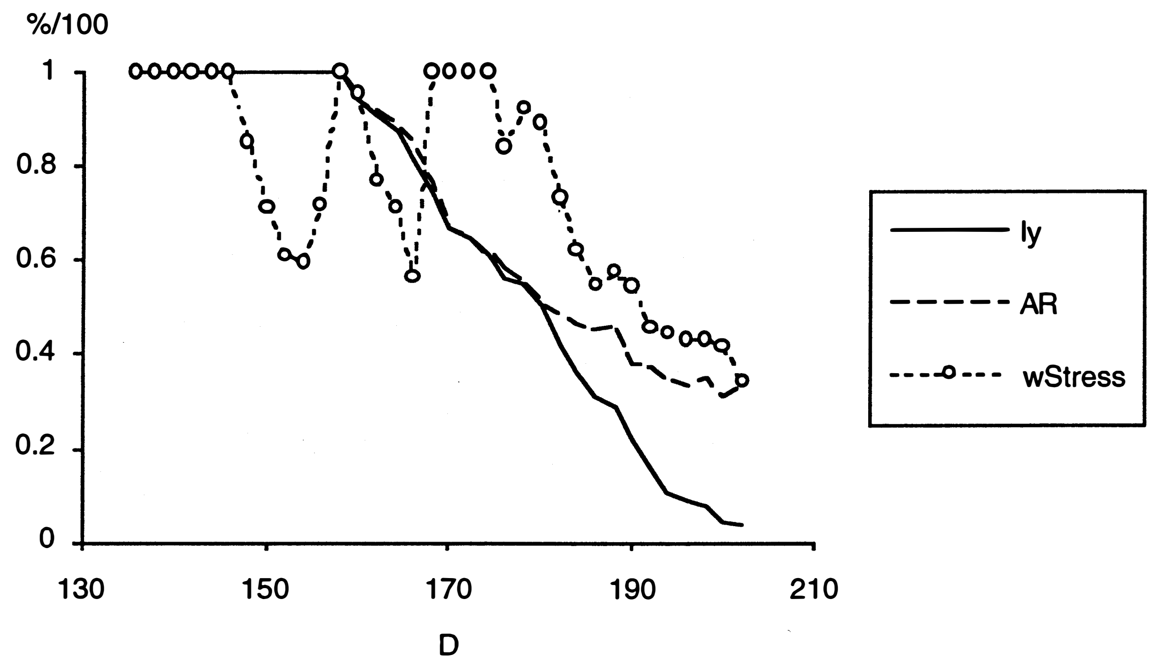

Fig. 2: Age dependent susceptibility to virus infections *AR*, which is a function of the fraction l_y of leaf mass younger than a physiological age threshold and the water stress factor *wStress*. D = julian day.

Potato tubers are less readily infected by viruses as plants grow older (BEEMSTER, 1987). This phenomenon is called "age resistance" or "mature-plant resistance". Its causes are unknown, but it seems to be related to the physiological activity of the leaves (VENEKAMP *et al.*, 1980). The submodel keeps track of the leaf mass produced per day as well as its physiological age (JOHNSON *et al.*, 1987; ROTH *et al.*, in press). We use the fraction l_y of leaf mass younger than a physiological age threshold as an estimate of the age dependent susceptibility to virus infections *AR*. The susceptibility to virus infections depends also on drought: WISLOCKA (1982) demonstrated that drought (suboptimal water supply) can favour tuber infection, apparently by partially breaking the age resistance. The effect of water stress *wStress* (1 = optimal growing conditions, 0 = no growth, see ROTH *et al.*, in press) is also included in the equation for *AR*:

$$AR = \begin{cases} 1-(1-l_y)(1-0.5(1-wStress)) & \text{if drought} \\ l_y & \text{otherwise} \end{cases}$$

The constant 0.5 is a weighting factor that describes the effect of drought on the susceptibility. Fig. 2 shows a typical evolution of *AR*. In young plants, *AR* equals 1, irrespective of drought. As the plants grow older, l_y decreases gradually to 0 and consequently *AR* decreases also. Drought can increase the susceptibility at this stage, i.e. the plants become more susceptible to virus infection compared with a situation, where water supply is optimal. Without drought, AR would be equal to l_y.

