CLIMATIC IMPACT ON THE PRODUCTIVITY OF SUGAR BEET IN EUROPE

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ABSTRACT

A recent study showed that drought stress was the major factor causing yield loss of the sugar beet crop in the UK. That study has been extended here by modelling potential and rain-fed yields (1961 – 1995) for European areas where irrigation of sugar beet is uncommon. Potential yields increased from north to south and from west to east due to increased radiation receipts. Drought losses were greatest in east Ukraine and southern Russia, at over 40% of potential yield (5 tha^{-1}). Losses were intermediate (15-30% or about 2 tha^{-1}) in central Ukraine, west Poland, east Germany and England (sandy soils) and lowest in NW Europe and west Ukraine. Model output was also used to examine the efficiency of sugar beet production across Europe. The impact of future climate change on sugar beet yields is assessed over western Europe using future (2021-50) climate scenario data from a General Circulation Model (GCM) and the Broom's Barn simulation model of rain-fed crop growth and yield. Yield increases due to future climate change are expected in northern Europe of around 1 t/ha of sugar for 2021-50 but decreases of similar magnitude in northern France, Belgium and west/central Poland, despite accelerated growth in warmer springs. Drought losses are expected to approximately double in areas with an existing problem and to become a serious new problem in NE France and Belgium. The annual variability of yield will also increase by half. These changes are independent of the 10% yield increase expected as a direct effect of the increase in atmospheric CO_2 concentration.

ABRÉGÉ

Une étude récente a montré que le stress dû a la sécheresse était le principal facteur causant des pertes de rendement en betteraves à sucre au Royaume Uni. La présente étude a été complétée par la modélisation du rendement potentiel et la modélisation du rendement des cultures uniquement approvisionnées en eau de pluie (1961-1995) dans les zones Européennes où l'irrigation est rare. Les rendements potentiels augmentèrent du nord au sud et d'ouest en est à cause de la plus grande irradiation reçue. Les pertes dues à la sécheresse furent plus importantes à l'est de l'Ukraine et au sud de la Russie : de l'ordre de 40% du rendement potentiel (5t/ha). Les pertes furent moyennes (15 a 30%); environ 2t/ha) au centre de l'Ukraine, ouest de la Pologne, est de l'Allemagne et Angleterre (sols sablonneux). Elles furent plus faibles au nord-ouest de l'Europe et à l'ouest de l'Ukraine. Les rendements modélisés furent aussi utilisés pour étudier l'efficacité de la production en betterave à sucre à travers l'Europe. L'impact des futurs changements climatiques sur les rendements en sucre est étudié à travers l'Europe de l'ouest grâce à l'utilisation de données provenant de scénarios concernant les futurs changements climatiques (2021-2050). Ces scénarios proviennent d'un modèle (General Circulation Model (GCM)) et d'une simulation de la croissance et du rendement de cultures approvisionnées en eau de pluie uniquement, à Broom's Barn. Les hausses de rendement dues aux futurs changements climatiques sont estimées autour de 1t/ha en Europe du nord en 2021-2050. Pourtant, des baisses de rendement d'un même ordre de grandeur sont prévues pour le nord de la France, la Belgique, l'ouest et le centre de la Pologne en dépit de l'accélération de la croissance lors des printemps plus chauds. Les pertes dues à la sécheresse se verront vraisemblablement doubler dans les zones connaissant déjà ce problème et cela deviendra un sérieux nouveau problème au nord-est de la France et en Belgique. La variabilité annuelle du rendement augmentera elle aussi de 50%. Ces changements sont indépendants des hausses de rendement de 10% attendues comme effet direct de l'augmentation de la concentration en CO_2 atmosphérique.

