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N.J. Rosenberg
R.C. Izaurralde
M. Tiscareño-Lopéz
D. Legler
R. Srinivasan
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September, 1997

Prepared for
the National Aeronautics and Space Administration
under Contract DE-AC06-76RLO 1830 and
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Pacific Northwest National Laboratory
Operated for the U.S. Department of Energy
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N.J. Rosenberg
*R.C. Izaurralde**
R.A. Brown
R.D. Sands
Pacific Northwest National Laboratory

M. Tiscareño-Lopéz
Instituto Nacional de Investigationes Forestales y Agropecuarias
D. Legler
Florida State University
Center for Ocean Atmosphere Prediction Studies
R. Srinivasan
Texas A&M University
Blacklands Research Center

* Formerly at Dept. of Renewable Resources, University of Alberta, Edmonton, Canada

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ABSTRACT

A group of Canadian, U.S. and Mexican natural resource specialists, organized by the Pacific Northwest National Laboratory (PNNL) under its North American Energy, Environment and Economy (NA3E) Program, has applied a simulation modeling approach to estimating the impact of ENSO-driven climatic variations on the productivity of major crops grown in the three countries. Methodological development is described and results of the simulations presented in this report.

EPIC (the Erosion Productivity Impact Calculator) was the agro-ecosystem model selected for this study. EPIC uses a daily time step to simulate crop growth and yield, water use, runoff and soil erosion among other variables. The model was applied to a set of so-called "representative farms" parameterized through a specially-assembled Geographic Information System (GIS) to reflect the soils, topography, crop management and weather typical of the regions represented. Fifty one representative farms were developed for Canada, 66 for the United States and 23 for Mexico.

El Niño Southern Oscillation (ENSO) scenarios for the EPIC simulations were created using the historic record of sea-surface temperature (SST) prevailing in the eastern tropical Pacific for the period October 1 – September 30. Each year between 1960 and 1989 was thus assigned to an ENSO category or "state." The ENSO states were defined as El Niño (EN, SST warmer than the long-term mean), Strong El Niño (SEN, much warmer), El Viejo (EV, cooler) and Neutral (within ±0.5 C of the long-term mean). Monthly means of temperature and precipitation were then calculated at each farm for the period 1960 - 1989 and the differences (or anomalies) between the means in Neutral years and EN, SEN and EV years determined (see maps in Figs. III.1 and 2 within). The average monthly anomalies for each ENSO state were then used to create new monthly statistics for each farm x ENSO-state combination. The adjusted monthly statistics characteristic of each ENSO state were then used to drive a stochastic-weather simulator that provided thirty years of daily-weather data needed to run EPIC.

Maps and tables of the climate anomalies by farm show climatic conditions that differ considerably by region, season and ENSO state. The ENSO impacts on crop yields and other factors modeled were rather complex and are not easily generalized. A few of the more obvious effects included: (i) warmer winters under EN in the Canadian prairies reduced spring wheat yields (with respect to yields in Neutral years); (ii) in Illinois, reductions in corn yields that occur during EN years were associated with increased summer temperatures and decreased winter and summer precipitation.

The SEN state is not merely an amplification of EN conditions. Indeed, the geographic and seasonal distributions of temperature and precipitation anomalies are quite different. Thus, the warmer temperatures of EN in the Prairie Provinces extend under SEN into the northern Great Plains and generally lower winter wheat yields there. Increased winter precipitation under SEN in the U.S. southeast benefited corn yields for that region.

The EV state brings lower winter temperatures to the Canadian Prairies and higher wheat yields. Decreases in corn yields in a region bounded by eastern Illinois, the Ohio Valley and the Great Lakes are related to decreases in spring or summer precipitation under EV. The simulations do show, in general, that yields respond most to water stress conditions (either too much or too little) brought on by the various ENSO states.

In addition to the simulation approach described above, the frequency of occurrence of the three non-Neutral ENSO states was altered systematically and impacts of these altered climatic time-series on yield calculated. When averaged over 50 years of run, yield effects were small but extended for a number of years after each alteration in sequence. And, unexpectedly, the frequency changes induced both positive effects and negative effects, illustrating the importance of antecedent conditions at the beginning of each crop year.

Impacts of EN, SEN and EV on evapotranspiration, runoff and soil erosion were complex, showing as much or more regional diversity than did yields. Especially in Mexico, impacts are strongly crop-specific.

Yields simulated in this exercise were used in an integrated assessment model (MiniCAM) to calculate regional, national and continental production changes associated with each of the ENSO states and their economic consequences. The three states, overall, reduce agricultural production (below that calculated for the Neutral state) from 3 to 9% with consequential effects on prices and world trade.

Acknowledgements

We gratefully acknowledge guidance and assistance of representatives of the agencies sponsoring this study—Robert Harriss and Diane Wickland of NASA's Mission to Planet Earth and Claudia Nierenberg and Caitlin Simpson of NOAA's Office of Global Programs. James O'Brien of Florida State University, J. Allan Jones of Texas A & M University, Ramon Martinez-Parra of INIFAP, Wayne Pettapiece of Agriculture and Agri-Food Canada, Brad Bass and Linda Sterling of Environment Canada and Jae Edmonds of Pacific Northwest National Laboratory (PNNL) provided technical guidance on various aspects of the research. César Izaurralde thanks Cristina Quiroga Jakas and Chung Nguyen at Univ. of Alberta for technical assistance. Thanks, too, to Elizabeth Malone, Suzetté Hampton and Laura Green of PNNL for the administrative support that facilitated completion of this work.

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I. INTRODUCTION

A. Project Background

A Southern Oscillation Index (SOI), the standardized sea level pressure difference between Darwin, Australia and Tahiti, French Polynesia (Tahiti minus Darwin), correlates negatively with anomalous sea surface temperatures (SSTs) in the eastern and central tropical Pacific. When negative values of SOI occur, warmer (El Niño) conditions prevail. When SOI values are positive, cooler than normal (El Viejo, sometimes termed La Niña) sea surface temperatures prevail. El Niño and El Viejo events occur with some regularity (2 to 9 year return periods) and usually last for only 1 or 2 years. However, there is much variability in their occurrence, timing and intensity.

Recent research has begun to link agricultural production in diverse locations around the world to El Niño-Southern Oscillation (ENSO) events. Cane et al (1994), for example, have correlated an El Niño index with both rainfall and corn yields in Zimbabwe. Phillips, Rosenzweig and Cane (1996) found that corn yields in the U.S. Cornbelt can be related to climate anomalies associated with ENSO and believe that advance forecasts of ENSO would enable farmers to adjust management practices to improve yields. Grain yields in the Nordeste of Brazil have been correlated with ENSO events and, it is claimed, a recent advance warning of ENSO permitted authorities in that region to take steps that avoided what would otherwise have been severe production shortfalls (Magalhaes, 1996). Lamb and Peppler (1990), on the other hand, found the relation of El Niño to rainfall in Morocco and other portions of western Africa to be weak. Rosenzweig (1994) has cautioned against too much reliance on El Niño-based forecasts of crop production. Crop productivity in any location, she points out, depends on a complex combination of climate, biophysical factors, and management. Also the actual impact of any particular El Niño event will depend not only on yields but on economic and trade conditions prevailing at the time.

In October of 1995 NASA's Mission to Planet Earth Program awarded a contract to the Pacific Northwest National Laboratory (PNNL) for conduct of a study entitled "Sensitivity of North American Agriculture to ENSO-based Climate Scenarios and their Socio-economic Consequences: Modeling in an Integrated Assessment Framework." The study was to be conducted by a consortium of natural resource modelers in Canada, the United States and Mexico organized by PNNL under its North American Energy, Environment and Economy (NA3E) Program. Participants in this research and their institutions are listed on the title page of this report. Subsequently, in May of 1996, NOAA's Office of Global Programs augmented NASA's support to expand the scope of the study.

The long-term objective of the study has been to aid NASA in identifying regional-scale environmentally-induced stresses that can be monitored using current or improved remote sensing technologies. As a first step in this direction it was proposed to identify impacts of ENSO-forced climatic variability on the yields of major crops grown under current technology in North America and to assess the significance of these impacts through an economics module incorporated in PNNL's Global Change Assessment Model (GCAM). In addition, impacts of ENSO on runoff and soil erosion were to be estimated as a first indicator of how effects of agriculture on environmental quality can be tempered or exacerbated by climatic variability.

Originally we had intended to evaluate the sensitivity of only 'high-tech' agriculture in the three NA3E nations under a set of climate scenarios that would typify differences in monthly means of temperature and precipitation when sea surface temperatures in the tropical Pacific are in their warm phase, cold phase, and neutral states. The NOAA support allowed us to extend the modeling effort as well to 'low-tech' subsistence farming which accounts for a substantial portion of Mexico's food production. In so doing, we gained the opportunity to test the extensibility of our modeling approach to regions of the world where low-tech farming is important. In addition, the NOAA support allowed us to study impacts on agriculture of possible changes in frequency in occurrence of the various ENSO states.

Our general research approach in this study was as follows:

- design farm enterprises representative of the major agricultural production regions in North America and apply to these farms a generalized process-based model that simulates crop yield, water use (evapotranspiration), runoff and soil erosion as a function of climatic conditions and/or farm management practice (e.g. crop cultivar, planting date, irrigation, fertilization and tillage). While these representative farms were designed separately by specialists in each of the three countries (R.C. Izaurralde of the University of Alberta in Canada, Robert Brown of PNNL in the United States and Mario Tiscareño of INIFAP in Mexico) the work was done according to protocols and formats standardized among the three countries to assure comparability of all the North American results.
- develop ENSO scenarios for application to the agricultural simulation models. This activity was undertaken by David Legler and James O'Brien of Florida State University's Center for Ocean-Atmosphere Prediction Studies (COAPS).
- apply the ENSO scenarios to the representative farms and simulate their impacts.

The development of both the representative farms and the climate scenarios required geographically-distributed input data that were provided by Raghavan Srinivasan of Texas A & M University's Blacklands Research Center who also provided a GIS framework for representing the results of the study.

B. North American Agriculture and its Sensitivity to Climatic and Other Stresses

Remarkable changes have occurred in the structure of the North American agriculture in this century. The number of farms has been greatly reduced. Irrigated acreage has greatly increased. New crops such as soybean (*Glycine max*) and canola (*Brassica* spp.) have been introduced. The yield potential of most important crops has been raised through plant breeding for heat, cold, drought, disease and insect resistance. Increased use of mineral fertilizers and pesticides and improved tillage practices have allowed expression of the yield potential embedded in the new cultivars.

Nonetheless, the trend of rising productivity is interrupted from time to time by natural events — droughts, floods, hailstorms, disease, and insect outbreaks making even the most advanced agricultural regions vulnerable to environmental stress. For example, Great Plains wheat production is often seriously reduced by drought (CAST 1992); a weather-related disease —the southern corn leaf blight— sharply reduced U.S. corn production in the 1970s (Waggoner et al., 1972); El Niño-related storms inflicted severe damage on California's high value fruit and vegetable crops in the winter of 1995.

Agricultural production is sensitive not only to physical and biological stresses. Demographic and economic trends are altering world food trade in ways that strongly influence demand for and supply of food. Pressures on the supply of land for agriculture are increasing because of urbanization. Future demands for biomass could further reduce availability of agricultural lands for food production (Rosenberg and Scott, 1994). In addition, irrigation may decrease as hydropower and fish and wildlife requirements compete more strongly for available water supplies in the future (Rosenberg and Scott, 1994).

The productivity of North America's agriculture is not the only issue of concern. It is also important to recognize that agriculture can be the cause of serious environmental problems. Monoculture and certain tillage practices accelerate soil erosion which reduces fertility of farm fields and dumps sediments into waterways and reservoirs (Pimentel et al., 1995). Erosion, runoff and leaching transport fertilizer and chemicals off the fields into streams or groundwater. Thus any study or inventory of agricultural vulnerability to environmental conditions must also consider agriculture's impacts on the environment.

C. ENSO and North America

ENSO events are now thought to explain the occurrence of unusual weather patterns throughout the world. However, ENSO signals are not always unambiguous, particularly in North America which, according to one expert,[1] receives more of a glancing blow than a direct hit. Generally ENSO effects are greater in Mexico and Central and South America and are also stronger in winter than in summer. Attempts are being made to quantify the relationship between SST anomalies in the tropical Pacific and anomalous temperature and precipitation patterns over North America. But because of limitations in data availability and quality, as well as the complex nature of the coupled atmosphere-ocean climate system and the role of other scales of variability (e.g. decadal-centennial, etc.), this relationship will likely remain unclear for some time. However, progress has been made in identifying *mean* climate anomalies associated with extreme phases of ENSO, namely the mean monthly temperature and precipitation anomalies associated with El Niño and El Viejo. Initial papers (Ropelewski and Halpert, 1986; Ropelewski and Halpert, 1987) identified regions where climate anomalies of precipitation were persistent and coherent. For the Great Basin region in the western U.S., wetter conditions tended to occur during the April - October period during the year of maximum Pacific SST anomalies. Additionally, anomalous wet conditions over the Gulf of Mexico region were found to be associated with warm events, but the anomalies occurred later in time, i.e. during the following October–March. Kiladis and Diaz (1989) confirmed these findings. In a more focused analysis of precipitation data from individual stations, Ropelewski and Halpert (1996) examined shifts in monthly median precipitation rankings and found considerable spatial variations within previously identified regions of ENSO-related seasonal precipitation anomalies, indicating that ENSO precipitation responses could be much more complicated than previously concluded.

Effects of at least one El Niño, that of 1982-83, were unambiguous. Severe storms battered the California coast, and flooding was widespread in the southeast. Another effect attributed to this ENSO event was the much higher than normal snowpack in the Wasatch mountains. Delayed spring runoff made rivers out of east-west boulevards in Salt Lake City and contributed to the rapid rise in level of the Great Salt Lake. Trenberth and Brandstadter (1992) believe that the severe drought of 1988 was related to the cold phase of ENSO.

In this report we describe the methodology developed by the NA3E group to: (a) represent the effects of ENSO events on North American agriculture through simulation modeling of a total of 140 representative farms; (b) design scenarios that represent historic temperature and precipitation anomalies in the vicinity of each of these farms when warm ENSO conditions (El Niño, EN), very warm (Strong El Niño, SEN) and cool conditions (El Viejo, EV) SSTs prevail in the tropical Pacific; and (c) design scenarios that alter the historic frequency of each of the ENSO-states while the others remain constant. We then report the simulated effects of these ENSO states on the yields of major crops grown in Canada, the United States and Mexico and the effects on evapotranspiration, runoff and soil erosion. The results of the yield simulations are evaluated in the context of an economic framework to assess the relative importance of ENSO events on the North American economy. In a final section we discuss the findings of this study that can guide future research on ENSO effects applicable to the NASA and NOAA missions.

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[1] Dr. Eugene Rasmusson, Dept. of Meteorology, University of Maryland, personal communication.

II. METHODOLOGY

A Modeling Crop Sensitivity to ENSO

A.1 The Erosion Productivity Impact Calculator (EPIC)

EPIC, the Erosion Productivity Impact Calculator (Williams et al., 1984; Williams, 1995) is the crop growth simulator used in this research. EPIC version 5320 is used in this study. EPIC models agricultural production on the scale of a single farm field. The model simulates photosynthesis, evapotranspiration, and other major plant and soil processes. It runs on a daily time step and requires the input of daily weather data as well as information on soil properties, crop-specific growth parameters and farm management practices. EPIC can use either actual daily weather records or simulate daily weather with the aid of a stochastic weather generator. WXGEN (Richardson and Nicks, 1990), which is seeded with monthly statistics of temperature, precipitation, solar radiation, relative humidity and wind speed, is the generator used in this application.

EPIC calculates the maximum daily increase in plant biomass made possible by the daily total of solar radiation incident on the field. The algorithms used to model potential plant growth (biomass accumulation) are driven by photosynthetically active radiation (PAR). The amount of solar radiation captured by the crop is a function of PAR and leaf area index (LAI). The amount of solar radiation converted into photosynthate (biomass) is a function of a crop-specific radiation-use efficiency. Solar radiation also provides the energy that drives evapotranspiration.

Temperature influences the rates of photosynthesis, respiration and transpiration. Photosynthesis increases with increasing temperature to an optimum and decreases with temperature beyond that point. EPIC takes account of the incidence of days on which temperature stress (heat or cold) occurs. In addition, temperature (described in terms of heat units) determines the rate of plant phenological development and duration of the growing season. Maturity is reached when the crop attains a number of heat units specific to the cultivar. Temperature also determines the rate of evapotranspiration and thus the availability of soil moisture.

Changes in timing or amount of precipitation affect soil moisture supply and crop yield. When atmospheric demand for water exceeds the rate at which the soil can supply it, plant leaves lose turgor and stomata close. Entry of CO_2 to the leaf is inhibited and photosynthesis, crop growth and yield are reduced. In EPIC, each day that atmospheric demand for soil moisture exceeds supply is a water-stress day that reduces potential crop yield by a fixed amount.

Atmospheric humidity modulates evapotranspiration and affects radiation use efficiency in photosynthesis. Stockle and Kiniry (1991) adjusted the radiation use efficiency in EPIC to account for the influence of vapor pressure deficit.

Elevated concentrations of CO_2 ([CO_2]) increase the rate of photosynthesis in C_3 plant species (small grains, legumes, most trees and root crops) grown under controlled conditions and reduce water use in both C_3 and C_4 species (tropical grasses such as corn, sorghum, sugar cane, millet) (see Kimball, 1983; Rosenberg et al. 1990; Kimball et al. 1990 for reviews). In addition, an increasing body of evidence indicates that yield increases due to elevated [CO_2] are *relatively* greater under conditions of heat and moisture stress and, possibly, under nutrient stress as well (Idso and Idso, 1994). In EPIC the effects of rising [CO_2] are expressed through increases in radiation use efficiency. This, among other effects, results in increased leaf area index (LAI) and increases in stomatal resistance that reduce transpiration. The EPIC algorithms that relate LAI and stomatal resistance to photosynthesis and transpiration were altered by Stockle et al. (1992a and 1992b) to accommodate the effects of changes in atmospheric [CO_2].

Nitrogen stress is another important factor that limits crop growth. Temperature and soil moisture conditions affect the rate of nitrogen mineralization. Precipitation determines the amounts of nitrogen lost to the crop by leaching and runoff. Demand for N is affected by the daily rate of plant growth, the phenological stage of growth and the duration of the growing season — all controlled by climate. Nitrogen is applied in our simulations in quantities consistent with typical farming practices in the regions studied. These quantities are not always large enough to preclude the occurrence of some nitrogen stress. Thus climate change affects the number of nitrogen-stress days by altering both the availability and demand for nitrogen.

Water erosion rates were simulated with the Moderate Rate Universal Soil Loss Equation (MUSS; Williams, 1995) while wind erosion was simulated with the Wind Erosion Continuous Simulation Equation (WECS; Williams, 1995). Estimation of runoff (Q) is an essential routine in EPIC to calculate water balance, water erosion, and pollutant transport. The Soil Conservation Service (SCS) method has been for many years the method of choice for calculating Q. Although the method is empirical, it is supported by many years of runoff data and soil characteristics. Recent work by Puurveen et al. (1997) found the method to reproduce runoff events associated with snowmelt processes in northern latitudes. The work reported here used a new subroutine that calculates runoff based on the Green and Ampt infiltration equation. This method offers an physically-based solution to the problem of infiltration and subsequent calculation of runoff by stating the infiltration rate ($f(t)$, mm h^{-1}) to be:

$$f(t) = K\left[\frac{\varphi\Delta\theta}{F(t)} + 1\right]$$

where K is the saturated hydraulic conductivity (mm h^{-1}), φ is the water suction (mm) at the wetting front, $\Delta\theta$ is the increase in water content ($m^3 m^{-3}$), and $F(t)$ is the cumulative infiltration (mm) at time t (h):

$$F(t) = Kt + \varphi\Delta\theta \ln\left(1 + \frac{F(t)}{\varphi\Delta\theta}\right)$$

where Kt is the hydraulic conductivity at time t and the other terms are as previously defined. Solutions for both equations are found by iteration. Although the Green and Ampt approach offers a physically-based solution to the problem of infiltration and subsequent runoff calculation, it is very sensitive to inputs of hydraulic conductivity values from the second soil layer (J.R. Williams, personal communication).

A.2 Agricultural Regions Studied

The primary agricultural regions in each of the three countries were selected for study. A set of representative farms were defined for each of these regions. The process of selection differed from country to country in recognition of the differences in land classification systems, data sources and other local factors. The sources of information used in building EPIC files and for establishing the validity of EPIC yield simulations are shown for the three partner nations in Table II.1.

A.2.1 Canada

Canada, through the cooperating work of Environment Canada and Agriculture and Agri-Food Canada, has adopted an ecosystem framework to provide natural divisions for analysis and ecological monitoring of natural resources (Ecological Stratification Working Group, 1995). This hierarchical approach includes three levels of ecological generalization: ecozones, ecoregions, and ecodistricts.

An *ecozone* is a large area of land characterized in a very general way by various abiotic and biotic factors. Canada was grouped into 15 ecozones (Fig. II.1) based on broad physiographic and ecological similarities (Wicken, 1986).

An *ecoregion* is a part of an ecozone characterized by distinctive regional ecological factors, including climate, physiography, vegetation, soil, water and fauna. A total of 194 ecoregions resulted from the application of this approach. All ecoregions were numbered and named after a prominent biophysical or physiographic feature (e.g. ecoregion #149 is the Boreal Plains ecoregion and extends from Manitoba to Alberta surrounding the Prairie ecozone from the North).

An *ecodistrict* is a part of an ecoregion that is characterized by distinctive combinations of regional landform, local surface form, permafrost distribution, soil development, textural group, vegetation cover/land use classes, range of annual precipitation, and mean temperature. Ecodistricts are also known as Land Resource Areas. The size of an ecodistrict is determined by the regional variability of the defining attributes. Ecodistricts are at least 100,000 ha in size and are designed for use at a map scale of 1:2,000,000.

Finally, each ecodistrict contains a number of soil polygons which, for the most part, follow the existing polygon outlines of the Soil Landscapes of Canada. In a few cases, polygons were re-delineated to accommodate the ecological framework and maintain the desired nesting of the hierarchy. According to the Ecological Stratification Working Group (1995) the "Ecological Land Classification is a cartographic hierarchy supported by more detailed data from the Soil Landscapes of Canada. They will provide a very powerful tool for environmental reporting, particularly since linkage via the soil development attributes can be used to access the NSDB (National Soil Data Base) soil name and soil layer file data.

Table II.1. Sources of information used for building EPIC files on representative farms and for comparing simulated and historic yields.

Country	Climate Data	Soils	Crop Managem ent	Historic Yields	EPIC Parameters
Canada	Environment Canada	Agriculture and Agri-Food Canada National Soils Database (CanSIS)	Agriculture Canada (1994); research reports	Statistics Canada, Provincial county yields	USDA-ARS; Kiniry et al. (1995)
Mexico	Servicio Meteorologico Nacional	INIFAP[†], Experiment Stations, INEGI	INIFAP Exp. Stations	INIFAP Exp. Stations, SAGAR, INEGI	USDA-ARS; INIFAP
United States	NCRS Historical Climate Network; Reek et al. (1992)	State Soil Geographic (STATSGO) Database (USDA-SCS)	The HUMUS Project – TAES/USDA-ARS	National Agricultural Statistics Service Crops County Database	USDA-ARS

[†] INIFAP, Instituto Nacional de Investigaciones Forestales y Agropecuarias; INEGI, Instituto Nacional de Estadística,Geografía e Informática; SAGAR, Secretaría de Agricultura, Ganadería y Desarrollo Rural

A.2.2 The United States

Two types of geographical mapping units were used to develop the mapping structure for agriculture in the United States. The first is the *Major Water Resource Region* of which 18 are identified by USGS maps of the contiguous 48 states (USGS, 1987). These units are identified by a 2-digit number in the legend of Fig. II.2. Another useful geographic unit is the *Land Resource Region (LRR)* classification developed by the Soil Conservation Service (now the Natural Resources Conservation Service) (USDA-SCS, 1981). This classification is based on physiography, soils, vegetation and land-use characteristics. Fig. II.3 shows the geographic distribution of the 20 LRRs in the conterminous U.S. To adequately describe current agriculture and agricultural sensitivity to climatic variability, we superimposed Fig. II.3 on Fig. II.2 so that LRRs are distributed and identifiable within the boundaries of the major water resource region (Fig. II.4). The numbers on the map in Fig. II.5 identify representative farms, the basic unit for EPIC-modeling of plant growth and yield (see section A.3). Corn *(Zea mays.* L) and winter wheat (*Triticum aestivum* L.), the two major U.S. grain crops, are used in the current study. The primary growing regions for these crops are shown for the U.S. in Fig. II.

A.2.3 Mexico

Available data for Mexico permit definition of agro-ecological regions on the basis of latitude, altitude and humidity. Such a classification is shown in Fig. II.7. Twenty three Mexican representative farms are also located in this figure. Three crops are simulated in Mexico—corn, wheat and beans (*Phaseolus vulgaris L.*). The growth of all three crops is simulated under both dryland and irrigated conditions. Fig. II.8 shows the primary Mexican growing regions for corn, wheat and beans, respectively.