Plant-Vector Interaction

The plants influence not only virus infection, multiplication and translocation, but also the development and behaviour of aphid populations, and therefore indirectly virus spread (IRWIN & KAMPMEIER, 1989; NEMECEK, 1993). The host suitability influences strongly vector behaviour and virus spread. NEMECEK (1993) has shown that noncolonizing vector species show more frequently epidemiologically relevant behaviour sequences and are therefore about twice as efficient as vectors, when considering only their behaviour.

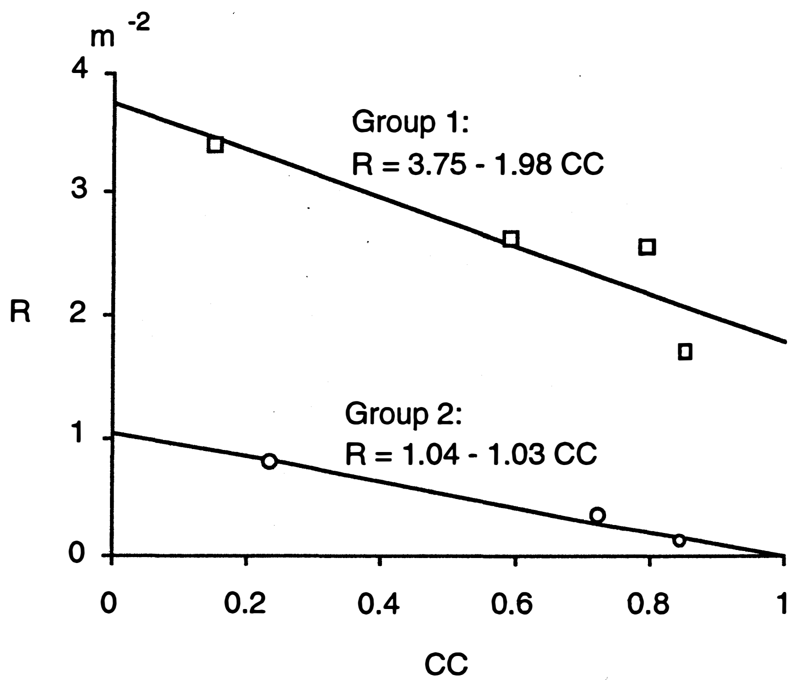

Fig. 3: Relative landing rate of virus vectors: *R* = ratio between landing rate [# m^{-2} d^{-1}] in a potato field and catches in a Taylor suction trap [#/d] in function of the canopy cover *CC* (= fraction of soil area covered by the canopy, [%/100]). Following species are contained in group 1: *Aphis spp.*, *Myzus persicae* SULZ. and *Macrosiphum euphorbiae* THOMAS; group 2: *Acyrthosiphon pisum* HARRIS, *Brachycaudus helichrysi* KALT., *Phorodon humuli* SCHRK. and *Rhopalosiphum padi* L.

Plant phenology influences the behaviour of vector populations. The relative landing rate *R* (number of aphids landing per m^2 for each aphid captured in the suction trap, TAYLOR & PALMER, 1972) decreases with increasing canopy cover (Fig. 3). The landing rate was calby NEMECEK & DERRON (1994). The crop model was capable of reproducing experimental data collected under wet and dry conditions with sufficient reliability.

EPOVIR is implemented in the programming language Modula-2 (WIRTH, 1985) by using the simulation environment ModelWorks (FISCHLIN *et al.*, 1990) on Apple™ Macintosh™ computers.

USE OF THE CROP GROWTH SUBMODEL

According the above definition of a plant-vector-virus pathosystem, the submodels for crop growth and soil water balance are used in three ways in the model EPOVIR: to calculate yield, to describe the influence of plant physiology on virus multiplication and translocation in plants and to describe the effect of plant phenology on vector behaviour.

Plants

Forecasting tuber yield and tuber size are of course highly important in the decision support system. The crop submodel calculates total tuber yield and the fraction being between arbitrarily chosen size limits. Fig. 4 gives an example of such a forecast.