KURZFASSUNG

Eine neuere Studie zeigte, dass Trockenheitsstress der Hauptfaktor für Ertragsverluste bei Zuckerrüben in Großbritannien ist. Diese Studie wurde hier durch Modellierung von potenziellen und regengespeisten Erträgen (1961–1995) für Gebiete Europas erweitert, in denen die Bewässerung von Zuckerrüben nicht üblich ist. Die potenziellen Erträge stiegen aufgrund einer gesteigerten Bestrahlungsmenge von Norden nach Süden und von Westen nach Osten. Trockenheitsverluste waren mit mehr als 40% des potenziellen Ertrags (5 tha^{-1}) in der Ostukraine und in Südrussland am größten. Die Verluste waren in der Zentralukraine, Westpolen, Ostdeutschland und England (Sandböden) mittelschwer (15–30 % oder etwa 2tha^{-1}), und am niedrigsten in Nordwesteuropa und der Westukraine. Der Modelloutput wurde auch zur Beurteilung von der Leistungsfähigkeit der Zuckerrübenproduktion in Europa verwendet. Die Auswirkungen von zukünftigen Klimaveränderungen auf den Ertrag von Zuckerrüben werden für Westeuropa mittels Daten zukünftiger (2021-50) Klimaszenarien auf der Grundlage eines atmosphärischen Zirkulationsmodells (General Circulation Model, GCM => HADCM2) und des Brooms-Barn-Simulationsmodells für Fruchtwachstum und -ertrag bei ausschließlicher Regenbewässerung bewertet. In Nordeuropa werden für die Jahre 2021-50 aufgrund zukünftiger Klimaveränderungen Ertragssteigerungen von etwa 1 t/ha Zucker erwartet, jedoch ist in Nordfrankreich, Belgien und West-/Mittelpolen trotz beschleunigtem Wachstum in wärmeren Frühlingen mit einem Rückgang in ähnlicher Höhe zu rechnen. Es wird erwartet, dass sich Trockenheitsverluste in Gebieten mit einem existierenden Problem ungefähr verdoppeln und in Nordostfrankreich und Belgien zu einem ernsthaften neuen Problem entwickeln werden. Die jährliche Ertragsvariabilität wird sich ebenfalls um die Hälfte steigern. Diese Veränderungen berücksichtigen nicht die Ertragssteigerung um 10%, die als wahrscheinliche direkte Auswirkung der

Zunahme der atmosphärischen CO_2-Konzentration erwartet wird.

INTRODUCTION

During most of the last 60 years of sugar beet production in the UK, interception of solar radiation has been the yield-limiting factor (SCOTT, R.K. & JAGGARD, K.W., 2000). However, major advances over this period in crop breeding, agronomy, physiology and mechanisation have maximised early canopy expansion rates and hence radiation interception, and now there is little scope for further improvement by earlier sowing because the temperature would be too cold to allow seed germination. Maximising canopy expansion and radiation interception inevitably increased crop water use. In addition, there was a move in the 1970s to concentrate beet production on sand or sandy loam soils, for mechanisation and economic reasons. Thus in considering future research strategy, work in England evaluated the yield losses due to drought between 1980-1995 (JAGGARD, K.W. *et al.*, 1998). The average annual loss was 10.5% of the national crop, valued at £28 million/year. The conclusion was that drought stress is now the major factor causing yield loss in the UK. This caused us to question the extent of these losses throughout Europe. This paper describes a simulation to investigate the importance of drought across Europe in the recent past (1961-1995) and in the future (2021-2050).

METHODS: 1961-1995

This modelling study uses the beet crop growth model (RICHTER, G.M. *et al., 2001*), the European monthly weather database 1901-1996 and assessments of the available water capacity (AWC) of the beet-growing soils across Europe.

The Broom's Barn crop growth model is a simple model containing a series of sub-routines calculating foliage cover, intercepted radiation, water balance, and total dry matter and sugar yields. Calculation procedures are described in detail by Werker and Jaggard (1997) and Jaggard and Werker (1999). The model has been expanded and validated for the effect of variable radiation use efficiency and the effect of drought on canopy size (RICHTER, G.M. *et al.*, 2001).