The effects of ENSO events on agricultural productivity and natural resources vary from region to region depending on climatic conditions and the types of agriculture practiced. Here we provide a general background on the major agroclimatic regions of Mexico so that the reader will be better able to understand their sensitivity to ENSO events.

The area of the Mexican republic is 1,967,183 km^2. Because of its varied climatic and physiographic conditions, Mexico contains very diverse ecosystems that range from jungles to coniferous and deciduous forest to arid and semiarid xerophitic matorral. The national territory has been divided into three major agroecological zones — the Arid and Semiarid, Temperate, and Tropical regions — taking into account climatic and vegetation features as well as agricultural activities and natural resource utilization (Fig. II.7).

The Arid and Semiarid Zone

Together, the arid and semiarid zones of northern Mexico encompass 95 million hectares or 49% of the nation's total area (COTECOCA, 1994a). The region is characterized by very low and irregular rainfall, ranging from near zero to 350 mm/year) and is distributed during the summer months. The dry season lasts for at least 7 months of the year. Native vegetation cover is less than 70%. The average temperature varies from 15 to 25°C throughout the year. Eighty percent of the Chihuahuan and 65% of the Sonoran deserts are in Mexico. In these (and including the Hidalguense desert) rangeland grasses cover some 24.3 million hectares; xerophytic matorrals cover 62.1 million hectares; forest-chaparral cover 3.5 million hectares; other types of vegetation cover the remaining 5 million hectares. Cattle grazing is the major agricultural activity of the northern region. However, irrigated agriculture is practiced in valleys where dams have been built to collect the runoff occurring from July to October or where aquifers yield enough groundwater for agricultural use. Dryland agriculture is also practiced on marginal lands in this region by poor subsistence farmers at a high risk of crop failure (Fig. II.7).

The Temperate Zone

The temperate climates of Mexico are found in the central part of the country (Fig. II.7), covering approximately 46 million hectares of land (COTECOCA, 1994b). The mean annual temperature ranges between 5 and 18°C, but temperatures below 0°C are common during winter months. Although in tropical latitudes, the *sierras* and internal valleys of this zone have a mild temperate climate during most of the year. Elevation ranges from 1,500 to 2,500 m amsl. Mean annual precipitation ranges from 500 to 2,500 mm, topography being the primary determinant of this distribution. Total annual precipitation tends to increase with elevation. The temperate regions are geographically delimited by the Sierra Madre Oriental, the Neovolcanic Transversal Belt, Sierra Madre Occidental and the Sierra Madre del Sur. Native vegetation in this region consists of deciduous and evergreen forests at medium to high elevations; grasslands and chaparrals dominate the low lands and valleys. Because of its mild climate, large areas of arable land in this region are devoted to the production of annual and perennial crops under both dryland and irrigated conditions. Due to the scarcity of prime land some steep lands are under cultivation and soil erosion on these lands can be serious. Corn, beans and wheat are the major annual crops. Grasslands are used to graze cattle, sheep and goats. Irrigated ryegrass and orchard grass pastures are utilized by cattle and sheep under intensive grazing systems.

The Tropical Zone

The tropical zone includes the Yucatán peninsula and the entire coast of the Gulf of Mexico. It covers most of the Pacific coast of Mexico, as well. The tropical zone covers about 56 million hectares, equivalent to 23.8% of the nation's land (COTECOCA, 1994c), and is sub-divided into dry and humid zones based on climatic conditions and vegetative cover. The Humid Tropics cover 24 million hectares—most of southeastern Mexico. This zone contains 18 distinct deciduous and sub-deciduous tropical forests types. Elevation is about 1,000 m amsl, mean annual temperature is about 20°C and mean annual rainfall is above 1,300 mm. The Dry Tropical zone covers an area of 31.7 million hectares, 16%

of the national territory, and encompasses 24 vegetation types. The ecological regions of the Humid Tropical zone are characterized by the presence of deciduous and sub-deciduous tropical forests at elevations of 2,000 m amsl at most. Mean annual temperature is above 18°C and total annual precipitation varies between 600 and 1,300 mm. Agricultural activities vary from region to region. Intensive mechanized and irrigated agriculture flourishes in the dry northwestern tropical zone, producing crops for export. In the humid southeastern tropical zone corn is the major crop produced by subsistence farmers in a slash-and-burn cropping systems.

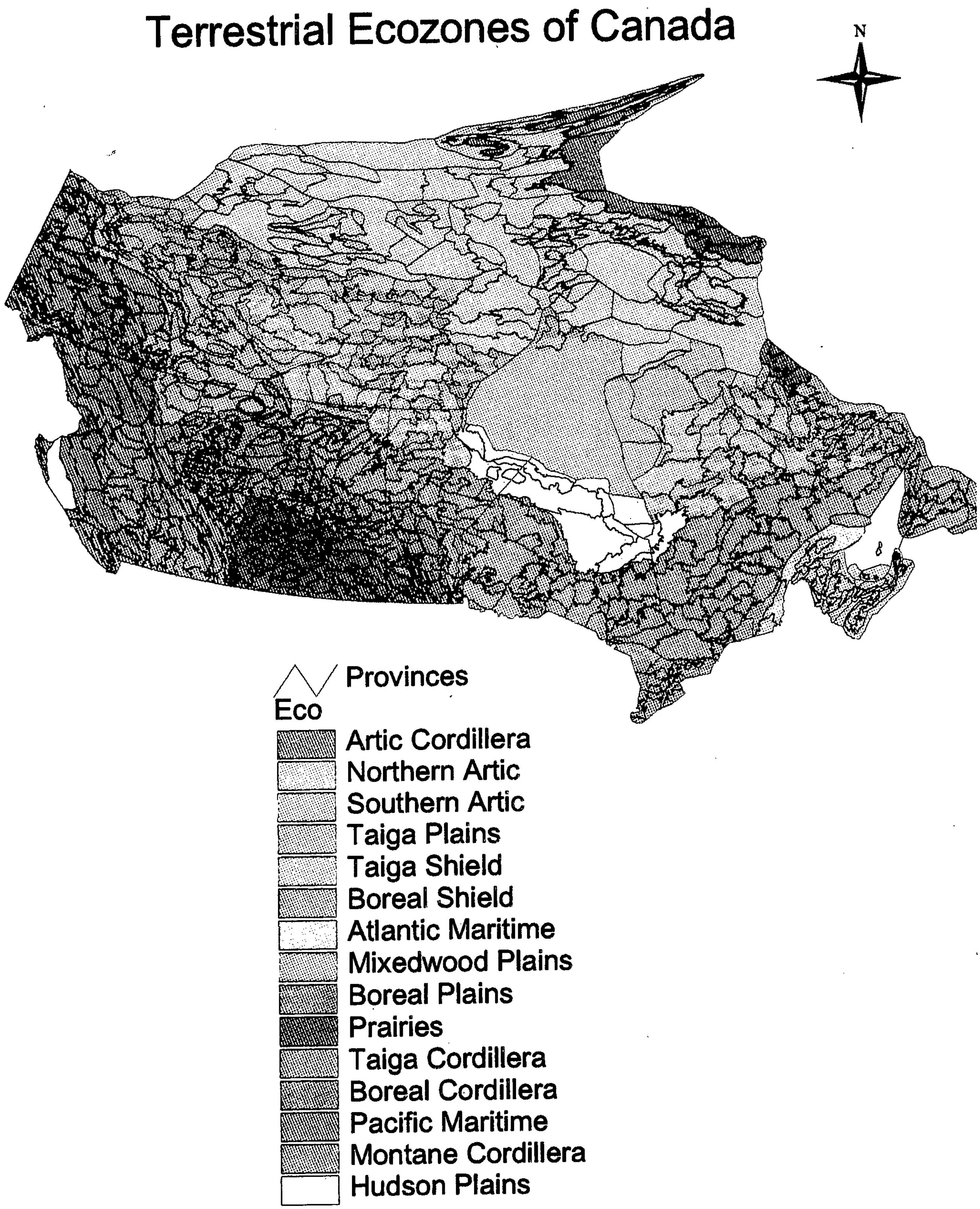


FIG. II.1. Ecoregions in the Canadian Prairie provinces.

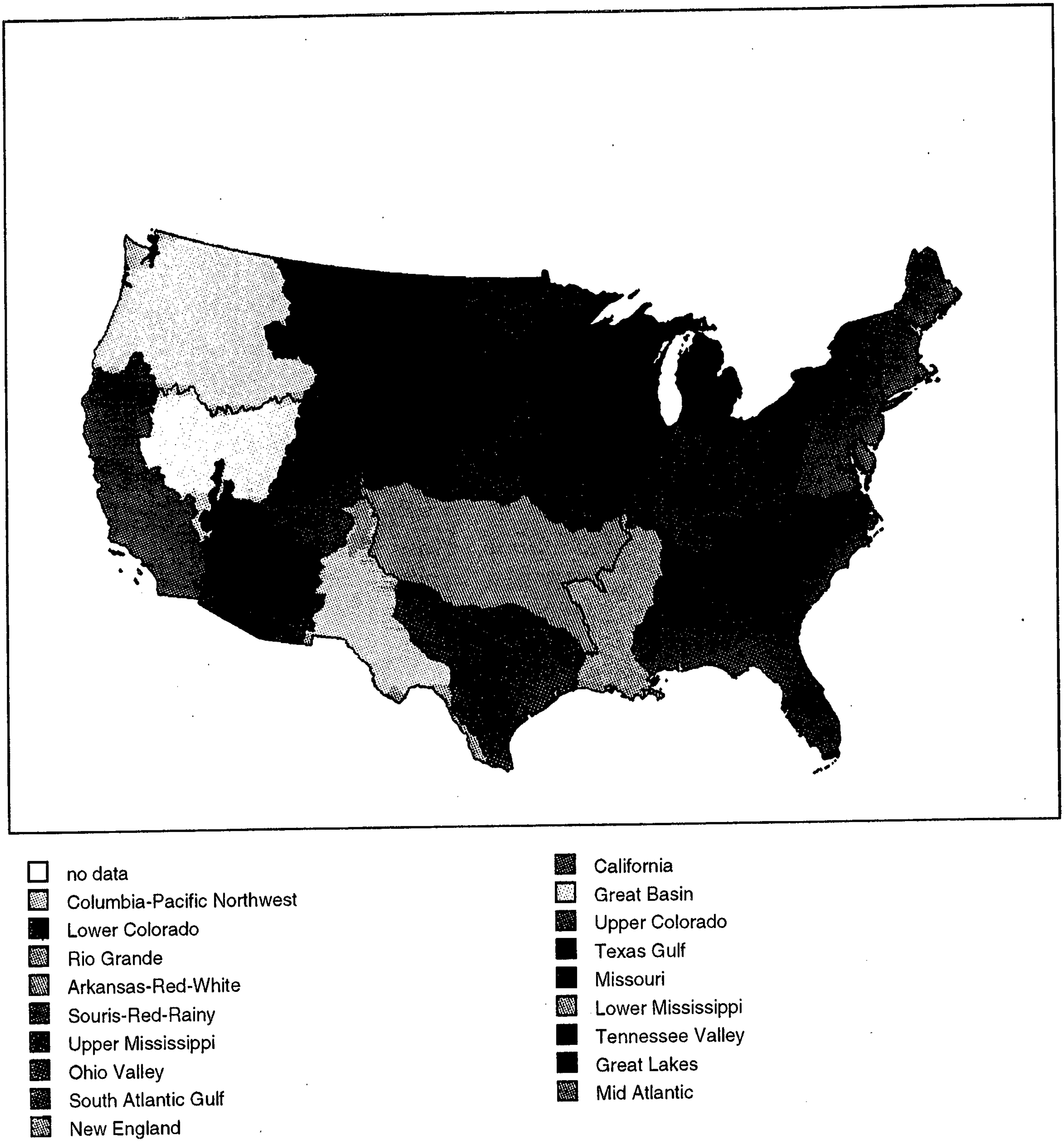
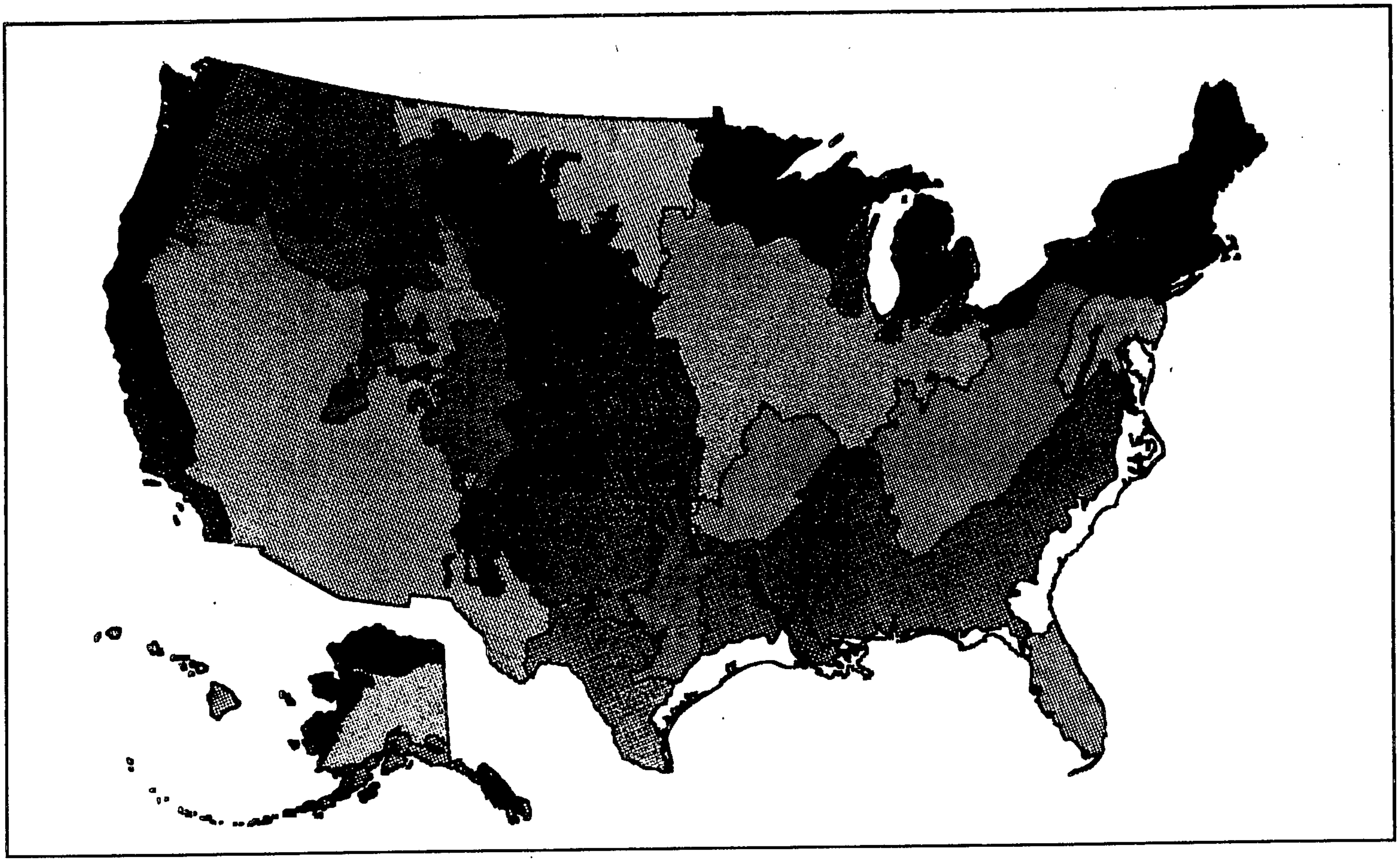


FIG. II.2. Major water resource regions of the conterminous United States.



- no data
- Northwestern Wheat and Range Region
- Western Range and Irrigated Region
- Northern Great Plains Spring Wheat Region
- Central Great Plains Winter Wheat and Range Region
- Southwestern Prairies Cotton and Forage Region
- Lake States Fruit, Truck, and Dairy Region
- East and Central Farming and Forest Region
- South Atlantic and Gulf Slope Cash Crops, Forest, and Livestock Region
- Northern Atlantic Slope Diversified Farming Region
- Florida Subtropical Fruit, Truck Crop, and Range Region
- Southern Alaska Region
- Arctic and Western Alaska Region
- Northwestern Forest, Forage, and Specialty Crop Region
- California Subtropical Fruit, Truck, and Specialty Crop Region
- Rocky Mountain Range and Forest Region
- Western Great Plains Range and Irrigated Region
- Southwest Plateaus and Plains Range and Cotton Region
- Northern Lake States Forest and Forage Region
- Central Feed Grains and Livestock Region
- Mississippi Delta Cotton and Feed Grains Region
- Northeastern Forage and Forest Region
- Atlantic and Gulf Coast Lowland Forest and Crop Region
- Hawaii Region
- Interior Alaska Region

Fig. II.3 Land resource regions of the conterminous U.S.

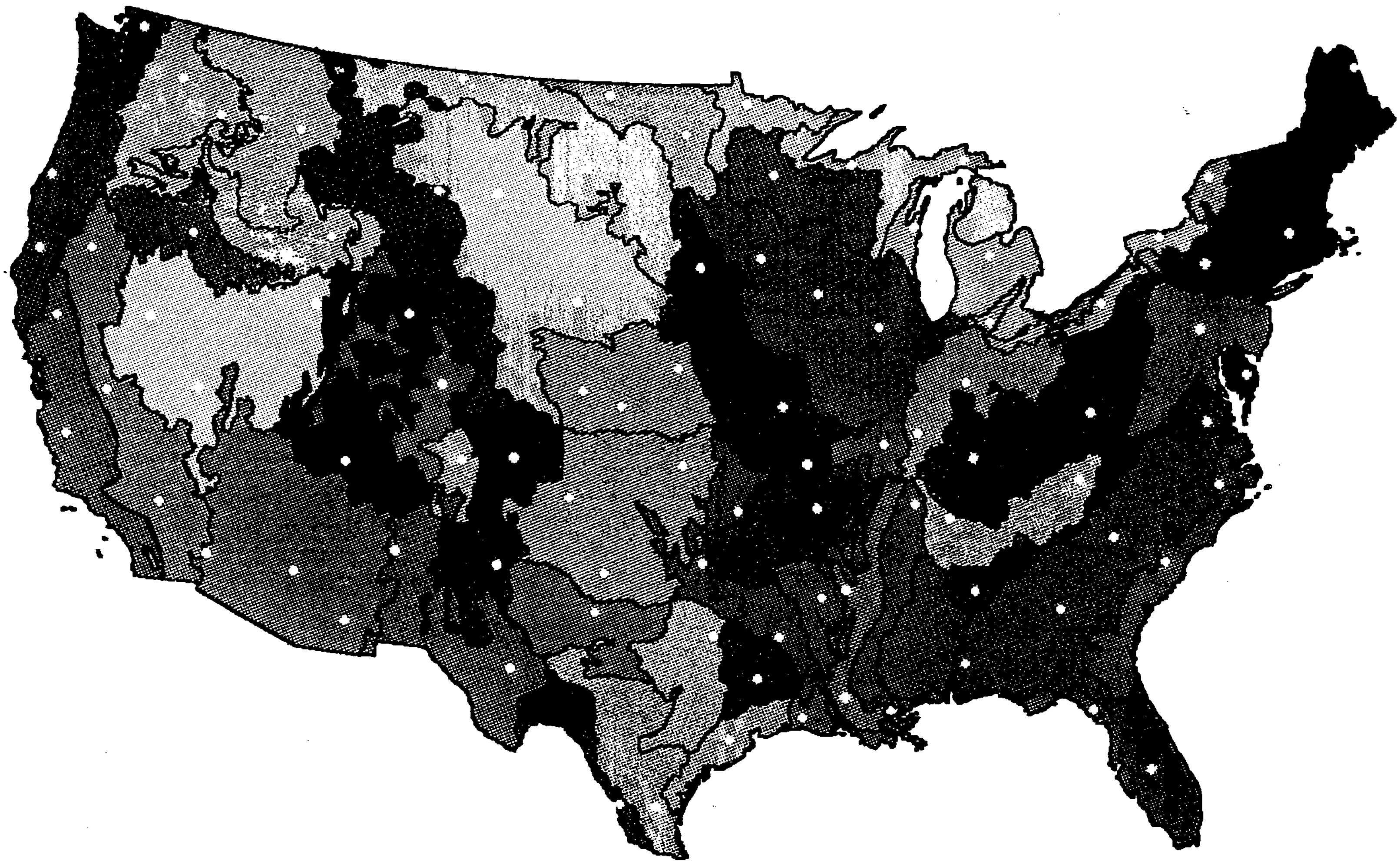


FIG. II.4. Representative Farms in the United States.

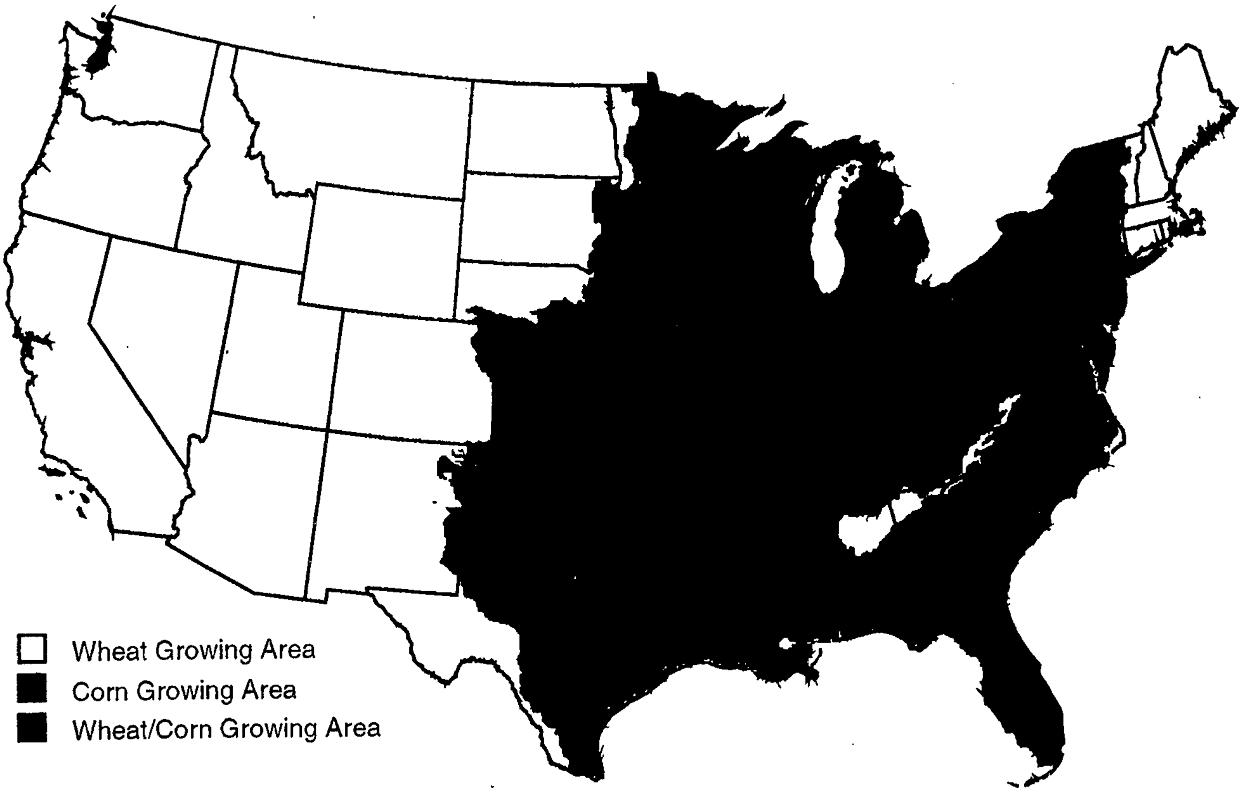


FIG. II.5. Major wheat and corn producing regions of the conterminous United States.

A.3 The Representative Farms

EPIC is a generic model in that, with proper localized inputs, it can represent farming in a variety of situations and locations. Inputs to the model include soils, weather, crop rotation, management practices such as tillage, fertilization, irrigation and other characteristics that typify farms within a given region. The crop growth module within EPIC operates at the scale of a single hectare to simulate enterprises that are called "representative farms."

As Easterling et al. (1992) explains, a representative farm is not an amalgamation of regionally averaged production practices, farm structure characteristics and the like. Rather, it is a description of a cohesive, functional farm enterprise, which typifies most of the actual farms in its particular region. The farm may use more or less fertilizer, irrigation water or other inputs than the average, and it may be more or less productive than the regional average but, as a functional entity, a representative farm should capture the complex nature of most farms in the surrounding region. The continental distribution of representative farms is shown in Fig. II.8.

In this study the representative farms tend to be more productive than the "average" farm since inputs are optimized (within reason) so that climate effects on yields will not be obscured by other factors. Sources of some of the input data used in EPIC modeling of the representative farms were identified in Table II.1.