Plant-Virus Interaction

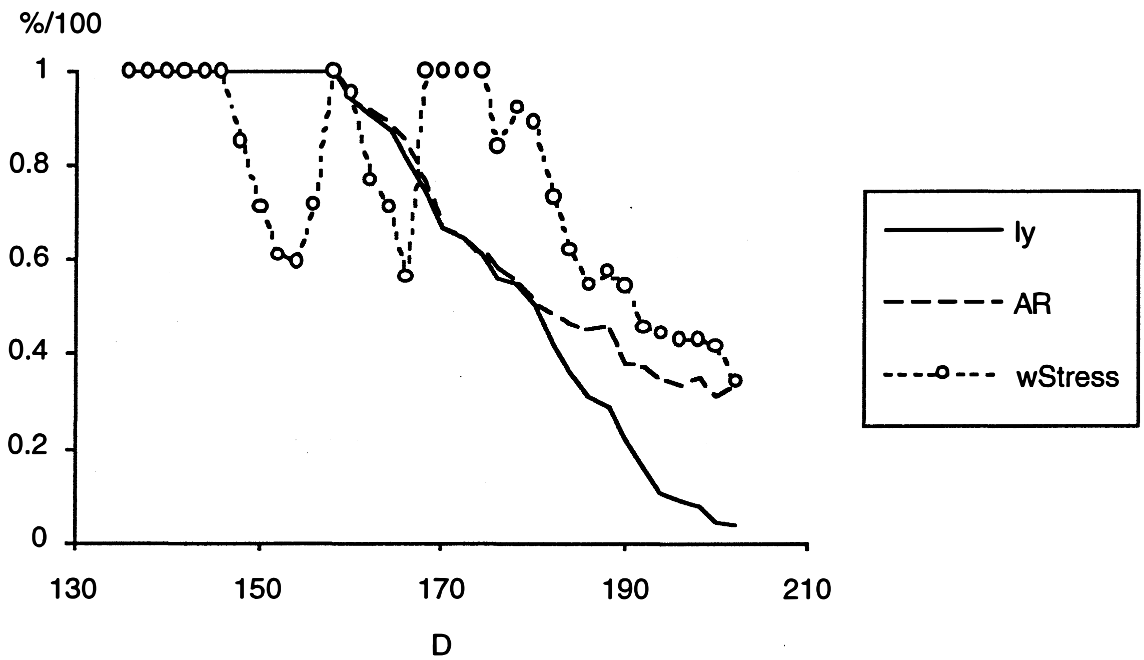

Fig. 2: Age dependent susceptibility to virus infections *AR*, which is a function of the fraction l_y of leaf mass younger than a physiological age threshold and the water stress factor *wStress*. D = julian day.

Potato tubers are less readily infected by viruses as plants grow older (BEEMSTER, 1987). This phenomenon is called "age resistance" or "mature-plant resistance". Its causes are unknown, but it seems to be related to the physiological activity of the leaves (VENEKAMP *et al.*, 1980). The submodel keeps track of the leaf mass produced per day as well as its physiological age (JOHNSON *et al.*, 1987; ROTH *et al.*, in press). We use the fraction l_y of leaf mass younger than a physiological age threshold as an estimate of the age dependent susceptibility to virus infections *AR*. The susceptibility to virus infections depends also on drought: WISLOCKA (1982) demonstrated that drought (suboptimal water supply) can favour tuber inculated indirectly from catches in a fisherline trap (DERRON & GOY, 1993) and their relationship to the landing rate on potato plants (DERRON *et al.*, 1989). The canopy cover is simulated by the crop submodel. Regressions between the average *R* and canopy cover were calculated for 3, 4, 5 and 10 groups with approximately the same number of data points. The regression with the highest r^2, i.e. the best linear relationship, was retained for the model (Fig. 3). Two groups of vectors can be distinguished, which differ on average by a factor 8.6 in their relative landing rates. Since the canopy cover is a variable calculated by the model, it was easy to include this relationship in the model. The landing rate and consequently virus transmissions will vary with canopy development.