The model simulates at a daily time step. Therefore the European meteorological data had to be scaled to recreate a daily format. This could not be done realistically by using a 'weather generator'. Therefore, for most weather parameters used by the model, we recreated a daily format by simple linear interpolation from the middle of one month to the middle of the next. However, rainfall has a discontinuous distribution over time and a different approach had to be adopted. Rain during any month was allocated uniformly to the recorded number of rain-days, which were allocated at random over the month.

Throughout Europe, all simulations finished on 31 October. In many countries harvest takes place at about this time, and elsewhere further growth during November and December is trivial (SCOTT, R.K. & JAGGARD, K.W., 1993).

To collect data on soils and agronomic practice, a simple survey was sent to experienced sugar beet agronomists in each country. They delineated the areas for beet production, the predominant soil texture and typical sowing dates in those areas. The soil texture descriptions were then used to estimate AWC, according to the analysis of Gregson *et al.* (1987). The dominant textures were loamy sands, silty loams and peaty loams, with assumed AWC of 12, 20 and 24% respectively.

METHODS: 2021 - 2050

For the future, we used the same crop growth model but with General Circulation Model (GCM) output for the present (Control) and future (Scenario) climate. Recent GCMs run several integrations (ensembles) using realistic estimates of emission scenarios, likely natural forcing changes and changes to initial conditions to simulate internal model variability (KATTENBURG, A. *et al.*, 1996; IPCC, 2001). The GCM used here is the second Hadley Centre coupled ocean-atmosphere integration (HadCM2) described by Johns *et al.* (1997). We selected the results for the years 1961-90 and 2021-50 from the sulphate (SUL) experiment. Here the GCM was run with known greenhouse gas forcing from 1861 to 1990, then estimates using IPCC's IS92a greenhouse gas emissions scenario from 1991 to 2100.

To establish the validity of using the GCM output, we compared, for the average of 1961-90, the simulated and observed climate data across Europe for April to September. This 'season' approximates the beet growth period in these regions. We concluded that for examining differences between recent past and future scenarios of rain-fed yields and drought losses, HadCM2 data are not close enough to reality to be useful for Europe east of 24°E (JONES, P.D. *et al.*, 2003). However, for western Europe there is generally good agreement between observations and this simulation, and hence differences between simulations of recent past and future beet crop yield are likely to be meaningful. Therefore, for all subsequent work, calculated rain-fed yields are only displayed for Europe west of 24°E.

The GCM output for the study area (23 model grid boxes) for 1961-90 was used as input data for the sugar beet growth model. Again, the number of raindays per month for each grid box was used to disaggregate the predicted monthly rainfall to a daily basis for use in the crop growth model.