A.3.1 Canadian Representative Farms

The selection and building of the modeling units for the study of ENSO variability on agricultural production and natural resources in Canada followed the approach used by Rosenberg (ed.) (1993) in the MINK study—an integrated assessment of how a return of the 1930s 'dustbowl' climate might affect the economy of the Missouri-Iowa-Nebraska-Kansas region. A total of 51 representative farms were assembled across the agricultural regions of Canada. The initial selection and concept testing was done for the province of Alberta. One or two ecodistricts were selected for each agriculturally important ecoregion. Each ecodistrict contained a proportionally dominant soil series that appeared not only in that ecodistrict but in other ecodistricts within the ecoregion. Each of these regionally-important soil series were then associated with characteristic landscape features such as slope, length and gradient. A total of 14 soil series (the soils component of the representative farm) was finally selected in close consultation with soil scientist W. Pettapiece of Agriculture and Agri-Food Canada. The procedure was then extended to the other two Prairie Provinces (23 soil series, 14 in Saskatchewan and 9 in Manitoba), eastern and Atlantic Canada (12 soil series) and British Columbia (2 soil series).

Soil layer and landscape properties for the 37 series in the Prairie Provinces were extracted from a digital database in EPIC format previously constructed and used to assess the impact of agricultural policies on soil degradation (Bouzaher et al., 1994; Izaurralde et al., 1996; and Lakhsminarayan et al., 1996). Soil layer and landscape properties for the other 14 series outside the Prairie Provinces were obtained from the provincial soil-survey scientists of Agriculture and Agri-Food Canada and complemented from published soil survey reports.

Canadian farmers grow a wide variety of crops for internal consumption and for export. Dominant crops in the Prairie Provinces are spring wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.) and canola (*Brassica napus and B. campestris*). Other important annual crops are corn (*Zea mays* L.) in British Columbia, Manitoba, Ontario and Quebec. Potato (*Solanum tuberosum* L.) is a major crop in three of the Atlantic Provinces (New Brunswick, Nova Scotia and Prince Edward Island) and also in British Columbia. We elected to model these crops arranging them in "simplified" but realistic crop rotations. Other ecological-census (Haugen-Kozyra et al., 1996) or regional-expert (Agriculture Canada, 1994) based approaches have been proposed and used in Canada. Following any of them would have meant a significant increase in the number of computer runs considering that for each of the 51 representative farms a total of five climatic scenarios had to be simulated (see section IIB).

The single crop rotation selected for the Prairie Provinces was canola-barley-wheat. For the two British Columbia farms the rotation was potato-corn-corn. In the two Ontario farms the rotation was corn-soybean. The Quebec rotation was corn-barley-barley. The rotation in the three Atlantic Provinces was potato-barley-barley. Details of the representative farms, their locations, soils and climates were given in Table II.2. Additional details and examples of management applied to these farms in the EPIC modeling are given for two farms in Appendix 1.

A.3.2 United States Representative Farms

A total of 92 representative farms were designed and distributed across the 48 conterminous United States. These farms represent different land areas formed by overlaying the Land Resource Regions by the Major River Basins (Fig. II.5). From the set of 92 representative farms, 66 were selected for use in this study to represent the major growing regions for corn and winter wheat. Their locations, elevations, soils and climates are listed in Table II.3 as are the crop(s) modeled on each farm. Unlike the situation in Canada, the major grain crops are more frequently grown continuously rather than in rotations in the United States. Additional details on the management inputs to EPIC for the U.S. farms are given in Appendix 1.

A.3.3 The Mexican Representative Farms

ENSO impacts on the productivity of corn, wheat and beans were studied in Mexico. Corn is grown in Mexico on 8.6 million hectares; there are 2.8 million hectares of beans and 993 thousand hectares of wheat. These crops are grown on more than 4.3 million farms (Fig. II.7) (INEGI, 1991).

A total of 60 agricultural production systems — representative farms — were designed throughout the country, based on available information of management practices and historic records of yields for the above-mentioned crops. These farms represent 23 locations in 22 States within the eight major agroecological regions of the country. Every selected farm was designed to be representative of the dominant production systems in its regions. Fig. II.6 shows the location of the 23 representative farms and Fig. II.7 indicates the distribution of corn, wheat, and bean culture in Mexico. Dryland subsistence production systems and irrigated high-input technology production systems are represented. ENSO effects on crop productivity were evaluated for the farms listed in Table II.4.

The representative farms were located between 14-32° N latitude and between, 96 and 115° W longitude. Their elevations ranged from mean sea level to 2250 m amsl. Precipitation varied from an arid 76 mm per annum in Baja California to a tropical humid 2243 mm per annum in Tabasco State. Mean annual temperature ranges from 10 to 27°C. Nine major soils types were represented. Crop management practices varied between regions according to local climate, soils and available resources including water for irrigation. Basic information on soils and crop management practices was provided by local researchers of the Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias (INIFAP).

Details of the management and other data input to operate EPIC are given in Appendix 1.

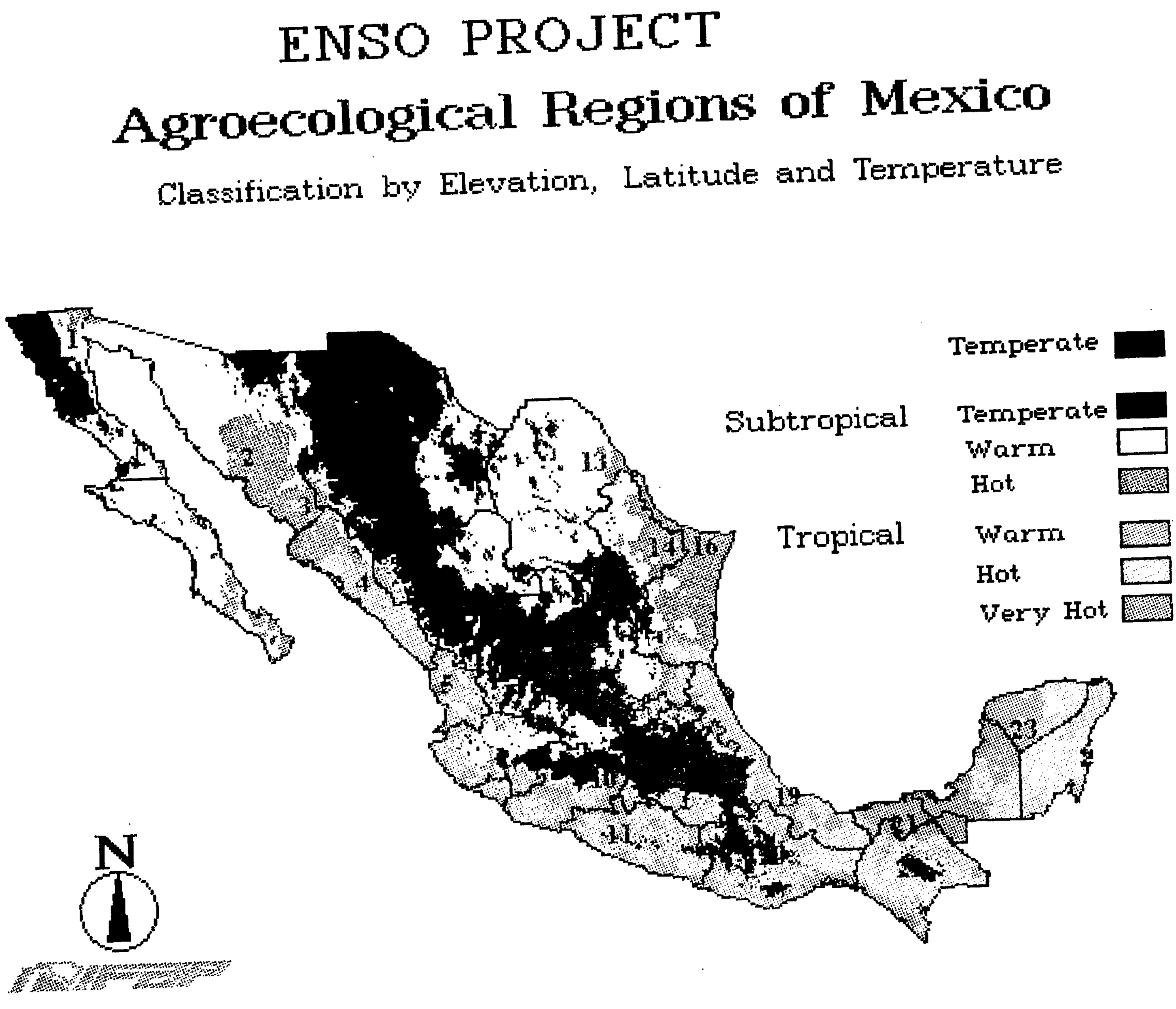


Fig. II.6. Mexican agroecological regions with representative farms.

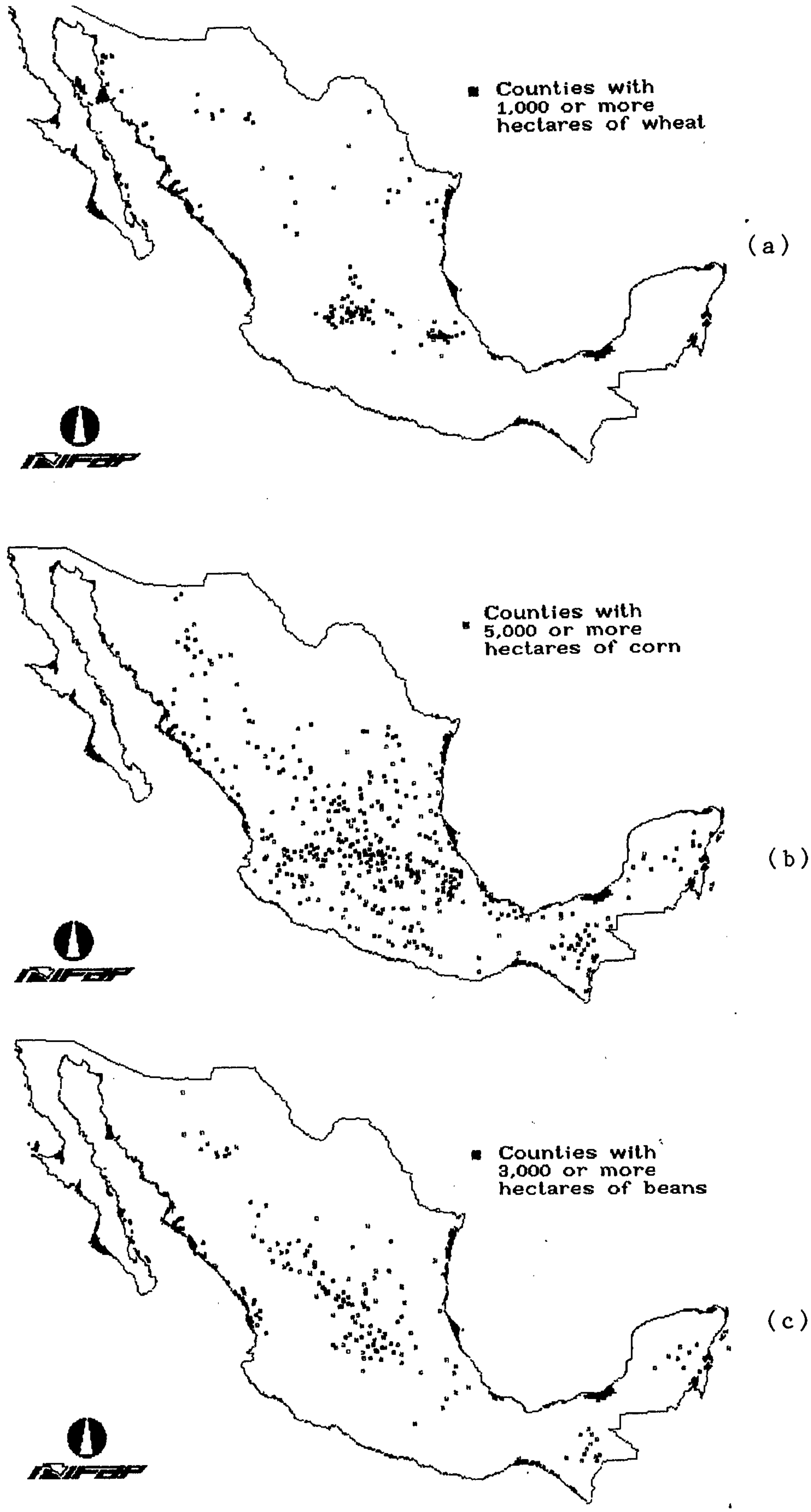


Fig. II.7. Major growing regions in Mexico for (a) wheat, (b) corn, and (c) beans

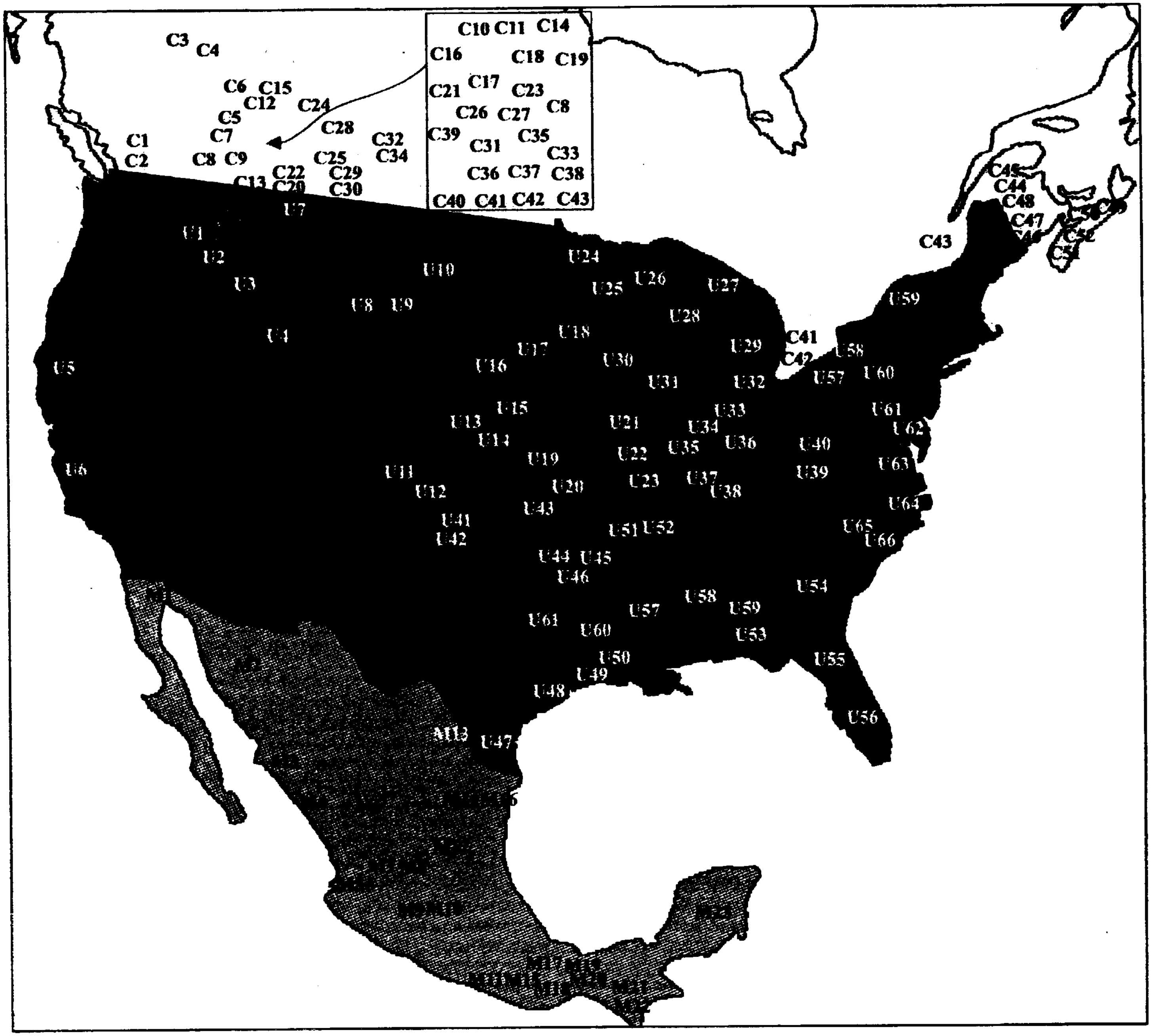


FIG. II.8. Distribution of the representative farms modeled in the three participating

Table II.2. Representative farms in Canada, their locations, soils, baseline climate and crops modeled.

Farm	Province	Latitude	Longitude	Elevation	Soil Order	Temperature				Precipitation				Crops Modeled		
						DJF	MAM	JJA	SON	DJF	MAM	JJA	SON			
		°N	°W	m amsl		°C	°C	°C	°C	mm	mm	mm	mm			
C1	B. Columbia	49.2	123.1	3	Aquoll	3.7	9.0	16.5	10.0	451	246	119	347	potato	corn	
C2	B. Columbia	49.2	121.9	13	Aquoll	3.4	9.7	17.5	11.0	714	405	195	526	potato	corn	
C3	Alberta	55.2	119.4	692	Boralf	-11.8	2.5	14.3	2.7	85	80	201	98	canola	barley	wheat
C4	Alberta	52.5	113.7	834	Boralf	-11.6	3.0	14.9	3.3	49	82	224	79	canola	barley	wheat
C5	Alberta	53.5	113.5	651	Boralf	-12.4	2.8	15.0	2.9	57	79	246	82	canola	barley	wheat
C6	Alberta	51.8	114.1	835	Boroll	-9.6	2.9	14.6	3.7	59	100	227	93	canola	barley	wheat
C7	Alberta	49.6	112.8	940	Boroll	-6.6	5.3	17.3	6.2	53	113	156	77	canola	barley	wheat
C8	Alberta	49.6	112.8	940	Boroll	-6.6	5.3	17.3	6.2	53	113	156	77	canola	barley	wheat
C9	Alberta	51.1	114.0	638	Boroll	-8.1	3.7	15.3	4.4	35	91	195	77	canola	barley	wheat
C10	Alberta	53.5	113.5	651	Boroll	-12.4	2.8	15.0	2.9	57	79	246	82	canola	barley	wheat
C11	Alberta	53.5	113.5	651	Boroll	-12.4	2.8	15.0	2.9	57	79	246	82	canola	barley	wheat
C12	Alberta	50.3	111.1	827	Boroll	-9.6	5.3	18.3	5.7	50	81	128	67	canola	barley	wheat
C13	Alberta	50.3	111.1	827	Natriboroll	-9.6	5.3	18.3	5.7	50	81	128	67	canola	barley	wheat
C14	Alberta	54.4	110.2	541	Boralf	-15.1	2.5	15.8	2.5	55	79	223	77	canola	barley	wheat
C15	Alberta	50.0	110.7	717	Boroll	-8.7	5.8	18.6	6.0	44	84	129	66	canola	barley	wheat
C16	Alberta	53.5	112.0	572	Boroll	-14.4	2.1	15.3	2.5	46	68	217	72	canola	barley	wheat
C17	Saskatchewan	52.8	108.2	548	Boroll	-15.4	2.5	16.9	3.1	50	77	182	61	canola	barley	wheat
C18	Saskatchewan	50.3	107.6	817	Cryert	-11.2	3.6	17.2	4.3	57	89	153	66	canola	barley	wheat
C19	Saskatchewan	50.3	107.6	817	Boroll	-11.2	3.6	17.2	4.3	57	89	153	66	canola	barley	wheat
C20	Saskatchewan	52.8	108.2	548	Boroll	-15.4	2.5	16.9	3.1	50	77	182	61	canola	barley	wheat
C21	Saskatchewan	50.3	107.6	817	Boroll	-11.2	3.6	17.2	4.3	57	89	153	66	canola	barley	wheat
C22	Saskatchewan	53.2	105.6	428	Boralf	-17.6	1.3	16.2	2.0	48	81	198	78	canola	barley	wheat
C23	Saskatchewan	53.2	105.6	428	Boroll	-17.6	1.3	16.2	2.0	48	81	198	78	canola	barley	wheat
C24	Saskatchewan	51.3	105.9	501	Boroll	-14.1	3.0	17.8	4.1	50	100	175	84	canola	barley	wheat
C25	Saskatchewan	50.4	104.6	577	Cryert	-14.4	3.0	17.8	3.8	44	87	165	68	canola	barley	wheat
C26	Saskatchewan	52.8	104.6	428	Boroll	-16.9	1.1	16.4	2.4	54	81	183	87	canola	barley	wheat
C27	Saskatchewan	52.8	104.6	428	Boroll	-16.9	1.1	16.4	2.4	54	81	183	87	canola	barley	wheat
C28	Saskatchewan	50.5	103.6	577	Boroll	-14.1	3.0	17.8	4.1	50	100	175	84	canola	barley	wheat
C29	Saskatchewan	49.7	103.9	572	Natriboroll	-13.3	3.6	18.2	4.5	49	98	164	75	canola	barley	wheat
C30	Saskatchewan	51.3	102.4	372	Boroll	-16.2	1.7	17.0	3.1	58	97	193	91	canola	barley	wheat
C31	Manitoba	52.1	101.2	304	Boroll	-16.6	1.6	17.2	3.2	67	104	213	113	canola	barley	wheat
C32	Manitoba	49.9	100.0	473	Boroll	-16.2	2.2	17.4	3.5	54	102	206	88	canola	barley	wheat
C33	Manitoba	51.1	100.0	304	Boroll	-16.0	1.8	17.3	3.7	56	109	210	117	canola	barley	wheat
C34	Manitoba	49.9	98.3	409	Boroll	-15.0	2.9	18.4	4.7	65	123	231	108	canola	barley	wheat
C35	Manitoba	49.9	98.3	409	Boroll	-15.0	2.9	18.4	4.7	65	123	231	108	canola	barley	wheat
C36	Manitoba	49.2	98.1	270	Boroll	-13.9	3.7	19.0	5.5	61	135	213	110	canola	barley	wheat
C37	Manitoba	49.9	97.2	239	Boroll	-16.1	2.7	18.3	4.4	53	120	232	103	canola	barley	wheat
C38	Manitoba	49.9	97.2	239	Udert	-16.1	2.7	18.3	4.4	53	120	232	103	canola	barley	wheat
C39	Manitoba	49.5	96.8	239	Udoll	-15.7	2.8	18.1	4.4	56	114	226	112	canola	barley	wheat

Table II.2. (continued) Representative farms in Canada, their locations, soils, baseline climate and crops modeled.

Farm	Province	Latitude	Longitude	Elevation	Soil Order	Temperature				Precipitation				Crops Modeled	
						DJF	MAM	JJA	SON	DJF	MAM	JJA	SON		
C40	Ontario	42.3	83.0	360	Ochrept	-3.7	8.0	21.1	10.9	180	228	267	215	corn	Soybean
C41	Ontario	42.3	83.0	360	Udalf	-3.7	8.0	21.1	10.9	180	228	267	215	corn	Soybean
C42	Quebec	45.5	73.8	100	Aquept	-8.8	5.4	19.4	8.1	202	210	268	254	corn	Barley
C43	N. Brunswick	45.9	66.5	140	Umbrept	-8.3	4.1	17.9	7.1	295	265	272	295	potato	Barley
C44	N. Brunswick	45.9	66.5	140	Boralf	-8.3	4.1	17.9	7.1	295	265	272	295	potato	Barley
C45	N. Brunswick	46.1	64.7	130	Boroll	-7.6	3.1	17.0	7.2	340	307	279	297	potato	Barley
C46	N. Brunswick	46.1	64.7	130	Umbrept	-7.6	3.1	17.0	7.2	340	307	279	297	potato	barley
C47	N. Brunswick	46.1	64.7	130	Humod	-7.6	3.1	17.0	7.2	340	307	279	297	potato	barley
C48	Prince Ed. Is.	46.4	63.8	76	Humod	-6.6	2.9	17.3	8.3	283	242	250	277	potato	barley
C49	Prince Ed. Is.	46.4	63.8	76	Humod	-6.6	2.9	17.3	8.3	283	242	250	277	potato	barley
C50	Nova Scotia	45.1	64.5	122	Humod	-4.8	4.4	17.5	8.9	299	241	251	292	potato	barley
C51	Nova Scotia	45.2	63.0	122	Udalf	-5.4	3.9	16.9	8.3	345	276	294	327	potato	barley

Table II.3. Representative farms in the United States, their locations, soils, baseline climate and crops modeled.