MODEL APPLICATION

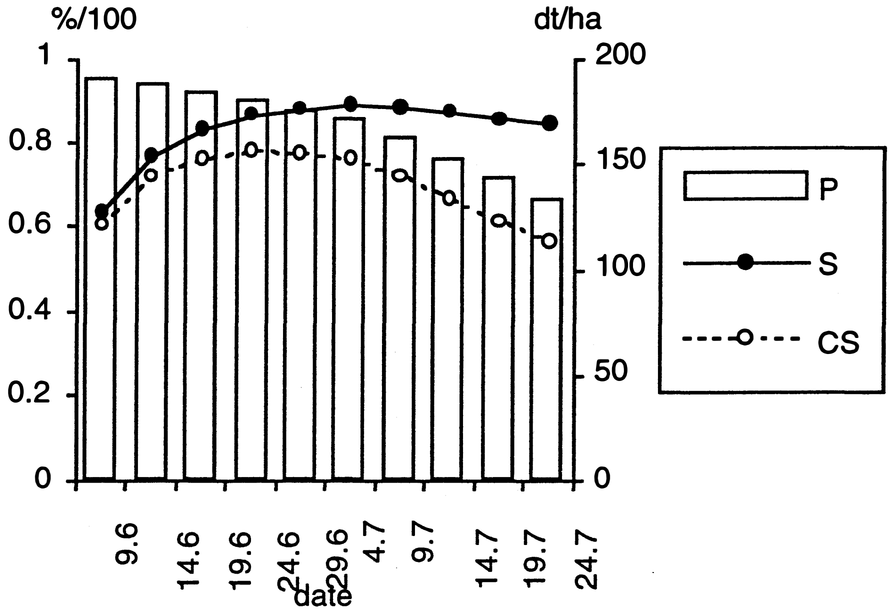

Fig. 4: Development of the probability *P* [%/100] to be certified, the expected yield in seed grade *S* [dt/ha] and the expected certified yield in seed grade *CS* [dt/ha]. The results are actually averages of 30 simulation runs: three situations (favourable, mean and unfavourable) were combined with the input data of the last 10 years after 14 June (up to this date the data of the current year have been used).

We show two examples of model application (see NEMECEK *et al.*, 1994 for further examples). The principal goal of "TUBERPRO" is to provide forecasts of the following variables for decision making:

- the expected tuber infection by PVY or PLRV and its variance;
- the expected tuber yield of a certain size grade and its variance.

Logit transformed forecasts of virus infection are approximately normally distributed. The mean and variance describe the probability distribution of the forecasts. They include the uncertainty caused by unknown future development of input time series (weather variables and aphid abundance), as well as the error in the estimates of certain parameters. Unknown future values of inputs are replaced by data of recent years. The scope of the simulations is always one field. However, it is also possible to define average situations that are representative for a regional or national production. Such an example is given in Fig. 4. In Switzerland, seed with a virus infection (PVY or PLRV) with up to 10 % can be certified as class A seed. The probability *P* that a lot will be certified is therefore the probability that the virus infection of tubers is ≤ 10 %, which is also the fraction of lots that are expected to be certified. The maximum expected yield in seed grade *S* is reached on 4 July. *P* and *S* allow to calculate the expected certified yield in seed grade *CS*, which is simply the product of the two variables ($CS = S \times P$). The maximum of *CS* is reached already on 24 June. Thus 24 June would be the optimal date to produce a maximum of certified seed.

Another strategy would be to maximize the farmer's income. The farmer is also interested in the larger tubers, since they can often be sold for human consumption. For this reason maximum expected income will usually be reached later than maximum expected certified seed. The user of TUBERPRO must define the strategy to achieve his objectives.