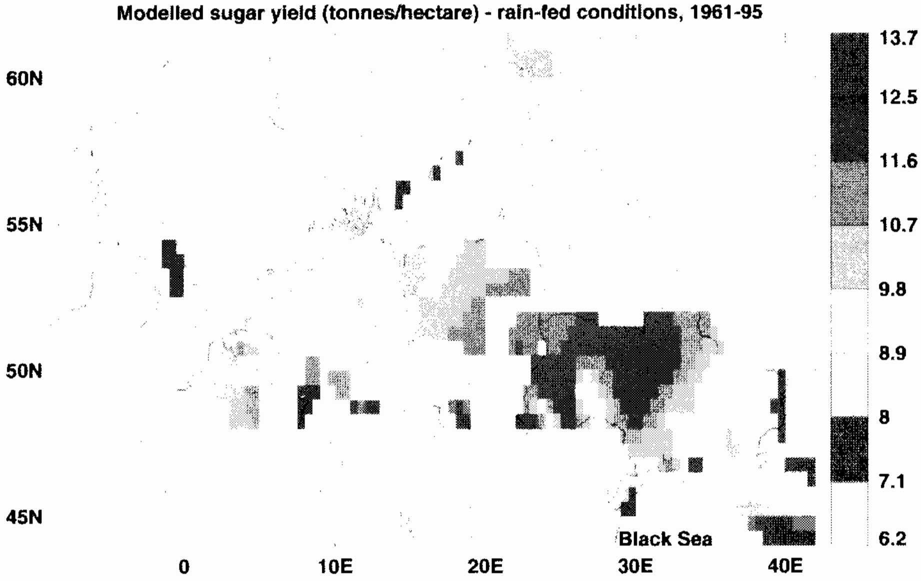
RESULTS AND DISCUSSION: RECENT PAST

In the absence of water stress, average yields of sugar (1961-1995) are estimated to vary from about 6.5 t ha^{-1} in Finland to more than 15 t ha^{-1} near the Black Sea, (Ukraine, Krasnodar), where it is warmer and sunnier, and where the growing season is longer. Simulated stress-free yields also increase from the West, e.g. Eire with 8 t ha^{-1} (where the weather is cool in early summer and where it is often cloudy) towards the East, as the climate becomes more continental sunnier.

Again, the smallest simulated rain-fed yields are predicted to be in Finland, followed by southern Sweden and northern England (Fig 1), while the largest yields are simulated for southern Krasnodar, N.W. Ukraine and southern

Germany. Within the European Union, average sugar yields in excess of 10 t ha^{-1} are simulated for southern Germany and parts of northern France and Belgium.

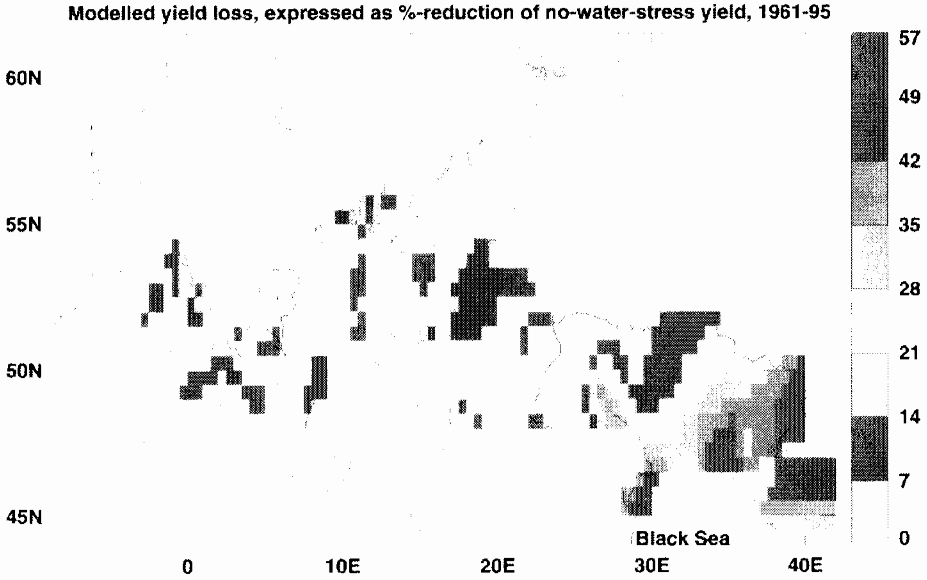
Figure 1. Simulated rainfed sugar yield (t/ha): 1961 - 1995



Year-to-year yield variation is a serious concern for the farmers and sugar processors who have supply contracts to meet. The coefficient of variation is less than 10% in Eire, northern France, Netherlands and western Germany, but more variable in England, central France, Scandinavia, Ukraine and Krasnodar. This variation depends very much on the variation in summer rainfall and the soil water holding capacity. Under the weather conditions of eastern England, the coefficient of variation may range from 6 % on silty soils to 10% on sands. Maximum and minimum yields may be as much as 20 % above or below the long-term average in sandy soils.