Farm	State	Latitude	Longitude	Elevation	Soil Order	Temperature DJF	Temperature MAM	Temperature JJA	Temperature SON	Precipitation DJF	Precipitation MAM	Precipitation JJA	Precipitation SON	Crops Modeled	
		°N	°W	m amsl		°C	°C	°C	°C	mm	mm	mm	mm		
U1	Washington	47.3	119.5	384	Alfisol	-0.7	10.0	20.8	10.0	80	53	29	58	wheat	
U2	Washington	46.5	117.6	579	Aridisol	1.8	10.3	21.1	11.2	143	105	62	97	wheat	
U3	Montana	46.5	114.1	1027	Mollisol	-3.0	6.5	16.9	6.6	93	99	103	86	wheat	
U4	Idaho	43.5	112.1	1442	Aridisol	-5.5	6.5	18.8	7.4	68	87	74	72	wheat	
U5	California	39.5	122.2	43	Alfisol	8.3	15.4	24.4	17.0	241	102	10	115	wheat	
U6	California	36.2	120.7	686	Vertisol	8.8	13.4	21.3	15.8	215	106	3	81	wheat	
U7	Montana	48.8	107.4	695	Entisol	-9.7	5.6	19.6	6.4	26	84	138	52	wheat	
U8	Montana	45.3	107.9	975	Mollisol	-3.0	8.6	21.4	9.5	54	139	115	95	wheat	
U9	Montana	45.4	105.4	924	Inceptisol	-6.0	6.7	20.0	7.2	36	119	128	75	wheat	
U10	North Dakota	46.4	101.6	762	Mollisol	-10.3	5.4	20.0	6.6	30	131	192	75	wheat	
U11	Colorado	37.7	103.9	1277	Alfisol	-0.2	11.0	23.4	11.9	21	80	128	50	wheat	
U12	Oklahoma	36.6	101.7	1271	Mollisol	1.0	10.7	22.2	12.1	27	117	197	87	wheat	corn
U13	Kansas	39.8	101.4	1024	Mollisol	-1.0	10.2	23.3	11.5	33	164	205	84	wheat	corn
U14	Kansas	39.4	99.8	771	Mollisol	-0.8	11.4	24.5	12.3	35	175	219	103	wheat	corn
U15	Nebraska	40.5	97.6	497	Mollisol	-2.9	10.9	23.7	11.8	52	236	267	174	wheat	corn
U16	Nebraska	42.4	101.8	893	Entisol	-4.3	8.5	22.3	9.8	33	164	226	96	wheat	
U17	South Dakota	43.5	96.7	433	Mollisol	-8.5	7.7	21.5	8.6	46	181	255	148	wheat	corn
U18	Minnesota	43.8	94.2	338	Mollisol	-9.2	7.2	21.2	8.6	63	205	314	176	wheat	corn
U19	Kansas	37.7	97.4	402	Mollisol	0.2	13.2	26.0	14.3	76	236	280	203	wheat	corn
U20	Oklahoma	36.3	95.3	351	Mollisol	3.4	15.4	26.1	16.3	161	317	293	314	wheat	corn
U21	Missouri	39.4	93.5	229	Mollisol	-1.3	12.5	24.4	13.5	109	280	324	281	wheat	corn
U22	Missouri	37.7	92.7	384	Alfisol	0.8	12.9	23.6	13.8	178	315	286	294	wheat	corn
U23	Arkansas	36.3	92.4	244	Alfisol	3.2	14.8	25.2	15.5	248	354	259	307	wheat	corn
U24	Minnesota	48.4	94.6	360	Entisol	-14.7	3.1	17.4	5.0	41	121	276	150		corn
U25	Minnesota	46.3	93.5	305	Alfisol	-10.8	5.9	19.8	7.2	66	178	309	180		corn
U26	Michigan	46.5	90.2	351	Alfisol	-10.3	4.5	18.1	6.8	109	193	300	240		corn
U27	Michigan	46.3	85.5	271	Alfisol	-8.3	3.4	16.6	6.7	170	175	247	242		corn
U28	Wisconsin	44.5	87.5	287	Alfisol	-6.0	6.2	19.5	9.6	105	202	260	218		corn
U29	Michigan	43.4	84.7	226	Alfisol	-5.0	7.3	20.4	9.9	122	201	236	228		corn
U30	Iowa	42.7	91.9	314	Mollisol	-7.3	8.3	21.3	9.7	83	239	329	212	wheat	corn
U31	Illinois	41.6	89.6	216	Mollisol	-4.9	9.8	22.6	11.3	114	262	308	232	wheat	corn
U32	Indiana	41.4	85.0	277	Alfisol	-3.9	8.8	21.2	11.0	151	250	269	221		corn
U33	Indiana	39.7	86.3	241	Alfisol	-2.7	10.3	22.3	12.1	184	287	291	225		corn
U34	Illinois	38.4	88.4	137	Alfisol	-0.7	12.4	23.8	13.6	202	313	282	244		corn
U35	Illinois	38.1	89.7	140	Alfisol	0.5	13.0	24.5	14.0	221	328	288	263	wheat	corn
U36	Kentucky	37.5	86.3	235	Alfisol	1.8	13.5	23.8	14.4	312	371	337	288		corn
U37	Tennessee	36.3	88.7	128	Alfisol	2.7	14.6	24.9	15.3	332	391	328	308		corn
U38	Tennessee	35.8	87.5	18	Alfisol	3.5	14.5	24.3	15.2	346	411	305	303		corn
U39	Tennessee	36.5	82.4	463	Ultisol	2.0	12.5	22.2	13.5	274	295	308	242		corn

Table II.3. (continued) Representative farms in the United States, their locations, soils, baseline climate and crops modeled.

Farm	State	Latitude	Longitude	Elevation	Soil Order	Temperature DJF	Temperature MAM	Temperature JJA	Temperature SON	Precipitation DJF	Precipitation MAM	Precipitation JJA	Precipitation SON	Crops Modeled	
U40	West Virginia	38.4	81.6	476	Alfisol	0.6	11.6	21.7	12.8	259	318	355	279		corn
U41	Texas	34.4	100.3	1061	Alfisol	5.3	16.6	27.2	17.0	48	132	211	143	wheat	corn
U42	Texas	33.3	100.6	613	Alfisol	5.9	17.0	27.3	17.3	58	141	197	164	wheat	corn
U43	Oklahoma	34.8	96.7	390	Alfisol	4.4	16.2	26.7	16.9	119	286	237	261	wheat	corn
U44	Texas	32.6	96.3	137	Vertisol	7.3	17.8	27.9	19.1	220	305	198	281	wheat	corn
U45	Louisiana	32.6	93.8	52	Ultisol	9.3	18.6	27.9	19.3	318	341	228	252	wheat	corn
U46	Texas	31.3	94.7	88	Ultisol	9.8	19.4	27.6	19.9	274	288	246	301		corn
U47	Texas	27.5	98.3	116	Mollisol	14.0	22.7	28.9	23.0	105	143	210	226		corn
U48	Texas	29.5	95.8	21	Alfisol	11.8	20.4	28.1	21.6	241	265	286	335		corn
U49	Louisiana	30.1	93.2	3	Vertisol	11.2	20.0	27.5	21.0	342	311	472	352		corn
U50	Louisiana	30.7	91.7	9	Vertisol	11.3	19.6	27.1	19.8	407	382	338	281		corn
U51	Arkansas	33.7	92.4	85	Ultisol	6.4	17.1	26.4	17.4	334	361	297	317		corn
U52	Arkansas	33.9	91.5	27	Ultisol	6.0	16.9	26.4	17.2	378	390	281	296		corn
U53	Alabama	31.4	87.4	67	Ultisol	9.3	18.5	26.3	19.0	410	389	506	321		corn
U54	Georgia	32.7	83.8	299	Ultisol	7.7	17.2	25.8	17.8	356	352	318	242		corn
U55	Florida	29.6	83.1	15	Ultisol	12.3	19.8	26.8	21.2	309	291	596	271		corn
U56	Florida	27.6	81.5	46	Oxisol	16.4	22.0	27.3	23.6	181	224	549	274		corn
U57	Pennsylvania	41.5	80.5	320	Alfisol	-2.8	8.7	20.5	11.2	181	253	296	248		corn
U58	New York	43.1	77.7	18	Alfisol	-3.5	7.6	20.4	10.9	192	214	244	260		corn
U59	New York	44.6	75.2	125	Inceptisol	-8.4	5.5	19.0	8.3	190	218	285	276		corn
U60	New York	42.1	76.1	290	Alfisol	-5.1	6.5	19.0	9.1	176	232	269	243		corn
U61	Pennsylvania	40.2	76.9	104	Alfisol	-1.0	10.4	22.4	12.5	216	274	278	257		corn
U62	Delaware	38.6	75.5	15	Ultisol	2.6	11.7	23.2	15.1	270	279	319	251		corn
U63	Virginia	37.5	77.3	49	Ultisol	3.8	14.1	24.6	15.6	262	273	329	266		corn
U64	North Carolina	35.6	77.4	9	Ultisol	5.7	15.5	25.1	16.7	285	285	382	250		corn
U65	South Carolina	34.6	81.5	155	Ultisol	6.7	16.5	25.6	17.1	309	303	341	250		corn
U66	South Carolina	33.7	79.8	15	Ultisol	7.5	17.1	25.9	17.8	283	285	415	232		corn

Table II.4 -- Representative farms in Mexico, their locations, soils, baseline climate and crops modeled.

Farm	State	Latitude	Longitude	Elevation	Soil Order	Temperature				Precipitation				Crops Modeled		
						DJF	MAM	JJA	SON	DJF	AM	JJA	SON			
		°N	°W	m amsl		°C	°C	°C	°C	mm	mm	mm	mm			
M1	Baja California	32.6	115.5	3	Regosol	13.6	20.3	31.4	23.2	33	8	19	26		wheat	
M2	Sonara	29.1	111.0	211	Vertisol	16.9	23.2	31.6	25.7	55	13	177	82	corn	wheat	bean
M3	Sinaloa	26.4	108.6	84	Vertisol	17.4	22.6	30.0	25.6	75	17	365	169	corn	wheat	
M4	Sinaloa	24.8	107.4	40	Haploborall	19.2	22.9	28.6	25.8	68	8	378	225	corn		
M5	Nayarit	21.8	105.2	39	Vertisol	23.8	26.0	29.6	28.7	76	17	852	447	corn		bean
M6	Durango	24.0	104.7	1889	Xerosol	12.4	18.7	21.7	17.6	37	30	271	179	corn		bean
M7	Aguascalientes	22.2	102.3	1912	Xerosol	12.4	18.2	20.0	16.6	36	44	262	123	corn	wheat	bean
M8	Zacatecas	23.0	102.7	1153	Xerosol	10.7	16.8	18.9	15.5	38	33	241	129		wheat	bean
M9	Jalisco	20.6	102.7	1420	Regosol	17.8	22.7	23.2	21.5	42	43	567	211	corn		
M10	Michoacan	20.1	101.5	1848	Vertisol	15.6	20.9	20.3	18.5	35	59	501	219	corn	wheat	
M11	Guerrero	18.5	101.4	200	Cambisol	27.6	32.0	29.5	29.0	27	23	450	179	corn		bean
M12	Guanajuato	23.5	100.8	1765	Vertisol	13.6	19.2	20.1	17.4	44	71	394	156	corn	wheat	bean
M13	Coahuila	28.3	100.8	388	Xerosol	14.8	23.8	29.2	23.1	38	146	155	147		wheat	
M14	Nuevo Leon	25.2	99.8	309	Vermodoll	14.1	23.2	28.2	22.3	73	210	317	363	corn	wheat	
M15	Morelos	18.5	99.3	1200	Vertisol	23.7	28.7	25.8	24.2	17	85	523	233	corn		
M16	Tamaulipas	26.0	98.1	28	Vermudoll	15.0	23.2	28.3	24.2	109	153	160	192	corn	wheat	bean
M17	Est. de Mexico	19.5	98.9	2250	Vertisol	13.0	17.5	17.5	15.6	25	101	334	149	corn		bean
M18	Puebla	18.9	97.7	2055	Regosol	13.8	18.2	18.4	16.9	24	123	269	161	corn		bean
M19	Veracruz	19.0	96.2	45	Vertisol	22.1	27.0	27.5	25.7	42	95	894	397	corn		bean
M20	Oaxaca	17.2	96.8	1450	Luvisol	16.6	21.0	19.9	18.5	14	147	380	180	corn		bean
M21	Tabasco	17.8	93.4	100	Fluvisol	22.4	27.1	27.5	25.7	366	190	859	829	corn		bean
M22	Chiapas	16.7	93.4	838	Fluvisol	21.5	25.7	25.4	23.9	39	85	468	250	corn		bean
M23	Yucatan	20.5	89.7	11	Luvisol	21.7	26.0	26.0	23.8	58	115	390	298	corn		

A.4 Validation of the EPIC Model for the Study of ENSO effects.

EPIC has been shown in a number of studies to reproduce long-term means and variability of actual crop yields in portions of North America. For example, Rosenberg et al. (1992) found good agreement of EPIC and actual yields for corn, wheat, sorghum, soybeans and pasture in the MINK region of the U.S.. Brown and Rosenberg (1997, submitted) found that EPIC-simulated yields of corn and winter wheat on dryland agreed well with actual long-term yields throughout their primary and secondary growing regions in the U.S.. Under generalized management, Izaurralde et al. (1992) found EPIC yields to agree well with ecodistrict-level yields reported by the Alberta Hail and Crop Insurance Corporation. Under highly-detailed management (e.g., actual fertilizer inputs, on-site weather), Izaurralde et al. (1994) reported good agreement between simulated and actual yields obtained on an artificial-erosion experiment on a Cryoboroll soil similar to that of farm C11. For other examples of tests of the crop-growth model in EPIC across a wide range of environments and crops, see Kiniry et al. (1990, 1995), Moulin et al. (1993), and Touré et al (1994).

However, if EPIC is to provide useful information on the sensitivity of North American crop yields to ENSO-driven interannual climatic variability, it must first be demonstrated that the model is able to mimic the actual interannual variability in a time sequence of yields. This has been done in each of the three partner countries on a subset of the representative farms.

A.4.1 Canada

Historic crop-district yields (1968 - 1994) for wheat and barley were extracted from the annual reports published by Statistics Canada for Alberta, Saskatchewan, and Manitoba agriculture. For potato crops grown in Atlantic Canada and British Columbia the annual yields were extracted from the Statistics Canada, Fruit & Vegetable Production series. After summarizing, the yield data by year and crop districts we then proceeded to calculate yield averages by ENSO year. All modeled crops in Canada are spring grown and, as is explained in section II.B, the calendar-year yield (e.g., 1988) was matched with the ENSO-year beginning on October 1 of the previous calendar year (e.g., 1987 El Niño, EN).

Three representative farms, two in Alberta (C8 and C11) and one in Saskatchewan (C21), were then selected to test if EPIC could reproduce general trends of crop-district yields using historic-daily weather. Thirty-year daily weather series were assembled for the three locations using records from Lethbridge Airport, Edmonton International Airport, and Swift Current. The crop was continuous wheat. Simulated yields were plotted against the crop-district historic yields.

Overall, EPIC simulated yields were higher than crop-district yields (Table II.5). Average differences between simulated and district yields ranged from 1.6 to -0.1 Mg ha^{-1} for all ENSO states (EN, SEN, EV, Neutral). Rosenberg et al (1992) and Brown and Rosenberg (1997, submitted) have argued that crop yields simulated with EPIC tend to agree better with experimental than with regional yields. The latter are the average result of a range of weather, soil fertility, tilth and pest conditions that occur in a given area and growing season. In addition, applications of fertilizers, pesticides, and irrigation water are less often optimal in real life than in experimental fields and model simulations.

The results in Table II.5 suggest that the EPIC simulations captured well the sign of the relative difference in yield during the various ENSO states in seven out of the nine comparisons. The major exception occurred in the SEN years at the C11 farm where the historic data revealed a 16.3% decrease in yield with respect to Neutral years while EPIC predicted a slight increase of 2.6%. In general, agreement between the magnitudes of the relative differences calculated for the historic and simulated yields was acceptable.

Table II.5. Average historic and EPIC-simulated wheat yields for three representative farms in Alberta and Saskatchewan, Canada.

Meteorological station	Farm	Period of comparison	Scenario	Average historic yield	Relative Difference	Average EPIC yield	Relative Difference
				Mg ha^{-1}	%	Mg ha^{-1}	%
Edmonton Int.	C11	1968 - 1994	Neutral	2.80		4.04	
			EN	2.80	-0.1	4.11	1.8
			SEN	2.35	-16.3	4.14	2.6
			EV	3.00	7.2	4.15	2.8
Lethbridge	C8	1968 - 1994	Neutral	2.10		2.98	
			EN	1.81	-13.4	1.66	-44.3
			SEN	1.68	-19.6	1.33	-55.5
			EV	1.51	-27.6	2.03	-31.9
Swift Current	C21	1975 - 1993	Neutral	1.75		2.12	
			EN	1.59	-9.4	1.89	-11.0
			SEN	1.90	8.2	2.28	7.5
			EV	1.94	10.7	3.33	57.1

We also examined the ability of EPIC to reproduce yield trends from year-to-year. Historic yields of district 11 in Alberta (AB-11) in Figs. II.9 a-c show an upward trend in real yields with time, possibly due to a general improvement in management practice (e.g., fertilizers and cultivars). Simulated yields were consistently higher than the historic yields during the first years of the simulation. Starting in 1987, agreement in the yearly yield trends between historic and simulated yields improved. At the C8 farm in Lethbridge (Fig. II.9b), EPIC yields mimicked rather well the year-to-year yield variation reported in the historic series from 1978 to 1994. At the C21 farm (Fig. II.9c), the tracking of yearly yield trends was somewhat less satisfactory. A notable disagreement occurred in 1981 when EPIC yields increased by 100% over those from 1980 but the historic yields were nearly unchanged at around 1.5 Mg ha^{-1}. The lowest yield of the historic series, recorded in 1988 after the onset of an El Niño year in October 1987, was reproduced by EPIC although the predicted yield was 1.1 Mg ha^{-1} greater than the historic. The yield-depressing effects of the pronounced drought of 1988 were also reproduced by EPIC at the C8 farm in Lethbridge (Fig. II.9b). The drought conditions did not extend to the C11 farm near Edmonton. In fact, growing conditions there were fine.

We conclude that EPIC does a satisfactory job at reproducing the year-to-year yield variations reported at the regional levels and the average effects of ENSO scenarios for the sample of the three Canadian farms examined.

A.4.2 The United States

Four farms were chosen for this comparison of EPIC and actual yields in the United States. These are U30 – Iowa corn; U61 – Pennsylvania corn; U14 – Kansas wheat; U44 – Texas wheat. The methodology was similar to that employed in Canada. Historic yields were derived from the USDA National Agricultural Statistics Service (NASS) county crop database for the years 1972-1990.

Historic yields are grouped and averaged in Table II.6 according to the ENSO-state defined to begin on October 1 of the year prior to harvest. EPIC yields were grouped similarly. In 50% of the cases, EPIC yields and historic yields have similar signs with respect to change from neutral. The wheat farms (U14, 44) display the greatest disagreement with only SEN for farm U14 showing agreement between historic and EPIC yields. In contrast, deviations with respect to neutral are similar in all cases for the corn farms (U30, 61) excepting EV for farm U61. In most cases, EPIC yields are less variable than are the historic yields. The small number of SEN years in the record (only two in the study period) may account for some of disagreement both in variability and sign reported in Table II.6.

Table II.6. Average historic and EPIC-simulated crop yields for four representative farms in the United States.

Meteorological station	Farm	Period of comparison	Scenario	Average historic yield	Relative Difference	Average EPIC yield	Relative Difference
				Mg ha^{-1}	%	Mg ha^{-1}	%
Oelwien, IA	U30	1972 - 1994	Neutral	7.94		7.14	
	corn		EN	7.47	-6.0	6.88	-3.5
			SEN	6.78	-14.7	6.64	-6.9
			EV	6.65	-16.3	7.03	-1.5
Harrisonburg,	U61	1972 - 1994					
PA			Neutral	5.65		5.91	
	corn		EN	4.96	-12.2	5.20	-12.1
			SEN	4.20	-25.6	3.86	-34.7
			EV	5.66	0.1	5.56	-5.9
Oberlin, KS	U14	1972 - 1994	Neutral	2.22		1.92	
	winter		EN	2.33	4.8	1.57	-18.4
	wheat		SEN	2.75	24.0	2.41	25.5
			EV	1.87	-15.7	2.10	9.2
Kaufman, TX	U44	1972 - 1994	Neutral	1.88		2.31	
	winter		EN	1.98	5.3	2.24	-3.0
	wheat		SEN	1.62	-14.1	2.70	16.9
			EV	1.37	-27.3	2.48	7.5

Figs. II.10a-d compare historic yields and EPIC simulated yields based on daily weather records for the four representative farms. EPIC overestimates historic yields on Farm U44. This is especially evident in the period 1972-1982 and may be due to the fact that in our EPIC simulations present day technology is assumed -- an artifact that increases mean yields. For farm U14, EPIC yields while matching the historic mean, are not able to track historic interannual variability. The discrepancies between EPIC and historic interannual yield changes for this farm are quite severe for years 1980-82 and 86-88. The best agreement between EPIC and historic yields for corn occurs on Farm U61. EPIC yields match the interannual variability in corn yields quite well. EPIC yields for farm U30 do not show as much variability as historic yields, especially with regard to increases above the mean.

As Table II.6 and Figs II.10a-d show, EPIC corn yields are closer in agreement to historic yields than are wheat yields. This difference points out some of the limitations of EPIC such as the fact that EPIC does not account for pest damage or other localized events (e.g. hailstorms, wind damage, etc.) which negatively impact yields. Also, EPIC has difficulty in correctly modeling the vernalization of winter wheat in warmer climates and may initiate spring wheat growth too soon in some cases[2]. These limitations result in wheat simulations being somewhat problematic – especially for warmer, more southerly climates (i.e. farm U44).

A.4.3 Mexico

The ability of EPIC to mimic interannual variability in crop yields was tested by comparing its simulations with historic corn and bean yields in the vicinity of farms M7 and M9. The validation for

[2] Personal communication with Dr. Verel Benson, USDA-NCRS, Blacklands Research Station, Temple, TX

both crops assumed dryland conditions since irrigated crops are much less sensitive to climatic variations, especially in precipitation. The EPIC simulations assumed constant technology for all years and were driven by actual weather records for the periods of comparison. Results are shown in Table II.7 and Fig. II. 11a-b.

Table II.7 Average historic and EPIC-simulated bean and corn yields for two representative farms in Mexico.

Meteorological station	Farm	Period of comparison	Scenario	Average historic yield	Relative Difference	Average EPIC yield	Relative Difference
				Mg ha^{-1}	%	Mg ha^{-1}	%
El Llano,	M7	1968 - 1990	Neutral	0.71		0.69	
Aguascalientes	beans		EN	0.68	-5.3	0.63	-9.1
			SEN	0.58	-18.2	0.23	-67.0
			EV	0.72	1.1	0.83	19.9
Ameca, Jalisco	M9	1971 - 1990	Neutral	6.59		6.18	
	corn		EN	6.53	-1.0	5.43	-12.2
			SEN	6.50	-1.4	7.20	16.6
			EV	6.40	-2.9	6.00	-2.9

The Jalisco farm (M9) is located in the temperate region with well distributed annual rainfall averaging 863 mm; the Aguascalientes farm is located in the semiarid region with much lower annual precipitation (465 mm). Actual corn yields at Jalisco were much less variable than were simulated yields: 10.0 and 16.2% variability, respectively. However, EPIC was able to detect yield deviations due to climatic variability. The averages of observed and predicted corn yields were 6.04 and 6.48 Mg ha^{-1} —satisfactory considering that management practices were assumed constant in the simulations for the entire length of the comparison (1966 to 1990).

Under sparse rainfall in the region of farm M7 in Aquascalientes long-term bean yields were low. This is due, in large measure, to a large interannual climatic variability. For example, SEN conditions beginning in October 1983 led to a near total crop failure in 1983. EPIC over-predicted historic bean yields by 0.4 Mg ha^{-1}, in ENSO year 1982. Over the period compared the means of observed and simulated bean yield were close (0.70 and 0.66 Mg ha^{-1}, respectively). In the case of farm M7, EPIC simulations minimized interannual variability (16.7 and 49.9% for simulated and actual variability, respectively). The same assumption of unchanging technology was used in the bean simulations.

A.4.4 Further to the validation issue

Agreement between the EPIC simulations and actual yields is shown in Figs. II.9 - II.11 for 3 Canadian wheat farms, 2 corn and 2 wheat farms in the U.S. and 1 corn and 1 bean farm in Mexico. A trend analysis is also presented in Table II.8 showing the frequency with which simulated yields rise and fall in synchrony with historic yields. The numbers of years in which high and low yields are concurrent in the simulated and historic time series are also shown.

Table II.8 indicates that on the 9 test farms simulated yields match rises and falls in the annual time series of historic yields in 50-88% of the years. Peaks and valleys in the simulated time series are, of course, less frequent coinciding in as few as 13% and as many as 53% of the years on the various farms.