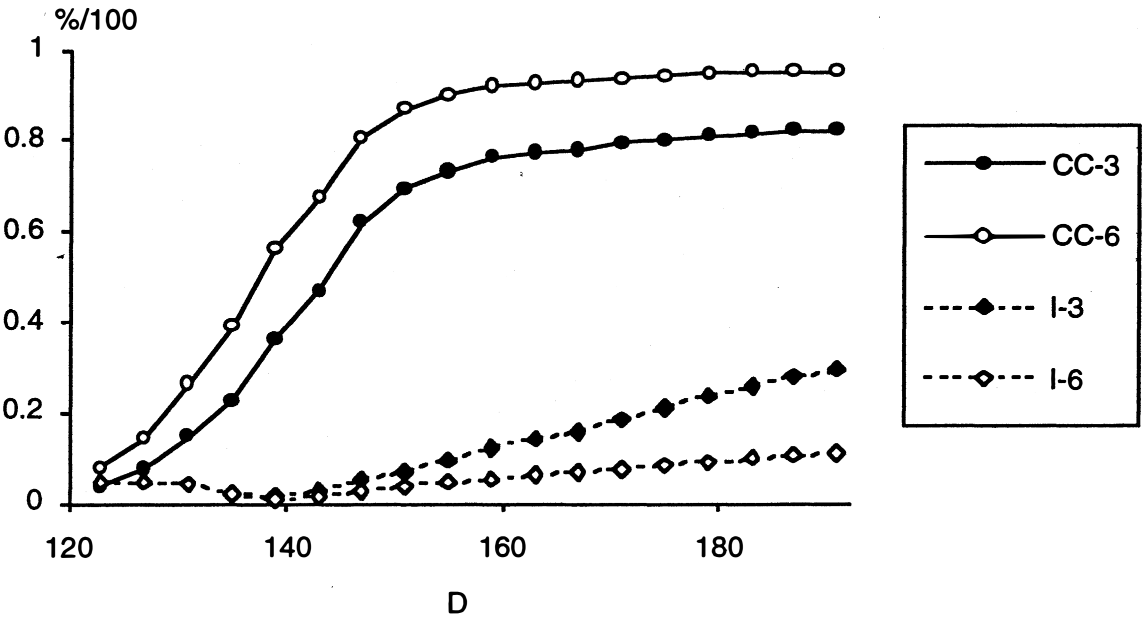

Fig. 5: Effect of planting density on virus spread: *I* = fraction of tubers infected by PVY, *CC* = fraction of soil covered by the canopy, D = julian day. The numbers 3 and 6 refer to the planting density of 3 respectively 6 seed pieces/m^2.

The simulation model can also be used to evaluate cultural practices. Fig. 5 shows that virus infection can be substantially reduced by increasing planting density. This is due to increased canopy cover (see Fig. 3) and a dilution effect (POWER, 1990 & 1992). Both factors lead to a lower number of vectors per plant, which will lower the percentage of infected plants. The high density planting reduced the average vector number per plant by 58 % and the virus infection by 62 % compared with the low density planting, i.e. virus infection was reduced even more than vector density. This difference is due to the fact that vector abundance was decreased mainly early in the growing season, when virus transmission is most dangerous (NEMECEK, 1993).

DISCUSSION

The crop reacts to influences exerted by the natural environment and by man. As the multiplication of potato viruses depends completely on the host plant metabolism, changes in the latter will also affect the epidemic process. E.g. if leaf growth continues longer, this will most likely favour virus spread by delaying age resistance. The vectors have a very close relationship to the crop as well. Such indirect influences on the epidemic process are best described by coupled virus epidemic-crop growth models.

Since well validated models are now available for many crops, we think that crop models should be more widely used in virus epidemic modelling. The use of a crop submodel makes the entire model more flexible and adaptable to other conditions, e.g. in other countries with different production schemes. By including the plant-virus and plant-vector relationships, the model becomes also more explicit and offers better possibilities to test hypothesis and to evaluate cultural measures (NEMECEK, 1993). A later unpublished version of the model of RUESINK & IRWIN (1986) considers also the effect of the canopy cover on the landing rate. However, the authors use measured time series as inputs. Thus, new experiments will be required each time growth parameters are changed, which is not necessary in our approach. The last argument for the use of crop submodels is perhaps the most obvious: the crop submodel calculates tuber yield and allows thus to optimize seed potato production according to different criteria (see Fig. 4). It allows also to evaluate the effect of virus control measures on yield.