The potential value of cultivars with improved tolerance to dry conditions is illustrated in Fig.2, which maps the percentage yield reduction due to drought. In Eire, the Netherlands, Belgium, N.E. France, western Germany and parts of the UK, the losses are small, less than 7%. However, in the UK about 50% of the crop is grown on unirrigated sandy soil with a water holding capacity of only 12%. In consequence, these parts of the UK suffer average sugar yield losses due to drought of 10-20% (Fig.2). There is a large range of potential drought losses within France, but the southern part of the French crop is usually irrigated and has been excluded from this study. Moving south and east the picture becomes more heterogeneous; most of central Europe suffers drought losses of 7-20% due to low rainfall, despite water-retentive soil. Nearby, in parts of Poland and W.Ukraine where the summer is usually wet, the losses are close to zero. However, dry parts of Ukraine and SE Russia suffer, on average, losses of more than 40% or more than 5 t ha^{-1} sugar.

Figure 2. Sugar yield losses (%) due to drought: 1961 - 1995



The rain-fed yield results depict several regions of high yield, which are also favoured with low annual variability. This is the best combination for a secure, highly productive industry. Northern France, large areas of north and central Ukraine, west and central Poland (on the better soils) and southern Germany are prominent in this category.

The pattern of drought losses is, of course, of major interest, and enables us to place in a European context the previously reported drought stress problem in eastern England (JAGGARD, K.W. *et al.*, 1998). By comparison, the combination of water retentive soils and higher summer rainfall means that, despite their larger evaporative demand, northern France, Belgium, Holland and southern Germany do not suffer appreciable drought losses. Neither do large areas of western Ukraine and the areas with better soils in Poland. The areas with intermediate drought losses (including eastern England) suffer from low summer rainfall and, in some cases (England, west Poland), from sandy soils. At the southern fringes of the French and eastern fringes of the German beet growing areas, the summer evaporative demand is large and potential drought losses are therefore intermediate. Large areas of eastern Ukraine, south west Russia and the Krasnodar region suffer regularly from severe drought losses, despite favourable soils, due to high evaporative demand and a low summer rainfall.

The output from this model can be used at several scales. For example, at the national scale, the model simulation of rain-fed yield can be compared with actual delivered tonnage for each year. This comparison can be calculated as an efficiency ratio that can be compared with that of other regions (PIDGEON, J. D. *et al.*, 2001).

Some of the national differences will be due to differences in the prevalence of diseases that are difficult to control.

RESULTS AND DISCUSSION - FUTURE

The sugar beet growth model used in this study did not take into account the potential 'fertilization' effects of the significant increase in atmospheric CO_2 concentration expected for 2021-2050. On the basis of season long CO_2 enrichment studies it is estimated that this alone will increase sugar yield by about 10% (DEMMERS-DERKS, H. *et al.*, 1998). The direct effects of increased CO_2 concentration on water consumption and the incidence of stree are expected to be small.

The yields produced using the observed data and the GCM output compare favourably over much of western Europe, as would be expected from the comparison between the two sets of input climate data. Figure 3 shows the increase in rainfed sugar yield due to climate change for 2021-50 compared to 1961-90. No changes were made to AWC, sowing date or the number of raindays. All northern European regions show an increase in yields; warmer temperatures will stimulate early growth of the foliage so that more sunlight is intercepted, and the imbalance between PET and rainfall (i.e. drought stress) is not so severe that this increase is eroded. Moderate decreases in average yield occur over the southern part of the study area, particularly in northern France, Belgium and southern Poland. Here, the advantages of warmer spring and early summer are more than offset by more frequent and severe water stress. Other areas e.g. East Anglia and Lincolnshire in England, and much of Germany, show little change in average yield: the benefits of enhanced spring growth are counterbalanced by increased drought stress in summer. The sugar yields in each grid box were weighted by the area now devoted to beet in each box. Over the area as a whole, yield is estimated to decrease, but only by 0.1%.