Table II.8 Similarity in year to year trend of EPIC and actual yields

Farm	Coincide				Opposite	Total		
	Rises (R)	Falls (F)	Peaks	Valleys		Years	(R+F)/(Tot-1)t	(P+V)/(Tot-1)
							%	%
C8	6	8	3	5	2	17	88	44
C11	5	6	2	2	5	17	69	25
C21	8	7	4	2	3	19	83	33
U30	5	5	1	2	7	17	62	19
U61	7	4	3	3	6	17	69	38
U14	3	7	3	1	7	17	62	25
U44	4	4	0	2	9	17	50	13
M7	7	8	4	6	5	20	79	53
M9	9	5	2	3	9	23	64	23

The data shows that temporal agreement between actual and EPIC modeled yields on the random selection of the representative farms during the time series that encompass the various ENSO states is less than perfect. A number of factors may contribute to this imperfection, particularly to the tendency of EPIC to overestimate real regionally averaged yields:

1) EPIC does not simulate the effects of many of the episodic events that reduce crop yields such as disease and insect attack, hail, windstorms, etc.
2) As we employ it here, EPIC assumes a generally high level of technology and management that is applied throughout the course of the simulation period. Applying technology of the mid-1990s can be expected to lead to yield overestimates in the order of 20 to 30 percent.
3) EPIC simulations often fail to represent yields well in the first few years because of initialization problems, due most often to assumptions about antecedent soil moisture conditions. This latter factor does not bias the results presented in the next section since the first three years of each simulation are discarded before means and standard deviations are computed.

We cannot ignore the possibility, as well, that some of the representative farms are not well parameterized (i.e., not truly representative). Of course all of these arguments raise the question of whether the good agreement that occurs in a substantial number of the validations (e.g., Figs. II.9b and c, 10b and 11b) is not simply fortuitous.

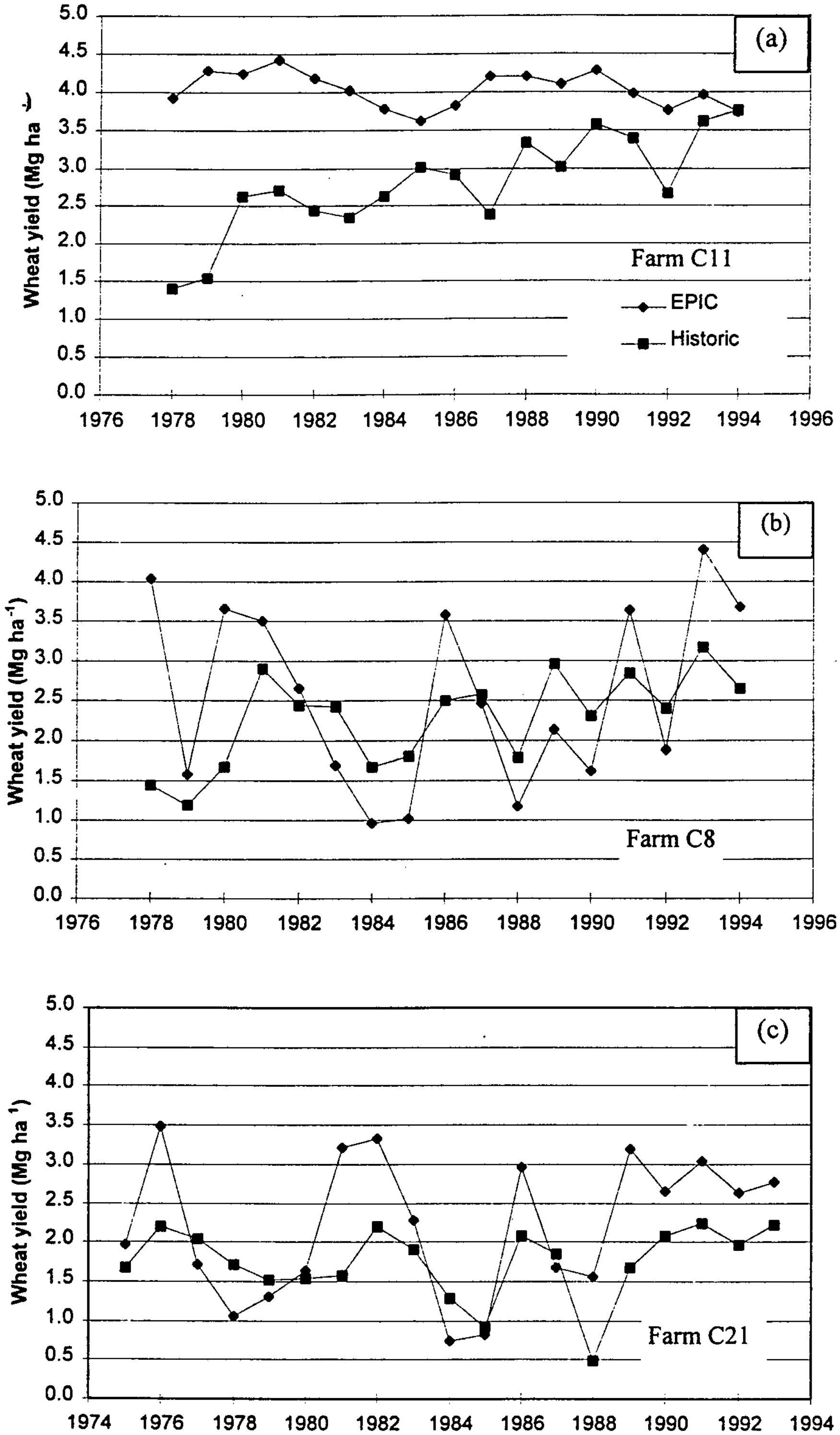


Fig. II.9. Comparison of historic and EPIC-modeled wheat yields in Canada at (a) Edmonton, AB (C8); (b) Lethbridge, AB (C11); and (c) Swift Current, SK (C21).

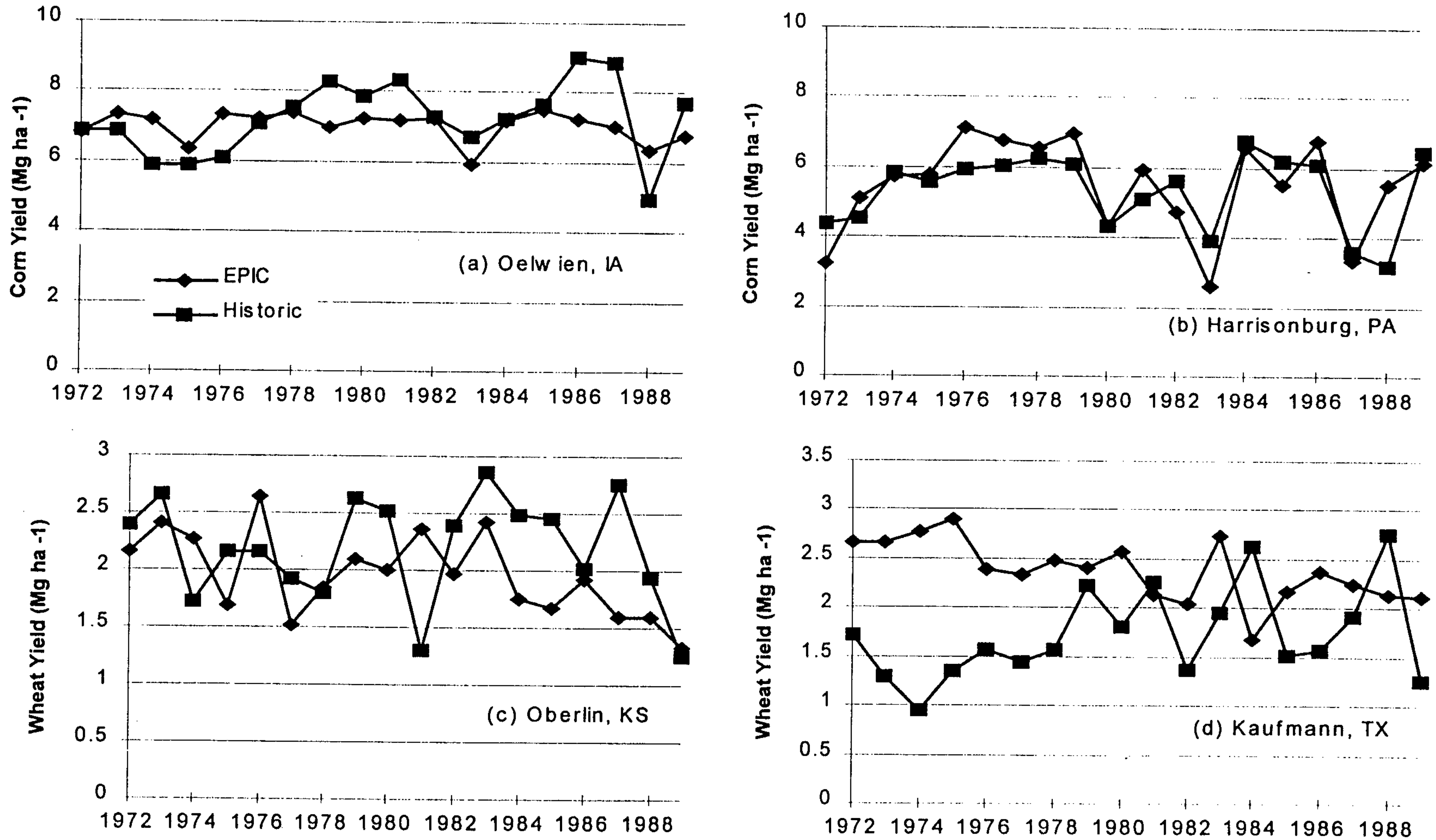


Fig. II.10. Comparison of historic and EPIC-modeled wheat and corn yields on four representative farms in the USA: (a) Oelwien, IA; (b) Harrisonburg, PA; (c) Oberlin, KS; and (d) Kaufman, TX.

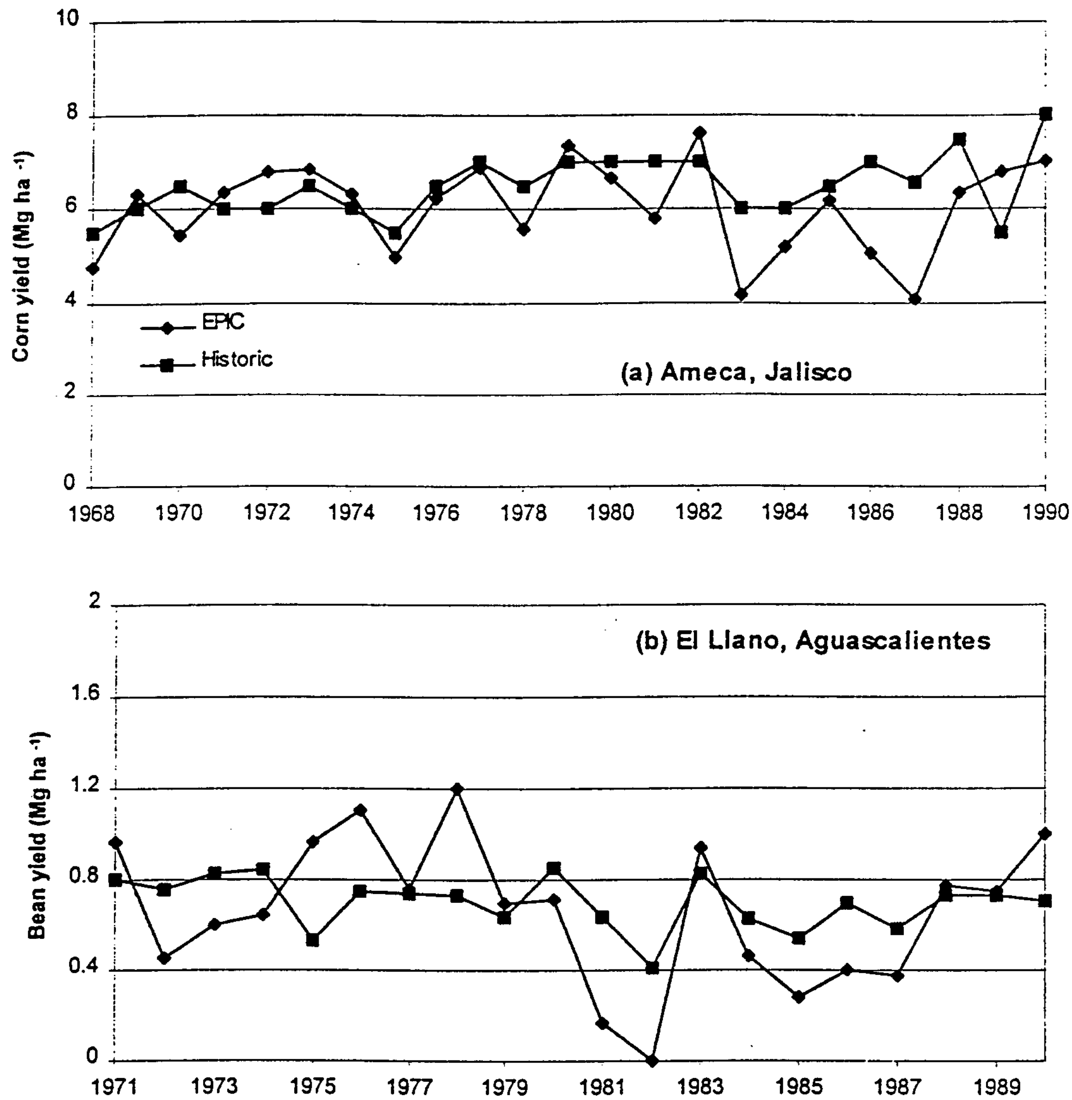


Fig. II.11. Comparison of historic and EPIC-modeled corn and bean yields at two sites in Mexico: (a) Ameca, Jalisco; (b) El Llano, Aquascalientes

B. Climate Scenarios

David Legler and Jim O'Brien at Florida State University (FSU) developed the scenarios of ENSO conditions that were applied to EPIC to model crop sensitivity in North America. They defined four ENSO conditions or "states", based on the index shown in Fig. II.12. These are: El Viejo (cold tropical Pacific sea surface temperature anomalies), El Niño (warm), Strong El Niño (very warm) and Neutral (neither warm nor cold). There were 7 El Viejo, 6 El Niño, 2 strong El Niño and 15 Neutral years in the period 1960-1989 (Table II.9). Hereafter the notation EN, SEN, EV and Neutral will be used to refer to the ENSO-states described above. For the El Viejo year selections, several differences from other classification methods are noted, but the classification of El Viejos is less agreed upon than the classifications of Los Niños, and the SST index supports these selections. In summary, based on historic daily weather data, mean monthly characteristics of thermal and precipitation conditions were estimated for each month of the ENSO year, i.e. the October prior to maximum SST anomalies through the September following these anomalies.

Table II.9. Distribution of ENSO Years between 1960 and 1989.

El Viejo	Neutral	El Niño	Strong El Niño
1964	1960	1963	1972
1967	1961	1965	1982
1970	1962	1969	
1971	1966	1976	
1973	1968	1986	
1975	1974	1987	
1988	1977		
	1978		
	1979		
	1980		
	1981		
	1983		
	1984		
	1985		
	1989		

Actual climate records of maximum and minimum temperature and precipitation totals for 45 stations in Canada, 92 in the conterminous U.S. and 251 in Mexico were used to develop monthly statistics relevant to the biophysical models employed in this study. The weather generator used to develop daily time step scenarios for multiple years requires means, totals and standard deviations of temperature and precipitation and statistics of skewness, number of rain days, probability of wet day following wet day and wet day following dry day. Thirty-year sequences representing the four ENSO states as well as a fifth sequence representing all years were developed for each station.

The development of climate scenarios for this project differs slightly from previous analyses of mean ENSO-related climate anomalies. First, the particular statistical characteristics chosen to describe the ENSO-specific scenarios include intra-monthly variability and probabilistic characteristics, something not previously examined. Our focus on linking ENSO-related climate anomalies to agricultural applications together with our choice of biophysical model to simulate plant growth (and hence yields) under the specific scenarios dictated the necessary climatic statistical characteristics. These statistics included characterizations of intra-monthly variability (i.e. higher moment) and probabilistic (e.g. probability of a wet day following a wet day) descriptions of the mean monthly climatic conditions in each of the selected ENSO states. Indeed the inclusion of ENSO-related intra-monthly climate characteristics has been demonstrated to have significant impact on simulated yields (Legler et al, 1997).

Secondly, it is generally recognized that ENSO-related climatic impacts have their largest magnitudes in the winter season (December - March). However, anomalies in seasons preceding and following the winter season are subject to some discussion and are less well-defined. For example, in Ropelewski and Halpert (1986), figures showing temporal evolution of regional anomalies for their composite warm event focus on seasons with persistent responses, and indeed indicate responses in the seasons preceding the winter season. However, these same figures also show other responses with relatively large amplitudes, but which lack the persistent nature that qualified them for detailed discussion. Given the complex processes involved in precipitation generation and the resulting localized nature of precipitation data, there is no compelling reason that discussion should be limited *only* to persistent response regions and seasons. Exploration of temperature data for the spring and summer seasons beyond the winter of the canonical ENSO year demonstrates statistical skill over the United States (Sittel - personal communication) and over Canada and Mexico (Green, 1996). For this project, we have focused on the time period from the October prior to maximum SST anomalies through the September following these anomalies.

Lastly, we have categorized the monthly historic climate data according to ENSO phase, but instead of a single category for El Niño, we have separated the El Niño and Strong El Niño categories to explore the climate anomalies associated with the very strong 1972 and 1982/83 El Niño events.

Data on daily precipitation and maximum and minimum temperature were obtained for the period 1960 - 1989 for all of the stations shown in Fig. II.8 and listed in Tables II.2-4. Several statistics were calculated for each month: mean and standard deviation of daily minimum and maximum temperature; monthly total and standard deviation of daily precipitation values; skewness of daily precipitation values; given a wet day, the probability of a wet day following (PWAW); given a dry day, the probability of wet day following (PWAD); and number of days in the month with rain (NDR). Each monthly set of statistics is categorized as belonging to one of four *phases or states* of ENSO.

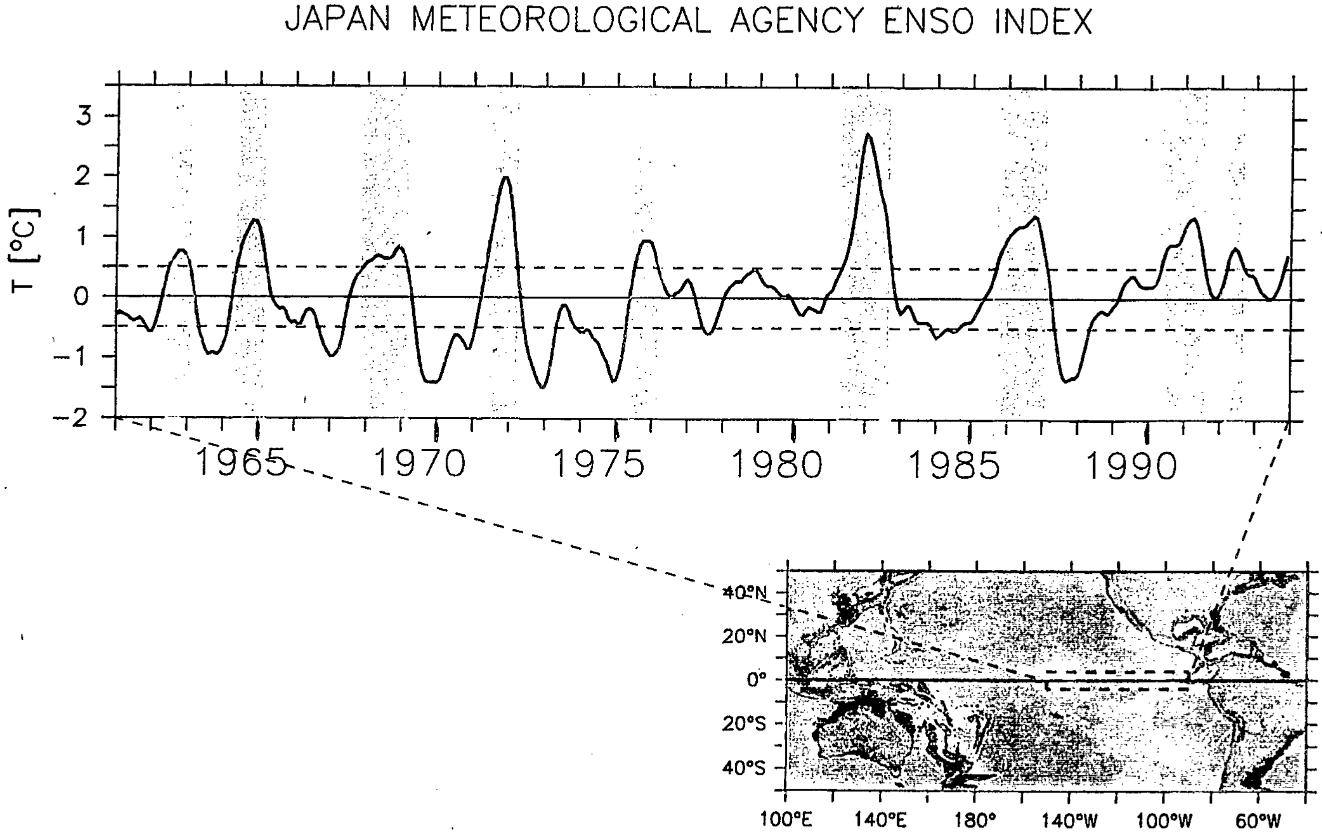


Fig. II.~~12~~ 14. The Japan Meteorological Agency ENSO Index of sea surface temperature deviations from the mean in the indicated region of the Tropical Pacific Ocean, 1961-1994.

C. The Economic Framework

PNNL has been developing the Global Change Assessment Model (GCAM) for integrated assessment of climate change. One part of the modeling system is a global economic model that simulates greenhouse gas emissions for eleven world regions over time. The initial focus of this economic model was on energy, especially carbon dioxide emissions from fossil fuel combustion. An agricultural component has been added to the economic model to simulate greenhouse gas emissions from land use change, interactions with the energy sector through the production of biomass energy, and to estimate the economic impact of changes in crop yields for the major field crops.

Another part of the GCAM modeling system is the link from a changed climate to changes in the productivity of field crops. The changed climate could be due to global warming, or as in this study, to ENSO events. The EPIC model has been used to provide this link from a changed climate to changes in crop yields for major field crops. Development of the entire GCAM modeling system is not complete, especially in the area of economic impacts of global change. However, a reduced-form version of GCAM, called MiniCAM, is operating. The first application of MiniCAM's agricultural sector was a global warming study using crop yield response surfaces derived from EPIC (Edmonds et al., 1996).

In the current study, the primary challenge is to link the global economic model in MiniCAM with simulated crop yields from very specific locations in North America. MiniCAM operates with eleven world regions: United States, Canada, OECD Europe, Japan, Australia and New Zealand, Eastern Europe and Former Soviet Union, China, Middle East, Africa, Latin America, and Southeast Asia. In MiniCAM, seven products are traded between world regions: oil, gas, coal, grains and oil crops, animal products, forest products, and biomass energy.

Our global economic model is very aggregate in its representation of the agricultural sector. Each of the agricultural products in MiniCAM is a composite good. For example, 'grains and oil crops' in the United States is a composite of wheat, corn, soybeans, and other field crops. 'Animal products' is a composite of meat, fish, and dairy products. Animal products are traded separately from grains because people in developing countries will consume a greater share of calories by consuming animal products as their per capita incomes converge to incomes in developed countries.

Within each region, land is allocated to grains, pasture, forests, or biomass production as a function of the economic returns to land in each of those uses. For grains, economic returns to land will increase if yields increase, or if the price received increases. An increase in grain yields will result in more land being allocated to growing grain.

Specific Steps for this Study were:

1. Construct average change in crop yields across EPIC farms.
2. Aggregate across crops within each region.
3. Modify productivity parameter in MiniCAM for the 'grains and oil crops' sector.
4. Note changes in output and international trade for this sector in the MiniCAM model.

Each EPIC farm simulates crop yields over a known geographic area. In the first step, crop yields are aggregated across EPIC farms within a country using harvested hectares as weights. This averaging process will tend to mask any ENSO effects that are location specific. It is quite possible that specific geographic areas will experience significant changes in yield, but have little effect on national or global markets.

In the second step, yields are aggregated across crops to create an average yield for the composite 'grain and oil crop' good in MiniCAM. Yields are aggregated using prices per metric ton as weights. Again, it may be the case that changes in yield for one crop may have relatively little impact on world markets if other crops do not experience the same change in yield. MiniCAM considers different types of grains to be close substitutes for one another.

Each global region in MiniCAM has a productivity parameter that can be adjusted to simulate changes in yield for the composite 'grains and oil crops' product. We are somewhat limited in this study in that we do not have estimates for changes in crop yields due to ENSO events for countries outside of North America. For step three, we therefore assume that crop yields outside of North America are unchanged. In step four, changes in output and international trade are summarized. In addition, sensitivity analysis is used to characterize a range of hypothetical scenarios.

A limitation of this analysis is the incomplete coverage of crops within each region, and lack of crop simulation results for regions outside of North America. Within the MiniCAM model, we address this limitation through sensitivity analysis on our assumptions about crop yields, especially in regions outside of North America.

Other economic studies have used the EPIC model to simulate the response of crop yields to ENSO events. Adams et al. (1995) estimated the economic value of improved long-range weather information in the southeastern United States. Solow et al. (1997) extended this analysis to all of U.S. agriculture. A key element of these studies is a behavioral model that selects profit-maximizing patterns of planting and harvesting.