Coupling a crop submodel to a virus epidemic model has also some drawbacks. The complexity of the whole model increases considerably and a lot more parameters are needed. As these parameters will not be available in all cases, default or average values must be used instead. By doing so, some advantages of the crop submodel will be lost. Finally, the development and coupling of models is laborious and time consuming, especially where no suitable crop model is available. The decision to use a crop submodel will depend on the objectives of the research, the availability of a suitable model and the available resources.

TUBERPRO is a powerful system management tool for the seed potato production. It allows to optimize the production according to various strategies. The strategies are chosen by the decision maker. A farmer will probably try to assure a certain income. A seed growers organization will perhaps try to increase its profits and the national service is mainly preoccupied with maintaining a high quality. TUBERPRO calculates the variables necessary to find optimal solutions at the different levels, especially to determine the haulm killing dates according to the specified goal. Moreover, it has revealed useful for the instruction of farmers and experts and for the evaluation of cultural and virus control measures (NEMECEK *et al.*, 1994). TUBERPRO is now being tested in practice in Switzerland. As it is very flexible, with a reasonable effort it should be possible to adapt it to other conditions.

Acknowledgements

We thank R. Schwärzel for his valuable contributions. We are also grateful to the Swiss Alcohol Board and the Swiss National Science Foundation (grant no. 31-8766.86) for their financial support.

References

Beemster, A.B.R., 1987. Virus translocation and mature-plant resistance in potato plants. In: De Bokx, J.A. & van der Want, J.P.H. (eds.): Viruses of potatoes and seed-potato production, 2nd ed., PUDOC, Wageningen, 116-125.

Derron, J.O. & Goy, G., 1993. Description et mode d'emploi d'un piège pour l'étude du vol des pucerons vecteurs de virus. Revue suisse Agric., **25**: 135-137.

Derron, J.O., Goy, G. & Genthon, M., 1989. Le piégeage des pucerons ailés: potentialités et limites de différents types de pièges. In: Cavalloro, R. (ed.), Euraphid network: trapping and aphid prognosis, Proc. of a meeting of the EC-Experts' group, Catania, Italy, 7.-9.11.88, ECSC-EEC-EAEC, Brussels, Luxembourg, 71-82.

Fischlin, A., Roth, O., Gyalistras, D., Ulrich, M. & Nemecek, T., 1990. ModelWorks: an interactive simulation environment for personal computers and workstations. Internal Report No. 8, Systems Ecology Group, ETH Zürich, 186p.

Irwin, M.E. & Kampmeier, G.E., 1989. Vector behaviour, environmental stimuli and the dynamics of plant virus epidemics. In: Jeger, M.J. (ed.), Spatial components of plant disease epidemics, Prentice Hall, Englewood Cliffs, NJ, 14-39.

Irwin, M.E. & Ruesink,W.G., 1986. Vector intensity: a product of propensity and activity. In: McLean, G.D., Garett, R.G., Ruesink, W.G. (eds.), Plant virus epidemics (monitoring, modelling, and predicting outbreaks), Academic Press, Sydney, 13-33.

Johnson, K.B., Johnson, S.B. & Teng, P.S., 1986. Development of a simple potato growth model for use in crop-pest management. Agricultu systems, **19**: 189-209.

Johnson, K.B., Teng, P.S. & Radcliffe, E.B., 1987. Coupling feeding effects of potato leafhopper, *Empoasca fabae* (Homoptera: Cicadellidae), nymphs to a model of potato growth. Environ. Entomol., **16**: 250-258.

Kendall, D.A., Brain, P. & Chinn, N.E., 1992. A simulation model of the epidemiology of barley yellow dwarf virus in winter sown cereals and its application to forecasting. J. appl. Ecol., **29**: 414-426.

Kisimoto, R. & Yamada, Y., 1986. A planthopper-rice virus epidemiology model: rice stripe and small brown planthopper *Laodelphax striatellus* Fallén. In: McLean, G.D., Garett, R.G., Ruesink, W.G. (eds.), Plant virus epidemics (monitoring, modelling, and predicting outbreaks), Academic Press, Sydney, 327-344.

Madden, L.V., Raccah, B. & Pirone, T.P., 1990. Modelling plant disease increase as a function of vector numbers: nonpersistent viruses. Res. Popul. Ecol., **32**: 47-65.