Figure 3. Modelled changes in sugar yield (t/ha) by 2021 - 2050

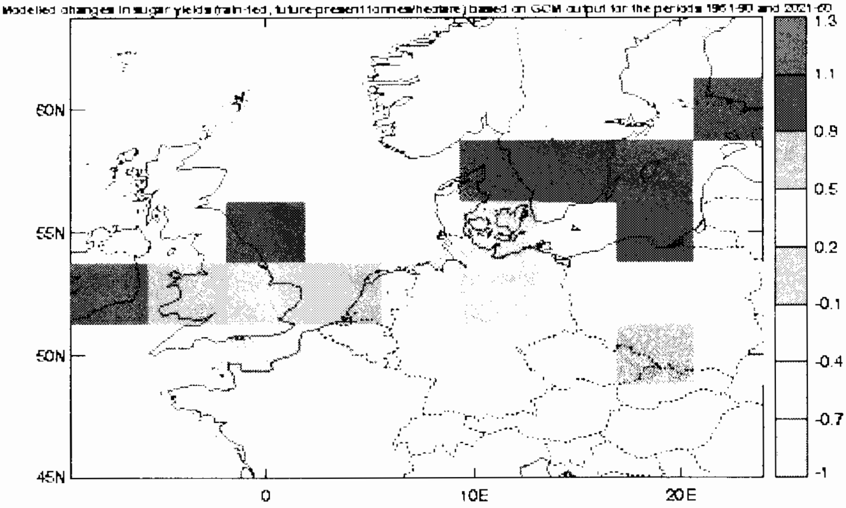
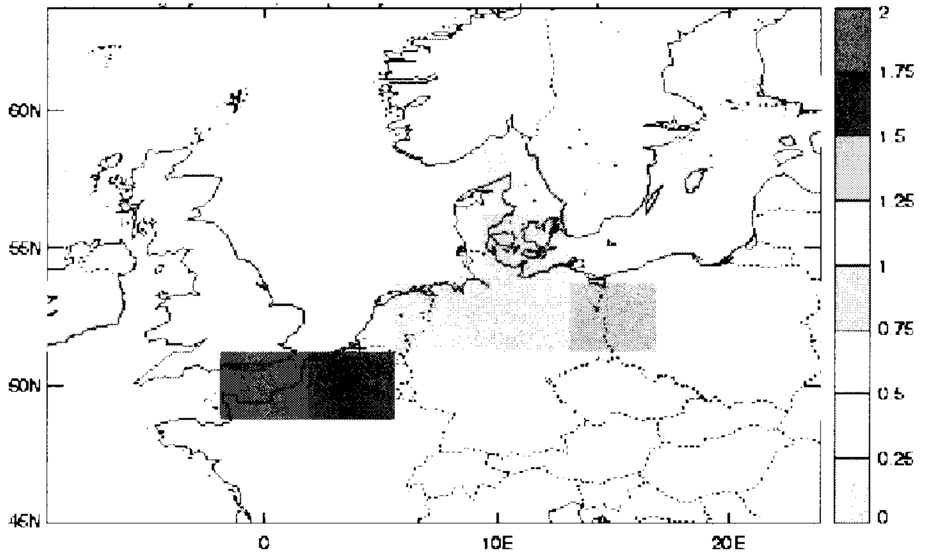