D. The NA3E Geographical Information System

Dr. Raghavan Srinivasan of the Texas A & M University Blackland Research Center at Temple is responsible for development of a GIS to support all of the work of the North American Energy, Environment and Economy (NA3E) program described in the Introduction to this report. Under his direction data has been collected and organized on the following physical factors: watershed boundaries, elevations, soils, land use/land cover and climate. Data on these factors has been gathered by various means and from various sources for the purposes of the current study. Much, but not all, of the information gathered has been incorporated into the GIS. GIS development is a continuing activity of NA3E.

Watershed Boundaries. The watershed boundaries for the entire North American Continent have been processed into the GIS and the map layers[3] are available.

Elevation. Raw digital elevation data were acquired for Mexico and processed into Digital Elevation Maps (DEMs) with 100 and 500m horizontal resolution. Canadian Digital Elevation Data (CDED) are yet to be acquired from the Centre for Topographic Information at Sherbrooke, Canada. These data are based on National Topographic System (NTS) maps at scale 1:250,000. Each digital file covers approximately one half of an NTS map sheet. Grid spacing is based on geographic coordinates at a minimum resolution of 3 arc sec. CDED files are produced with ANUDEM (Australian National University Digital Elevation Model) software. Negotiations are underway with appropriate Canadian officials to acquire this data. DEMs at 100 and 500m resolution are available for United States. All the processed DEMs are displayed in Albers Equal Area projection with a vertical resolution of 1m.

Soil Maps and Database. The Natural Resources Conservation Service (NRCS) STATSGO soils database and map are available for the United States. Food and Agricultural Organization (FAO) soil survey data were assembled for Mexico by Dr. Mario Tiscareño, a member of the NA3E team. The FAO data, less detailed than the STATSGO data, report only on soil texture (percent sand, silt, and clay) and a few other basic characteristics. Since EPIC requires information on other soil characteristics not provided

[3] Layer: "a logical set of thematic data described and stored in a map library. Layers organize a map library by subject matter (e.g., soils, roads, and wells), and extend over the entire geographic area defined by the spatial index of the map library." (from Environmental Systems Research Insitute (ESRI). 1997. Understanding GIS: The ARC/INFO Method. GeoInformation Int., Cambridge, UK.)

by FAO, it has been necessary to estimate these by establishing similarities of Mexican and U.S. soils and extrapolating from the STATSGO database. In this way it was possible to create for Mexico a soils map and database comparable in format and structure to that of STATSGO. Canadian soils data used in the EPIC modeling were gathered by Dr. R. César Izaurralde. These data have not yet been processed into the NA3E GIS.

Land Use/Land Cover. An AVHRR land use/land cover (LULC) image for all of North America was obtained from United Nations Environmental Programs EROS Data Center at Sioux Falls, South Dakota. The raw map has a fairly high level of categorization. Rules were created for reclassifying map units into different aggregation levels. In addition to this the USGS Anderson Level II LULC map is available for the United States.

Climate. Thirty years of daily climatic data (maximum and minimum temperatures and precipitation), available for approximately 8000 stations in the United States have been incorporated in the GIS. Although Mexico and Canada were able to provide the climatic data required for this study. However, only a few years worth of Mexican data for a limited number of stations have been installed in the NA3E GIS at this writing. Daily climatic records for the current climatic period (1961–1990) are available for 57 Canadian meteorological stations and will be installed in the NA3E GIS.

III. RESULTS

A. Introduction

This section of the report is organized to provide an overview of the primary results linking ENSO-induced climate anomalies and crop yields. The climatic anomalies are illustrated in a set of continental maps which show deviations attributable to EN, SEN, and EV of winter and summer maximum temperature and precipitation from the mean situation during Neutral years. These maps are followed by a set of tables in which the mean temperature and precipitation anomalies observed during EN, SEN and EV years are detailed by season for each farm in each country.

The climate anomaly maps are followed by another set of figures—snapshots illustrating the effects of the ENSO states on EPIC simulated corn and wheat yields in North America. Corn and wheat under dryland conditions are the only crops we have modeled in all three participating countries. Next, detailed information on these crops and on the others modeled—barley, canola and potatoes in Canada and beans in Mexico—are presented in tables by country and farm. Data are presented on both dryland and irrigated yields for each of the crops grown in Mexico. In order to provide a mechanistic explanation as to how ENSO state influences crop yields these tables also include information on differences from Neutral in the number of water, temperature and nitrogen stress days that occur under EN, SEN and EV conditions.

The analysis of yield effects is followed by presentation of detailed tabular information (again by country and farm) of the ENSO effects on potential and actual evapotranspiration (PET and ET), runoff and soil erosion. Relationships between and among these parameters are explored.

The penultimate portion of the Results section returns to the question of crop yields. In it we describe an approach to testing the sensitivity of yields in North America to ENSO events—this time to a changing frequency of EN, SEN and EV years rather than to an overlay of constant anomalies on the actual historic record.

The final portion of this section is a brief assessment of the economic implications of our findings with regard to crop yields.

B. Climate Anomalies in North America Associated with ENSO Extremes

B. 1. Continental Summary

The North American climate anomalies associated with ENSO extremes vary in magnitude and are very localized. Graphical outputs of the statistics developed by Florida State University show seasonal and geographic patterns of ENSO climate variability clearly. Figs.III1 a-f show anomalies of maximum temperature at each of the stations associated with the representative Canadian and U S farms and a larger subset of Mexican meteorological stations. FigsIII.1 a, b show EN effects for winter (DJF) and summer (JJA); Figs.III.1 c, d show SEN effects for the same periods; Figs.III.1 e, f relate to EV.

In winter EN creates a warm zone in the Canadian Prairies and the north central portions of the U.S. (Fig. III 1 a). Most of Mexico is cooler than normal in winter. Warming is more moderate in summer of EN years (Fig. III 1 b) and is confined to the U.S. Great Plains, Midwest and Atlantic Coast states. During the winters of SEN years (Fig. III 1 c) the U.S. Northeast, Midwest and Plains states and the Prairie Provinces are significantly warmer than under neutral conditions. The U.S. Southwest and Northern Mexico are cooler. In SEN summer (Fig. III 1 d) the Atlantic coast, Cornbelt and Plains and the southern Prairie Provinces are slightly warmer than in the Neutral State. The west coast of the U.S. and Northern Mexico are cooler. During the winters of EV years (Fig. III 1 e) the Canadian Prairies are cooler than normal; the U.S. Great Plains, Midwest and Southwest are warmer. Mexican stations are highly variable. EV summers (Fig. III 1 f) are cool over most of the North American continent, especially so in central Mexico.

Precipitation in winter during EN years (Fig. III 2 a) is largely unchanged or modestly reduced from Neutral across the continent except for some West Coast locations where reductions are large. In portions of central Mexico precipitation is increased by 10-30 mm. During SEN winters (Fig. III.2 c) precipitation is increased in the U.S. southeast, parts of the Cornbelt and southeastern Plains, Texas, and California/Oregon and in Northern Mexico and the southern portion of Baja California. During EV years (Fig. III.2 e) winter rainfall is sharply reduced in California and at a few sites on the Mexican Gulf coast. It is increased moderately in portions of the U.S. Southeast and Midwest. Summer precipitation is moderately increased in the Prairie Provinces and portions of southern Mexico in EN years (Fig. III.2 b) and moderately reduced in much of the eastern U.S.. In SEN summers (Fig. III. 2 d) precipitation is largely decreased or unchanged over most of the U.S. with the exception of the Great Basin region and Northern California, increased in portions of the Prairie provinces, sharply decreased in parts of northern and the southwest coast of Mexico, but increased in the southern half of Baja California. The Prairie Provinces, the Gulf Coast and parts of the U.S. South receive more precipitation during EV summers (Fig. III.2 f). There are evident bands of increase and decrease across Mexico.

Are we right to have differentiated between the 'ordinary' and strong El Niño categories in this analysis? Figs.III.1 and 2 in this sequence allow comparison of the climate anomalies associated with the SEN ENSO-state with those of EN and highlight some interesting characteristics of the anomalies related to strength of the warm events. It can be seen that a strong El Niño does not translate linearly into stronger (larger amplitude) El Niño climate anomalies. The warmer winter anomalies for SEN are shifted more to the east and southeast, are greatest in magnitude in the northern plains of the U.S., and extend through the northeast states and even slightly into the southeast. In contrast, under EN warmer conditions peak in Canada with an extension to the U S southwest. The southeast is slightly cooler than Neutral. One characteristic is common to both the EN and the SEN cases, namely the southwest U.S. and Mexican stations are cooler than Neutral. But the magnitude of the anomalies is greater under SEN. Accordingly, winter precipitation totals for SEN indicate wetter conditions over the eastern half of the continent, probably due to increased southerly circulation. In the West Coast states, SEN and EN are associated with, respectively, wet and dry conditions. During the summer months, SEN and EN are both characterized by warm temperature anomalies over the northern and eastern U.S. SEN indicates similar conditions, but larger magnitudes for stations in southern Canada and along a line from northern New York through central Oklahoma. Only SEN indicates slightly cooler temps in the West Coast states. Similarly, precipitation totals for the same period indicate that SEN leads to stronger dry conditions near Illinois and Iowa, but wetter conditions in east Texas and in regions of eastern Mexico. The foregoing comparisons support our contention that SEN and EN lead to a quite different geographical distribution of seasonal climatic anomalies and must be treated separately in analysis of their impacts on agriculture. In App. 2 we conduct a more rigorous statistical comparison between the EN and SEN conditions.

Average seasonal climatic anomalies under EN, SEN, and EV conditions are shown for each farm in Tables III.1 – III.6, and are accompanied by narrative descriptions in Sections A.2.1 through A.2.3.

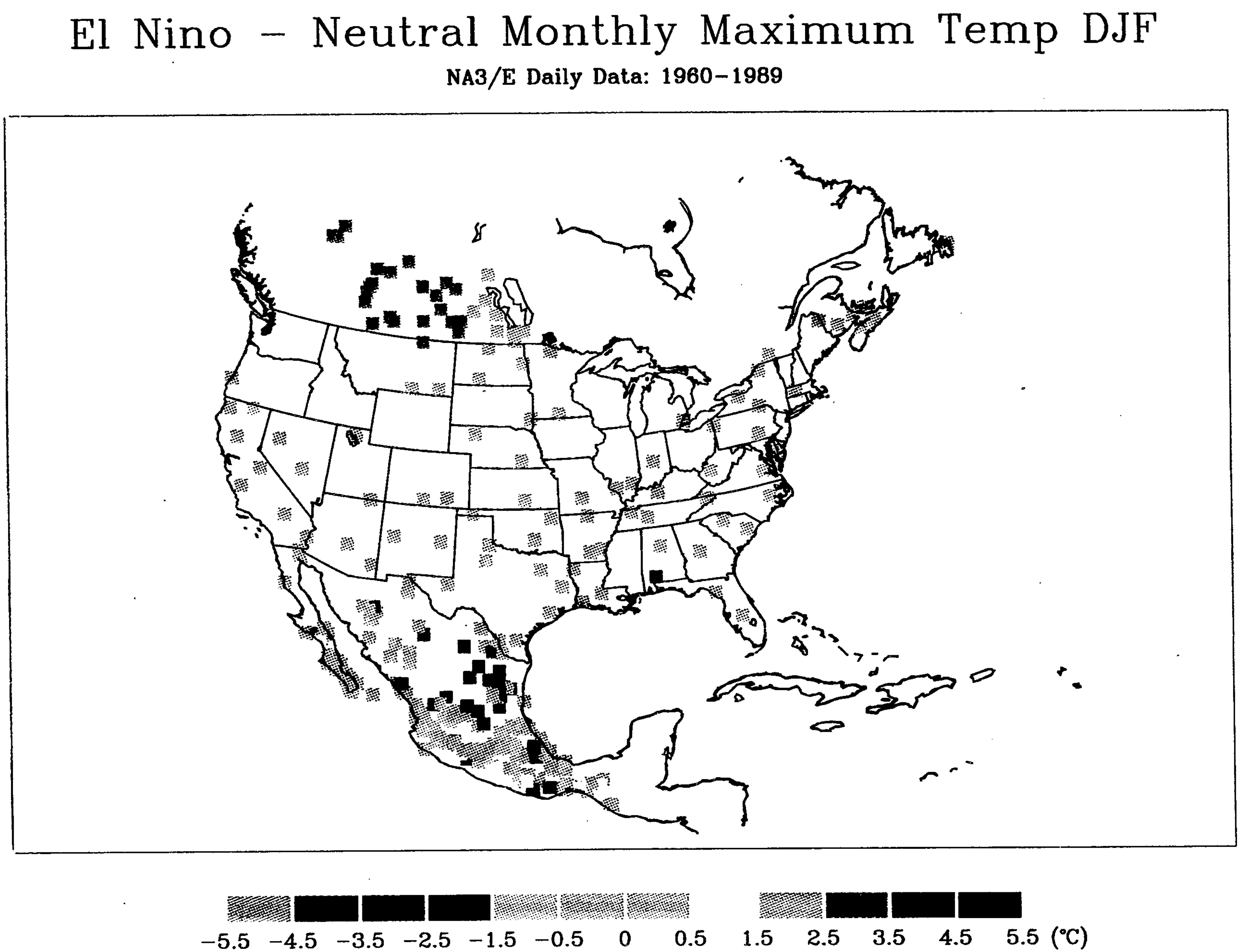


FIG. III.1 a. Temperature anomalies in winter (EN-Neutral) at the representative farm sites.

El Nino – Neutral Monthly Maximum Temp JJA

NA3/E Daily Data: 1960–1989

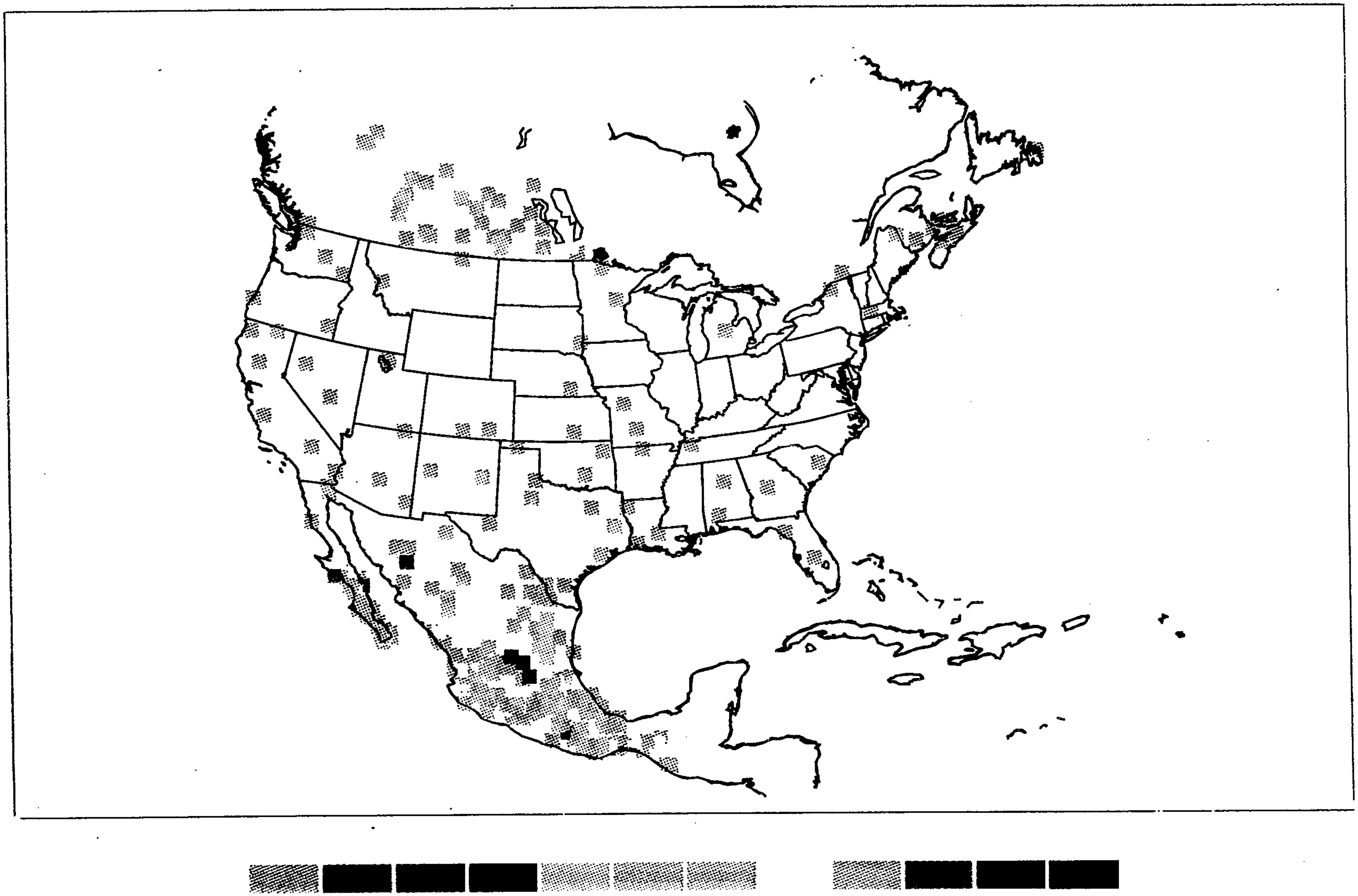


FIG. III.1 b. Temperature anomalies in summer (EN-Neutral) at the representative farm sites.

Strong El Nino – Neutral Monthly Maximum Temp DJF

NA3/E Daily Data: 1960–1989

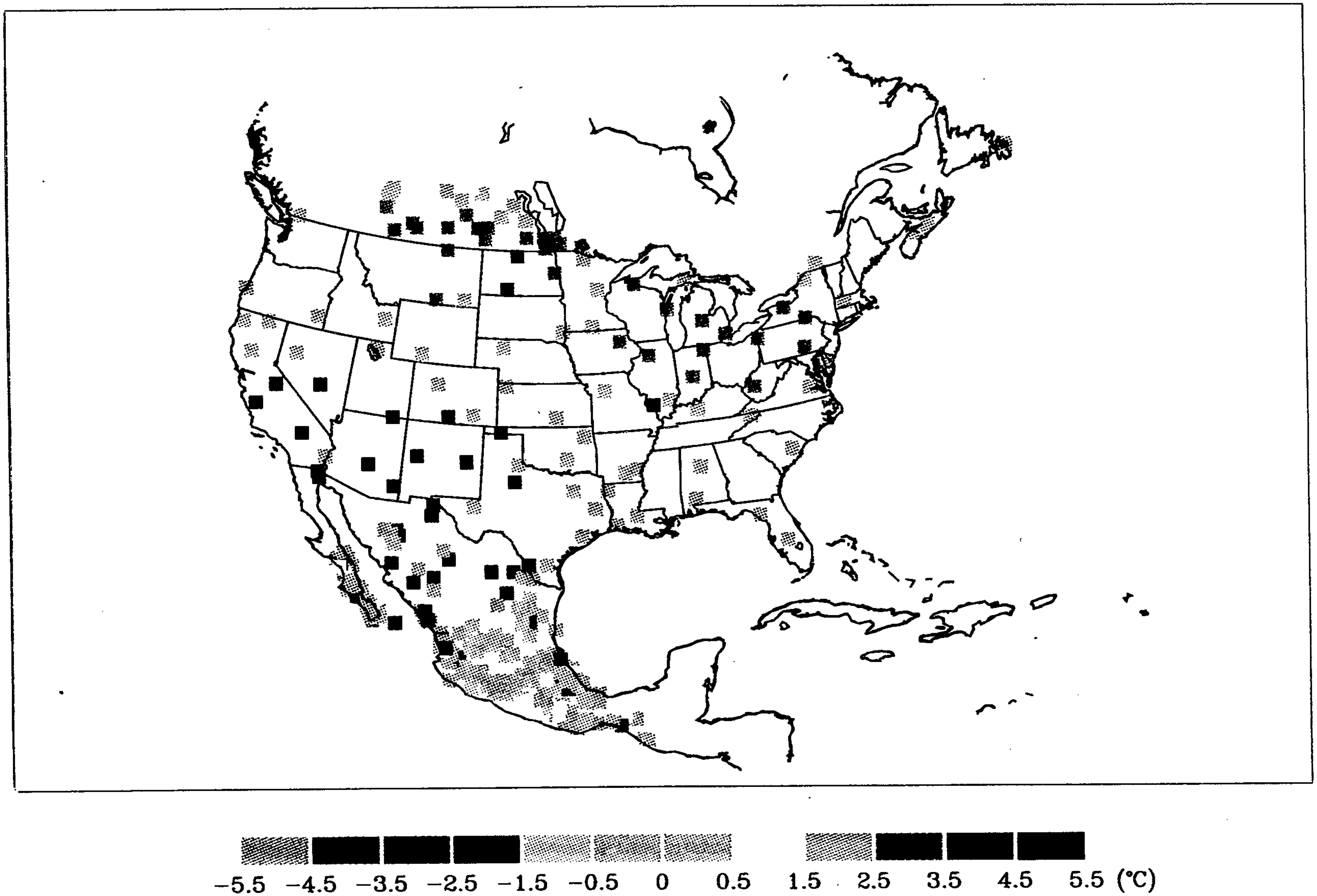


FIG. III.1 c. Temperature anomalies in winter (SEN-Neutral) at the representative farm sites.

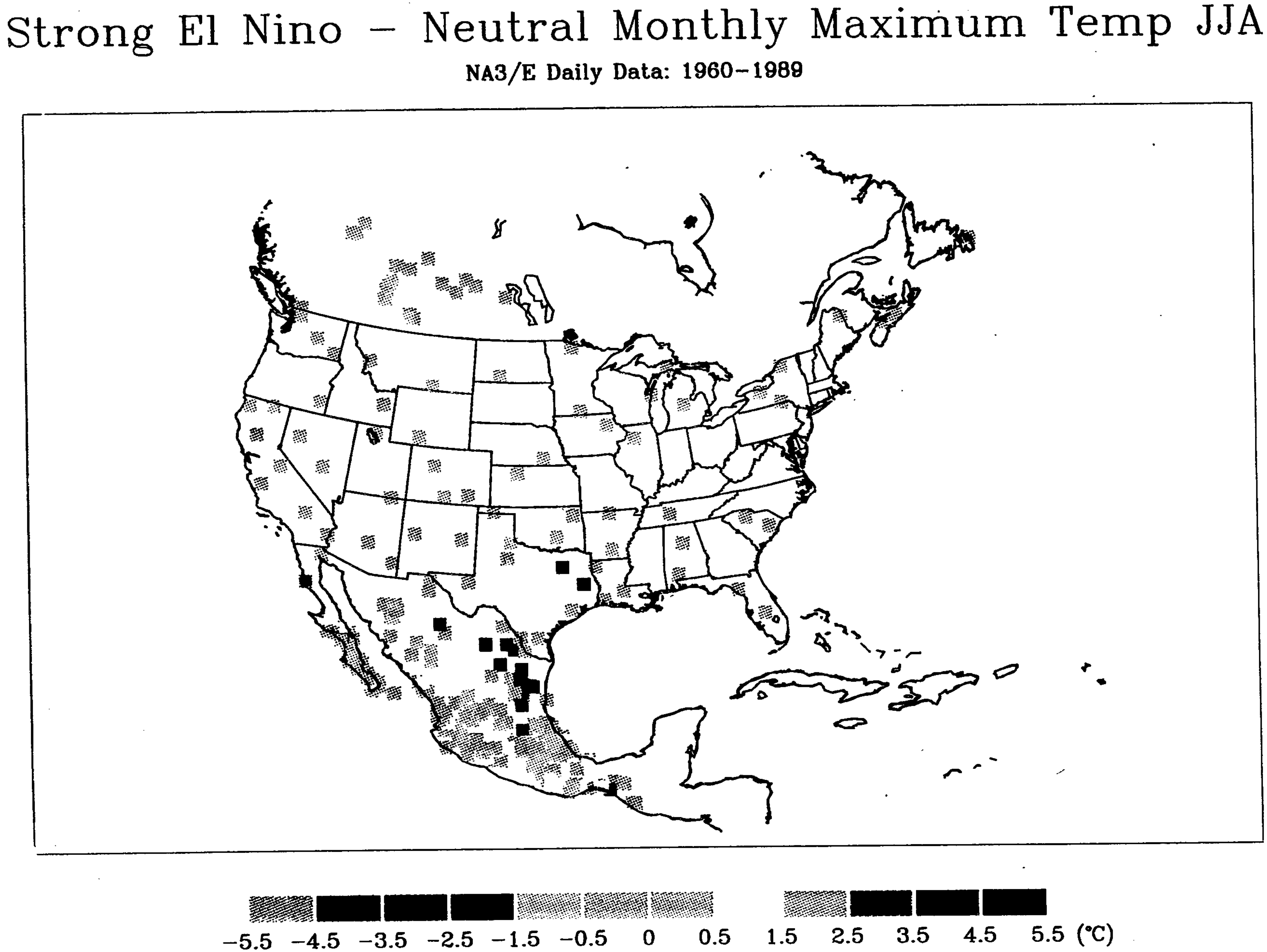


FIG. III.1 d. Temperature anomalies in summer (SEN-Neutral) at the representative farm sites.