Marcus, R. & Raccah, B., 1986. Model for the spread of non-persistent virus-diseases. J. appl. Stat., **13**: 167-175.

Miyai, S., Kiritani, K. & Nakasuji, F., 1986. Models of epidemics of rice dwarf. In: McLean, G.D., Garett, R.G., Ruesink, W.G. (eds.), Plant virus epidemics (monitoring, modelling, and predicting outbreaks), Academic Press, Sydney, 459-480.

Nemecek, T., 1993. The role of aphid behaviour in the epidemiology of potato virus Y: a simulation study. Ph. D. Thesis. No. 10086, ETH Zürich, Switzerland, 232p.

Nemecek, T. & Derron, J.O., 1994 (in press). Validation et application d'un modèle de croissance de la pomme de terre. Revue suisse Agric., **26**: 00-00.

Nemecek, T., Derron, J.O., Schwärzel, R., Fischlin, A. & Roth, O., 1994. Un modèle de simulation au service des producteurs de plants de pommes de terre. Revue suisse Agric., **26**: 17-20.

Power, A.G., 1990. Cropping systems, insect movement and the spread of insect transmitted diseases in crops. In: Gliessman, S.R. (ed.), Agroecology (Ecological studies 78), Springer, New York, 47-69.

Power, A.G., 1992. Host plant dispersion, leafhopper movement and disease transmission. Ecol. Ent., **17**: 63-68.

Robinson, R.A., 1976. Plant pathosystems. Springer, Berlin, 184p.

Roth, O., Derron, J., Fischlin, A., Nemecek, T. & Ulrich, M., in press. Implementation and parameter adaptation of a potato crop simulation model combined with a soil water subsystem. In: van de Broek, B. & Marshall, B. (eds.), Proc. of the 1st Internat. Workshop on Potato Modelling, May 29-31, 1990, Wageningen, Netherlands. Wageningen Press, 30p.

Rouse, D.I., 1988. Use of crop growth-models to predict the effects of disease. Ann. Rev. Phytopathol., **26**: 183-201.

Ruesink, W.G. & Irwin, M.E., 1986. Soybean mosaic virus epidemiology: a model and some implications. In: McLean, G.D., Garett, R.G., Ruesink, W.G. (eds.), Plant virus epidemics (monitoring, modelling, and predicting outbreaks), Academic Press, Sydney, 295-313.

Sigvald, R., 1986. Forecasting the incidence of potato virus Y^O. In: McLean, G.D., Garett, R.G., Ruesink, W.G. (eds.), Plant virus epidemics (monitoring, modelling, and predicting outbreaks), Academic Press, Sydney, 419-441.

Taylor, L.R. & Palmer, J.M.P., 1972. *Aerial sampling.* In: van Emden, H.F. (ed.): Aphid Technology, Academic Press, London, 189-234.

Van der Werf, W., Rossing, W.A.H., Rabbinge, R., de Jong, M.D. & Mols, P.J.M., 1989. Approaches to modelling the spatial dynamics of pests and diseases. In: Cavalloro, R. & Delucchi, V. (eds.), Parasitis 88, Proc. of a scientific congress, Barcelona, 25.-28.10.88, 89-119.

Van Keulen, H. & Wolf, J. (eds.), 1986. Modelling of agricultural production: weather, soils and crops. Pudoc, Wageningen., 479p.

Venekamp, J.H., Schepers, A. & Bus, C.B., 1980. Mature plant resistance of potato against virus diseases. III: Mature plant resistance against potato virus Y^N, indicated by decrease in ribosome-content in ageing potato plants under field conditions. Neth. J. Plant Path., **86**: 301-309.

Wirth, N., 1985. Programming in Modula-2. Springer-Verlag, Berlin a.o., 3rd ed., 202p.

Wislocka, M., 1982. Einfluss der Trockenheit vor und zu verschiedenen Zeitpunkten nach Inokulation auf den Knollenbefall der Kartoffelsorte 'Uran' mit Kartoffelvirus Y. Pot. Res., **25**: 293-298.