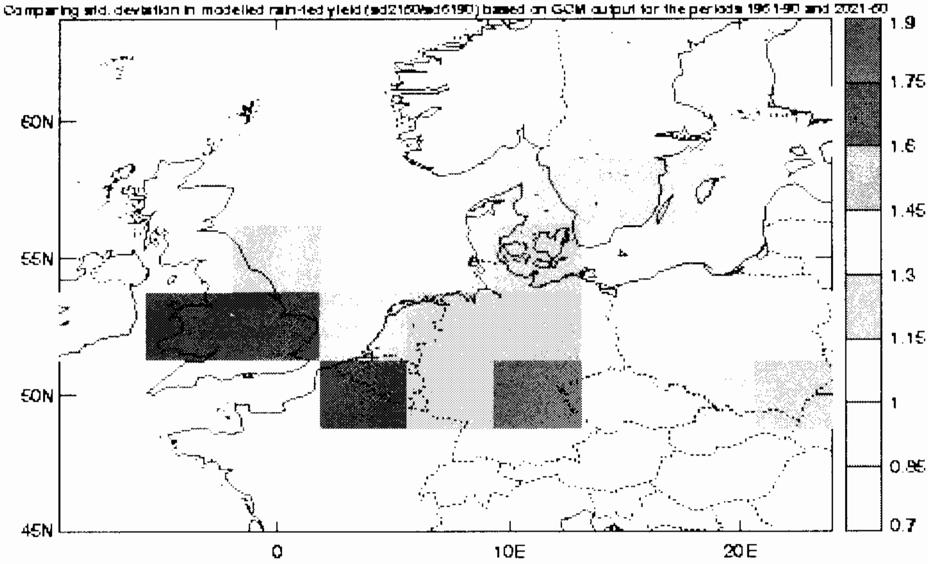
Figure 4 provides additional understanding: it shows the changes in sugar yield due to drought between the future (2021-2050) and present (1961-1990) periods. Drought losses are again calculated as the difference between potential (no water stress) and rain-fed simulated yields (JONES, P.D. *et al.*, 2003). Our results show major increases in drought losses across most of western and central Europe. This approximately doubles an existing drought problem in East Anglia, northern France, eastern Germany, and much of Poland, and will be a serious new problem for NE France and Belgium. The effect is most severe in the high density beet production area of NE France and Belgium, where increased water stress will no longer be buffered by the deep, water retentive soils. Overall, the weighted average drought loss for the area of this study rises from 7% or 1.1 Mt for 1961-90 to 18% or 2.8 Mt. This reinforces our contention that breeding for drought stress tolerance should be a pan-European research priority.

Figure 4. Increased mean sugar beet drought losses (t ha⁻¹) for the years 2021 – 50 over 1961 – 90 based on GCM output



In addition to changes in average yields, changes in year-to-year variability also occur. Figure 5 shows the ratio of the standard deviation of yields for 2021-50 to those of 1961-90. It is important to remember here that we have not incorporated any change to the number of raindays. Increases in year to year variability (due to higher yield following warmer springs and wet summers, and lower yields due to increased drought in dry summers) occur over northern France and Germany (the two largest producers of sugar in the EU), together with Belgium, Holland and the beet producing areas of England. These areas account for 60% of EU sugar production. The coefficient of variation (CV) over the period 1961-95 was about 10% of sugar yields which averaged about 8 t/ha. Figure 5 shows that the CV will rise to about 15%. This means that the year-to-year variations in yield can be expected to change from a range of 6.4 – 9.6 t/ha up to a range of 5.6 – 10.4 t/ha in future. Extreme seasons (1 year in 20) will fall outside this range. This increased variation has implications for future security of sugar supplies if swings in productivity are synchronised across large areas of Europe.

Figure 5. Changes to the coefficient of variation (%) of annual sugar yields in 2021-2025 compared with 1961 - 1995



CONCLUSION

We have not attempted to model the pest and disease changes as consequences of climate change or their likely effect on yield. However, plant breeders are already increasing the disease tolerance in their varieties. Conversely, breeding for drought tolerance has hardly begun. In the main, the crop is either grown in hot areas where irrigation water has seemed to be plentiful, or it is grown in deep, water retentive soils in northern and central Europe and has not suffered severely from drought hitherto. This study shows that drought will become a yield limiting factor in much of the important northern European production areas. Increases in the use of irrigation for sugar production will seldom be an option. Breeding for drought stress tolerance should therefore be a truly pan European research objective.

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