El Viejo – Neutral Monthly Maximum Temp DJF

NA3/E Daily Data: 1960–1989

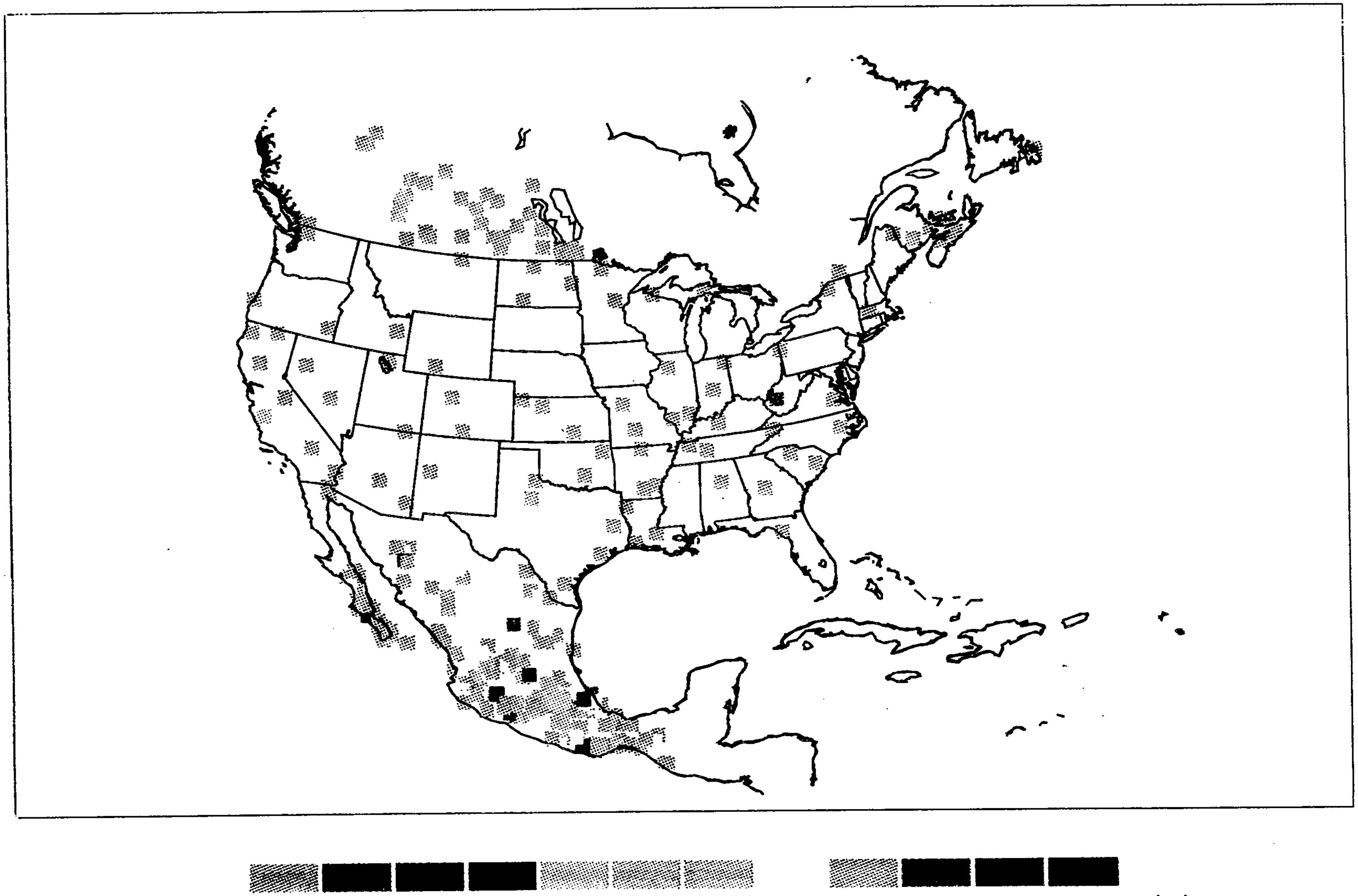


FIG. III.1 e. Temperature anomalies in winter (EV-Neutral) at the representative farm sites.

El Viejo – Neutral Monthly Maximum Temp JJA

NA3/E Daily Data: 1960–1989

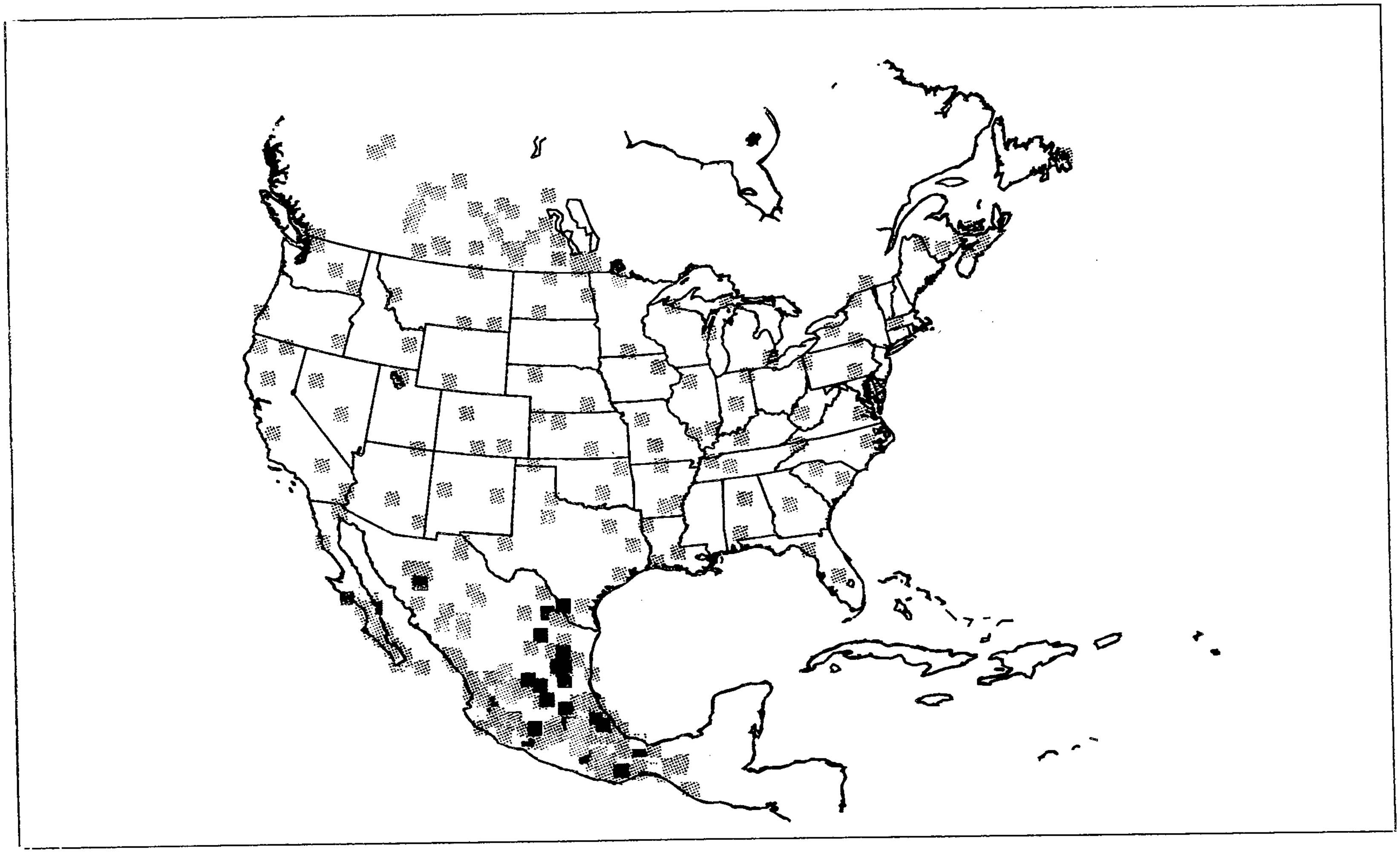


FIG. III.1 f. Temperature anomalies in summer (EV-Neutral) at the representative farm sites

El Nino – Neutral Monthly Precip Total DJF

NA3/E Daily Data: 1960–1989

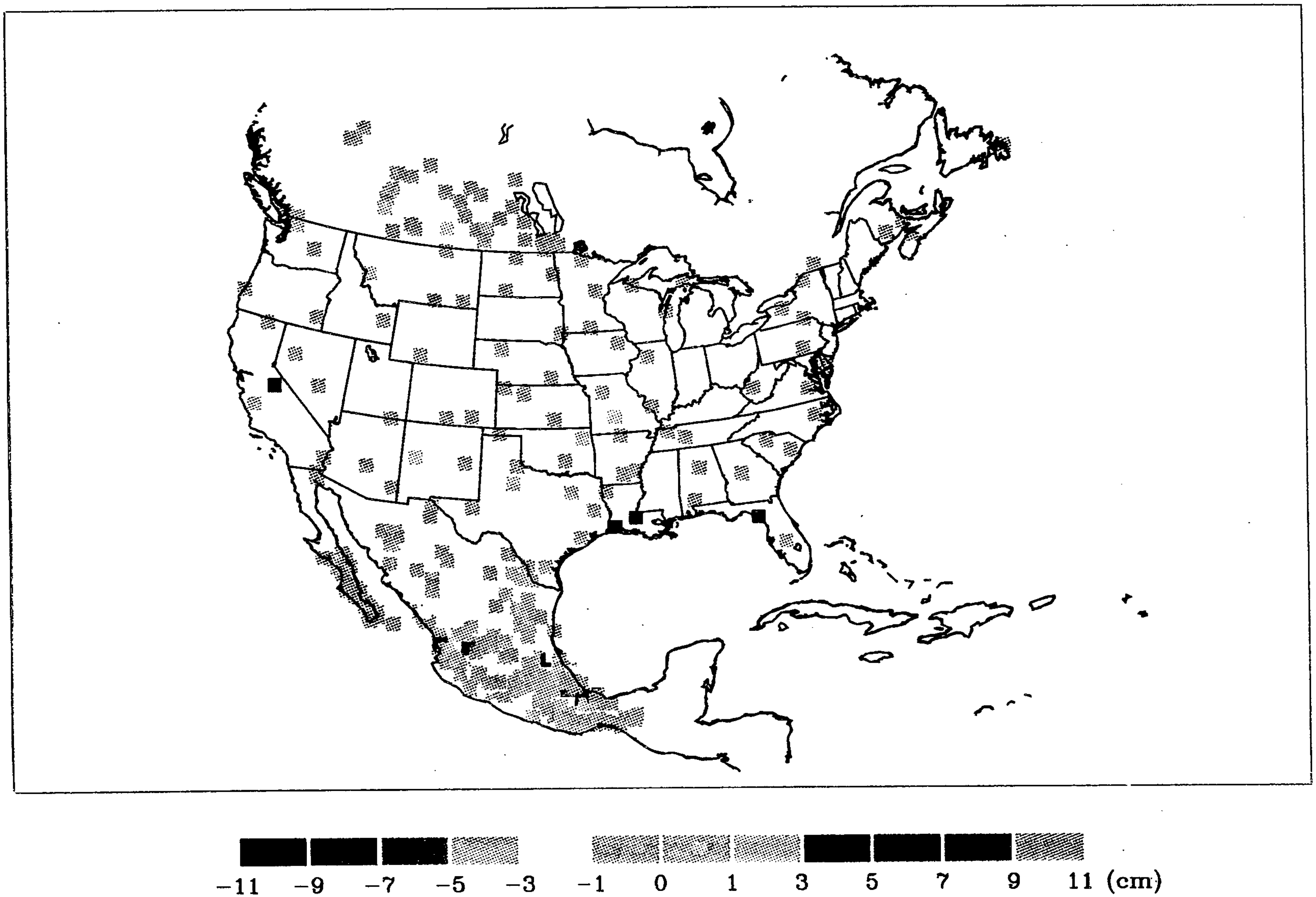


FIG. III.2 a. Precipitation anomalies in winter (EN – Neutral) at the representative sites.

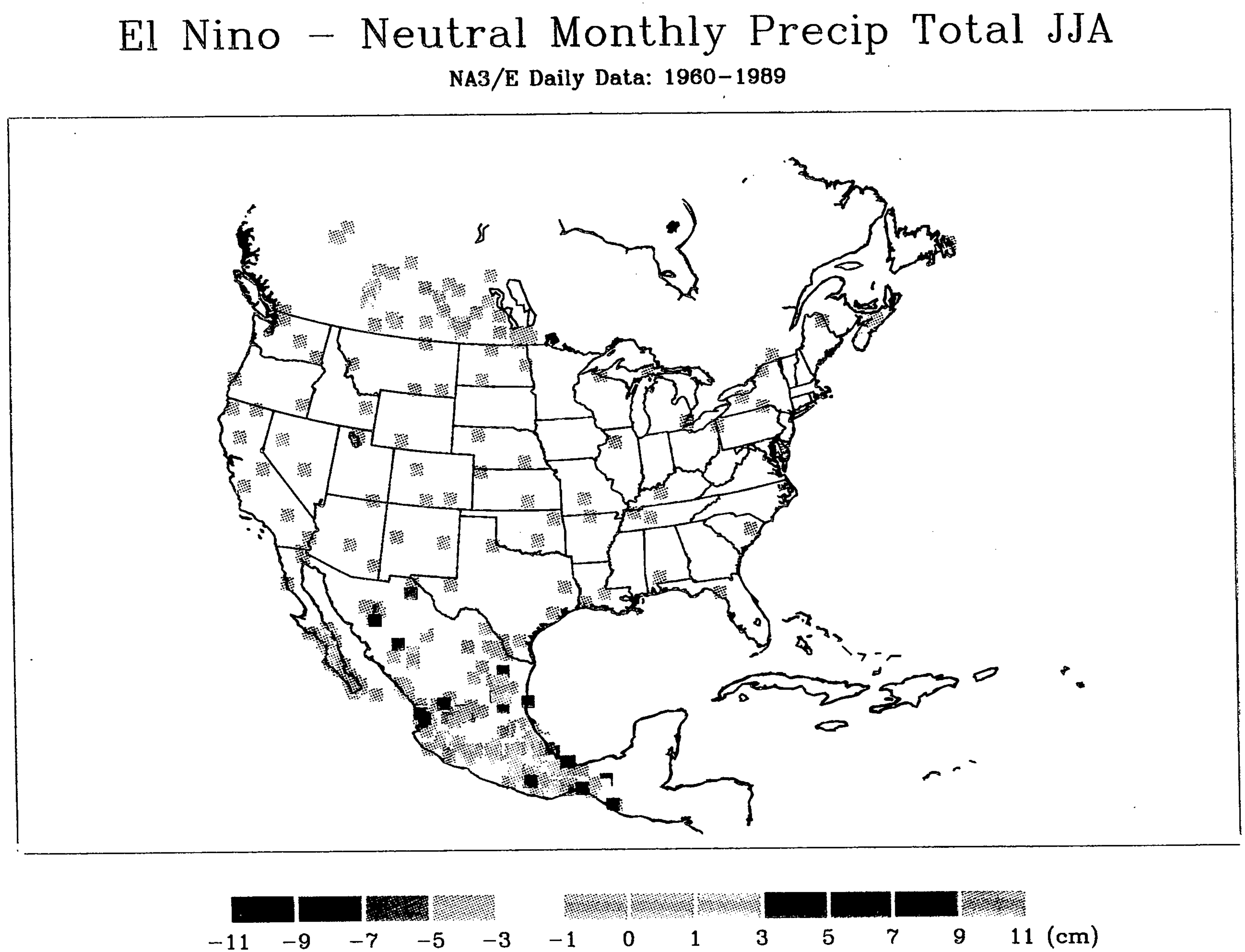


FIG. III.2 b. Precipitation anomalies in summer (EN – Neutral) at the representative sites.

Strong El Nino – Neutral Monthly Precip Total DJF

NA3/E Daily Data: 1960–1989

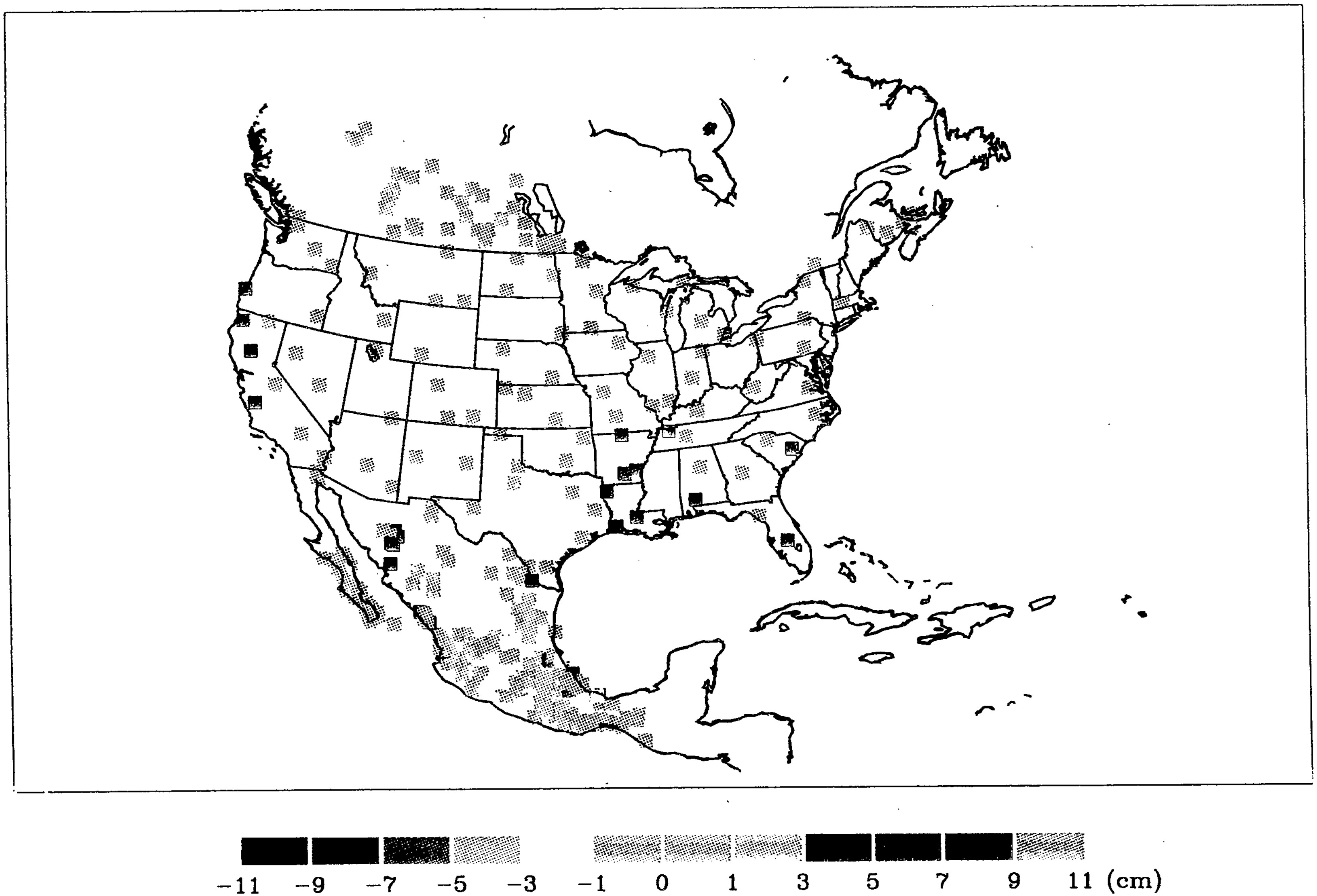


FIG. III.2 c. Precipitation anomalies in winter (SEN – Neutral) at the representative sites.

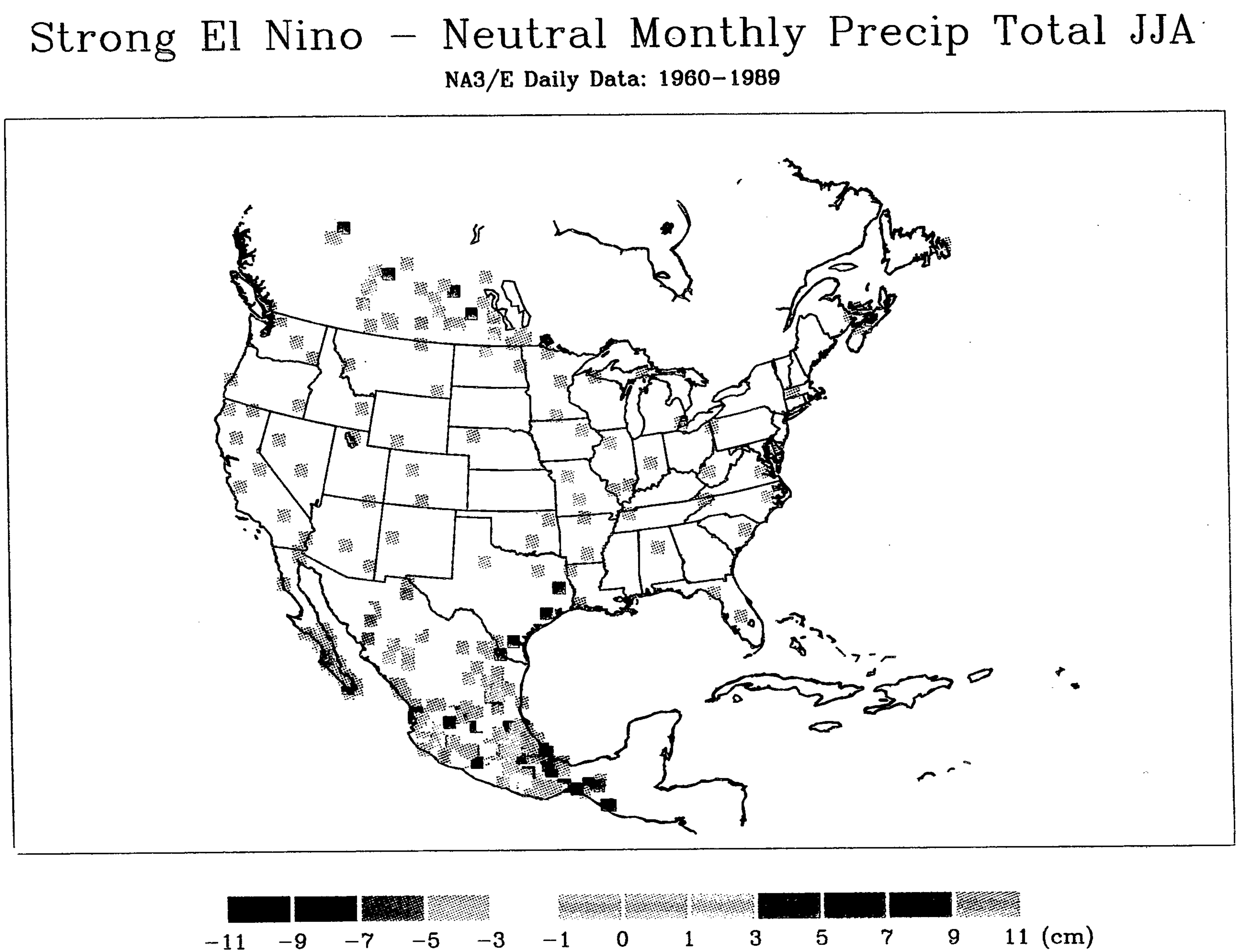


FIG. III.2 d. Precipitation anomalies in summer (SEN – Neutral) at the representative sites.

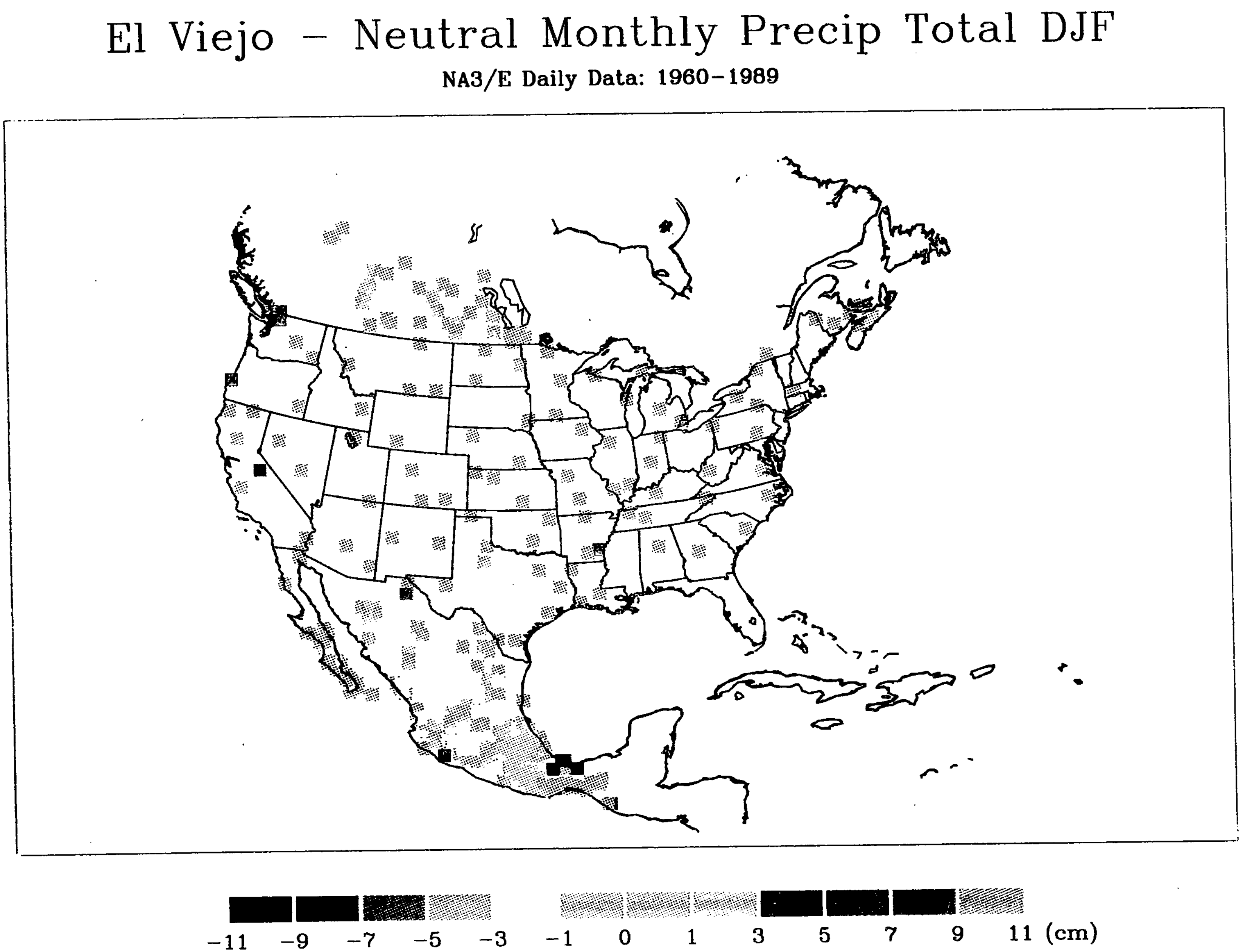


FIG. III.2 e. Precipitation anomalies in winter (EV – Neutral) at the representative sites.

El Viejo – Neutral Monthly Precip Total JJA

NA3/E Daily Data: 1960–1989

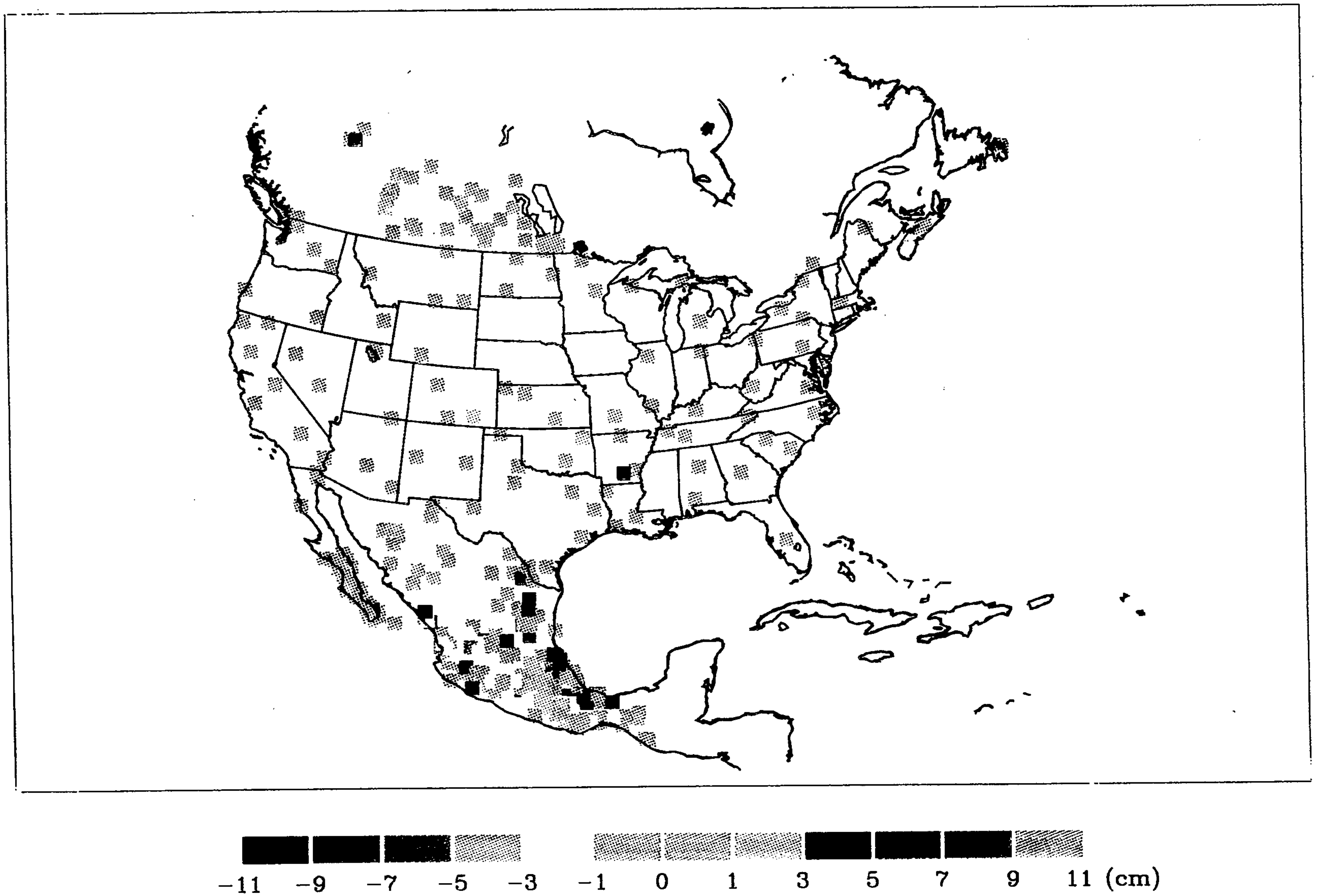


FIG. III.2 f. Precipitation anomalies in summer (EV – Neutral) at the representative sites.

B. 2. National Summaries

B. 2.1 Canada

Average winter air temperatures in Neutral years ranged from a minimum of -17.9 (C22 and C23) to a maximum of 3.6 °C (C1) (Table III.1). El Niño (EN) conditions in winter induce a consistent increase in air temperatures with respect to the Neutral condition across western Canada. The largest increases in temperature (~ 3 °C) are observed in the three Prairie Provinces (Alberta, Saskatchewan, and Manitoba). Correspondingly, slight decreases in winter air temperatures are observed in Atlantic Canada (New Brunswick, Nova Scotia, and Prince Edward Island). El Viejo (EV) induces small (~ 1 °C) but consistent decreases in air temperature across the Canadian territory (with the exception of farms C40 and C41 where a 1.3 °C increase has been recorded. In the Strong El Niño (SEN) situation, winter air temperatures in the Prairie Provinces get warmer than in Neutral years but with a notable shift: air temperature deviations on the western side of the Prairie Provinces do not attain the levels reached under EN but they surpass them on the eastern side (e.g., 1.5 °C on farms C37 and C38).

In contrast, average summer air temperatures ranged from a minimum of 14.7 (C3 and C6) to a maximum of 20.9 °C (C40 and C41). Air temperature deviations during summer are considerably smaller both in magnitude and range than those observed in winter. The maximum positive deviation under EN was 0.8 °C (C40 and C41) while the minimum was -0.7 °C (C3). The deviations induced by EV conditions were small but consistently negative (~ -0.1 °C).

Average winter precipitation in Neutral years ranged from a minimum of 35 mm (C9) to a maximum of 703 mm (C2) (Table III.2). The generally warmer conditions induced by EN are accompanied by less precipitation (~ -16%). With a few exceptions, winter precipitation under EV increases with respect to the Neutral condition (~ 16%) and can be as much as 53% more (C4). Winter precipitation deviations during SEN years are more pronounced than during EN years (+24% to -52%). The decrease in winter precipitation under SEN averages -20%.

Average summer precipitation in Canada ranges from 113 mm (C12 and C13) to 295 mm at (C45, C46, and C47). Overall, summers during EN years are wetter than under Neutral years (~ 8%). This is especially true in the Prairie Provinces where the differences are in the order of 20%. In Atlantic Canada, summers during EN years are actually drier than during Neutral years (~ -15%). Summers during EV years are not much different than those during EN years. Percent differences under SEN appear to be more pronounced than under the other two ENSO states (-30% to +98%).

B. 2.2. The United States

Data on seasonal temperature and precipitation anomalies on the U.S. representative farms are presented in Tables III.3 and III.4.

El Niño. Temperatures in the United States are generally above Neutral during winter in EN years, especially so in the Northern, South-Central and Eastern Plains; in California, the South-Central Cornbelt, the Gulf and Delta regions and the Atlantic Coast temperatures are lower under EN. Under EN in spring the U.S. is mostly warmer than Neutral, especially in the North Central and South-Central Cornbelt; it is cooler in the South-Central Plains, Texas and Gulf regions. In summer EN brings moderately warmer conditions to most of the U.S., particularly the Northern and Eastern Plains and part of the Northeast and Central Cornbelt; cooler to the Pacific Northwest, Gulf and Delta regions. In fall the Pacific Northwest, California and the Northern Plains are moderately warmer under EN; temperatures are moderately cooler than Neutral over the rest of the U.S..

Precipitation under EN conditions deviate from Neutral as follows: significantly lower than Neutral precipitation in winter in most of the U.S. (by as much as 45%) except for portions of the South Central Plains, Texas, the Gulf and Delta Regions and the Southeast where it is increased by as much as

46%. The pattern in spring for EN is similar to that in winter with even more of the U.S. experiencing decreases in precipitation. Only scattered locations in the Eastern Plains, the Northern Plains and Lake regions and the Gulf coast receiving more. Almost all of the U.S. experiences decreased precipitation under EN during summer. The sparse summer precipitation in California is decreased even further. Increases occur only in the Pacific Northwest, Gulf and eastern Lake States. Decreases under EN in fall are severe in most of the U.S.— worst in the PNW, California and Northern Plains states. Increases occur only in the South Central Plains, Texas, the Southeast and South Atlantic region.

Strong El Niño. Winter in the United States under SEN conditions is sharply warmer the Northern and Eastern Plains, the Lake States, Northeast and Central Cornbelt and the North Atlantic region; it is moderately warmer through the rest of the U.S. except mildly cooler in California and the Gulf region. Spring is sharply cooler in the North and South Central Plains, Texas, the Gulf and Delta regions and moderately warmer in the rest of the U.S. Summer is sharply warmer in the Northeast and Central Cornbelt, the eastern Lake states and the North Atlantic region; moderately warmer in the rest of the U.S.; cooler in Texas, the Gulf and Delta regions. Fall under SEN is cooler than Neutral in the Pacific Northwest, California, Northern and South Central Plains, Texas and Gulf; mildly warmer elsewhere.

Precipitation patterns under SEN in winter are as follows: increases occur throughout much of the U.S. with the largest in the South Central and Eastern Plains, Texas, the Gulf and Delta and the Southeast the Northern Plains are short of precipitation as are parts of the Pacific Northwest and the Eastern Lake States. In spring increases in precipitation ranging from 10 to 80% occur in the Central and Eastern Plains, the Cornbelt and southern U.S. from Texas to the South Atlantic and in the North Atlantic as well only the Pacific Northwest, California and the Northern Plains experience decreased precipitation. Much of the U.S. experiences significantly decreased precipitation in summer under SEN conditions. Increases occur only in the Northern and Eastern Plains, Northern and Central Cornbelt, Texas, the Gulf and Delta the Southeast, eastern Lake States and Atlantic coast. Precipitation in fall is increased (above Neutral over most of the U.S. Increases greater than 100% occur in California and in the Eastern Plains; the Pacific Northwest region is short of precipitation and decreases also occur in a small number of widely scattered locations.

El Viejo. Winter temperatures under EV conditions are sharply above Neutral in the South central and eastern Plains, the North Central Cornbelt, Texas, the Gulf and Atlantic Coast; it is mildly cooler only in California and the Northern Plains. Spring under EV is mildly warmer throughout the U.S except for mildly cooler in the Pacific Northwest, California, Northern Plains, the Lake States and scattered locations elsewhere. Summer is generally cooler throughout the U.S. (but not by more than 1 C); scattered locations are mildly warmer. Deviations from Neutral are modest in fall; most of the U.S. is slightly warmer but California and North, South Central and Eastern Plains are slightly cooler.

Increases in precipitation, generally moderate, are typical of winter under El Viejo; decreases do occur in California, the South Central and Eastern Plains, the Northern Plains and Lake regions, Texas and the Atlantic Coast. In spring under EV moderate decreases in precipitation predominate over the U.S but increases occur in the Lake States and Northern Cornbelt, Texas and the Gulf Coast. Precipitation is increased in summer under EV conditions in the Pacific Northwest, the Northern Plains, the South Central Cornbelt, Texas and the Delta region. In California the few additional millimeters yield a very large relative increase (>200%). Changes in fall are relatively minor. Increases predominate but no one farm experiences a change >30% and most increases are much smaller.

B.2.3. Mexico

There are regional differences in ENSO effects on temperature and precipitation in Mexico Temperatures increase most in the Arid and Semiarid Northern region during the winter and spring during EN events; however, the highest seasonal temperature increase encountered (0.8 °C in summer occurred under EV conditions (Table III.5). Under all ENSO conditions the farms in this region confront warmer conditions, except during fall under SEN when temperatures are 0.2 °C below Neutral.

The largest deviations from Neutral temperatures occur in the Temperate region. The maximum temperature increase of 2.1 °C occur in winter on farm M12 under EN conditions; the greatest temperature reduction of 2.3 °C occurs in winter on farm M15. Also, the greatest regional scale reduction in temperature (0.6°C) occurs during summer under EN. The Central Temperate region is cooler in both EN and SEN years. Cooler weather extends to the fall months in most parts of the country only when SEN conditions prevail.

The Humid Tropical Southeastern region is warmer than Neutral during EN events-- 0.7 °C in winter and 0.6 °C in spring. Temperatures are lower than Neutral in all seasons during SEN years. The Dry Tropical region has reduced temperatures in summer and fall but in winter and spring temperatures are above Neutral under all ENSO states.

Precipitation tends to increase under EV and SEN at most locations in Mexico (Table III.6). The Arid and Semiarid Region shows greater than Neutral precipitation under EN conditions throughout the year. Under EV precipitation is increased by 48% in spring but reduced by about 40% in winter. Under SEN precipitation is reduced by 25% in spring. In EN years the Humid Tropical region experiences reductions in total annual rainfall due to seasonal shortages of 10% in winter, 12% in spring, 3% in summer and 9% in the fall. However, the opposite situation prevails in the Dry Tropical region in which rainfall increases above Neutral most of the time under all three ENSO conditions.

In general, under EN, SEN or EV conditions, farms in the Arid/ Semiarid and Dry Tropical regions are wetter than in Neutral years, while farms of the Temperate and Humid Tropical regions are drier for at least part of the year. Temperature and precipitation deviations from Neutral occur throughout the year and throughout the country and significantly impact crop productivity, runoff and erosion, as reported in the sections that follow.

Table III.1. Seasonal average air temperatures for 51 Canadian farms in Neutral (N) years and deviations from Neutral in El Niño (EN), Strong El Niño (SEN), and El Viejo (EV) years.

Farm	DJF				MAM				JJA				SON			
	N	EN	SEN	EV	N	EN	SEN	EV	N	EN	SEN	EV	N	EN	SEN	EV
	°C	---- deviation (°C) ----			°C	---- deviation (°C) ----			°C	---- deviation (°C) ----			°C	---- deviation (°C) ----		
C1	3.6	0.8	0.6	-0.4	9.1	0.0	0.6	-0.4	16.8	-0.4	-0.7	-0.5	10.0	0.4	-0.6	-0.2
C2	3.3	0.8	-0.6	-0.4	9.8	0.0	0.6	-0.1	17.6	-0.2	-0.8	-0.2	11.1	0.1	0.1	-0.4
C3	-12.3	3.5	1.1	-1.1	2.5	0.4	0.8	-0.6	14.7	-0.7	-0.9	-0.6	3.0	0.4	-0.9	-1.1
C4	-12.0	2.8	1.5	-1.1	2.9	0.7	0.9	-0.6	15.0	-0.1	-0.2	0.0	3.5	0.4	-1.1	-0.9
C5	-12.8	3.0	1.6	-1.4	2.8	0.6	0.7	-0.9	15.2	-0.4	0.0	-0.4	3.2	0.3	-1.2	-1.3
C6	-10.2	3.3	1.9	-1.0	2.8	1.0	0.5	-0.5	14.7	-0.3	0.0	-0.1	3.9	0.5	-1.0	-1.0
C7	-7.4	3.2	3.2	-0.4	5.1	0.9	0.8	-0.3	17.3	0.0	0.5	-0.2	6.3	0.6	-0.7	-0.8
C8	-7.4	3.2	3.2	-0.4	5.1	0.9	0.8	-0.3	17.3	0.0	0.5	-0.2	6.3	0.6	-0.7	-0.8
C9	-8.7	3.2	2.5	-0.8	3.6	0.7	0.6	-0.5	15.4	-0.1	0.3	-0.2	4.6	0.5	-0.7	-0.9
C10	-12.8	3.0	1.6	-1.4	2.8	0.6	0.7	-0.9	15.2	-0.4	0.0	-0.4	3.2	0.3	-1.2	-1.3
C11	-12.8	3.0	1.6	-1.4	2.8	0.6	0.7	-0.9	15.2	-0.4	0.0	-0.4	3.2	0.3	-1.2	-1.3
C12	-10.3	3.3	3.0	-0.6	5.1	1.2	1.1	-0.4	18.2	0.2	0.2	-0.2	5.9	0.4	-1.3	-0.8
C13	-10.3	3.3	3.0	-0.6	5.1	1.2	1.1	-0.4	18.2	0.2	0.2	-0.2	5.9	0.4	-1.3	-0.8
C14	-15.6	3.0	1.8	-1.2	2.4	0.5	0.9	-0.3	15.9	-0.4	0.3	0.0	2.7	0.2	-1.2	-0.9
C15	-9.5	3.0	3.2	-0.4	5.6	1.1	0.9	-0.2	18.6	0.0	0.3	-0.1	6.3	0.1	-1.2	-1.0
C16	-15.0	3.2	1.6	-0.8	1.9	1.0	1.0	-0.4	15.2	0.1	0.4	0.1	2.8	0.2	-1.1	-1.2
C17	-16.0	2.9	2.5	-0.8	2.4	0.9	0.7	-0.4	16.9	-0.1	0.5	0.1	3.4	0.2	-1.3	-0.9
C18	-11.9	2.9	3.3	-0.6	3.5	1.2	0.6	-0.5	17.1	0.1	0.8	-0.2	4.5	0.3	-1.2	-0.9
C19	-11.9	2.9	3.3	-0.6	3.5	1.2	0.6	-0.5	17.1	0.1	0.8	-0.2	4.5	0.3	-1.2	-0.9
C20	-16.0	2.9	2.5	-0.8	2.4	0.9	0.7	-0.4	16.9	-0.1	0.5	0.1	3.4	0.2	-1.3	-0.9
C21	-11.9	2.9	3.3	-0.6	3.5	1.2	0.6	-0.5	17.1	0.1	0.8	-0.2	4.5	0.3	-1.2	-0.9
C22	-17.9	2.5	2.0	-1.1	1.2	0.8	0.2	-0.4	16.2	0.0	0.6	-0.2	2.3	0.0	-1.2	-0.7
C23	-17.9	2.5	2.0	-1.1	1.2	0.8	0.2	-0.4	16.2	0.0	0.6	-0.2	2.3	0.0	-1.2	-0.7
C24	-14.7	2.7	3.2	-0.8	3.0	0.9	-0.1	-0.8	17.7	0.3	1.0	0.0	4.2	0.4	-0.8	-0.6
C25	-14.9	2.6	3.3	-0.9	3.0	1.0	0.3	-0.9	17.8	0.1	0.8	-0.1	4.1	0.1	-1.1	-0.8
C26	-17.4	2.6	1.9	-1.0	1.0	1.0	0.0	-0.5	16.5	0.0	0.3	-0.4	2.7	0.1	-1.3	-0.8
C27	-17.4	2.6	1.9	-1.0	1.0	1.0	0.0	-0.5	16.5	0.0	0.3	-0.4	2.7	0.1	-1.3	-0.8
C28	-14.7	2.7	3.2	-0.8	3.0	0.9	-0.1	-0.8	17.7	0.3	1.0	0.0	4.2	0.4	-0.8	-0.6
C29	-13.8	2.6	3.1	-0.8	3.6	1.0	-0.2	-0.8	18.1	0.4	1.0	-0.2	4.8	0.2	-1.1	-0.9
C30	-16.6	2.3	2.0	-0.9	1.8	0.7	-0.5	-0.9	16.9	0.2	0.9	-0.2	3.3	-0.1	-1.1	-0.6
C31	-17.0	2.1	2.3	-0.8	1.7	0.5	-0.7	-0.8	17.1	0.2	0.8	-0.2	3.4	0.0	-1.0	-0.6
C32	-16.6	1.7	3.5	-0.8	2.2	0.8	0.6	-0.6	17.3	0.4	1.1	-0.1	3.7	0.0	-0.6	-0.5
C33	-16.4	2.4	2.2	-0.8	1.7	0.9	-0.4	-0.5	17.1	0.4	1.1	0.0	3.8	0.0	-0.8	-0.3
C34	-16.6	1.7	3.5	-0.8	2.2	0.8	0.6	-0.6	17.3	0.4	1.1	-0.1	3.7	0.0	-0.6	-0.5
C35	-15.4	1.9	3.3	-0.7	2.8	1.1	0.6	-0.5	18.2	0.5	1.2	-0.1	4.8	0.2	-0.8	-0.2
C36	-14.4	2.0	3.7	-0.5	3.6	1.1	0.8	-0.6	18.8	0.7	1.3	0.1	5.5	0.2	-1.0	-0.1
C37	-16.4	1.6	3.1	-0.9	2.7	0.8	0.6	-0.9	18.2	0.5	1.2	-0.2	4.5	0.1	-1.0	-0.1
C38	-16.4	1.6	3.1	-0.9	2.7	0.8	0.6	-0.9	18.2	0.5	1.2	-0.2	4.5	0.1	-1.0	-0.1

Table III.1 (continued). Seasonal average air temperatures for 51 Canadian farms in Neutral (N) years and deviations from Neutral in El Niño (EN), Strong El Niño (SEN), and El Viejo (EV) years.

Farm	DJF				MAM				JJA				SON			
	N	EN	SEN	EV	N	EN	SEN	EV	N	EN	SEN	EV	N	EN	SEN	EV
	°C	---- deviation (°C) ----			°C	---- deviation (°C) ----			°C	---- deviation (°C) ----			°C	---- deviation (°C) ----		
C39	-15.9	1.0	3.4	-1.1	2.7	0.9	1.3	-0.7	17.8	0.7	1.4	0.0	4.4	0.0	-0.5	0.1
C40	-4.3	0.4	3.1	1.3	7.9	0.9	0.3	-0.3	20.9	0.8	1.4	0.0	10.8	-0.1	0.2	0.5
C41	-4.3	0.4	3.1	1.3	7.9	0.9	0.3	-0.3	20.9	0.8	1.4	0.0	10.8	-0.1	0.2	0.5
C42	-8.8	0.2	1.5	-0.4	5.2	1.1	0.8	-0.5	19.3	0.2	1.2	-0.4	7.9	0.0	0.3	0.7
C43	-8.1	-0.2	0.7	-0.9	3.9	0.8	1.3	-0.1	17.9	-0.2	1.0	-0.2	7.2	-0.7	-0.1	0.2
C44	-8.1	-0.2	0.7	-0.9	3.9	0.8	1.3	-0.1	17.9	-0.2	1.0	-0.2	7.2	-0.7	-0.1	0.2
C45	-7.4	-0.3	0.6	-0.6	2.8	0.8	1.4	0.3	17.0	-0.1	0.9	-0.1	7.4	-0.5	-0.5	0.1
C46	-7.4	-0.3	0.6	-0.6	2.8	0.8	1.4	0.3	17.0	-0.1	0.9	-0.1	7.4	-0.5	-0.5	0.1
C47	-7.4	-0.3	0.6	-0.6	2.8	0.8	1.4	0.3	17.0	-0.1	0.9	-0.1	7.4	-0.5	-0.5	0.1
C48	-6.4	-0.3	0.4	-0.7	2.6	0.6	1.2	0.2	17.3	-0.1	0.8	-0.1	8.4	-0.6	-0.4	0.0
C49	-6.4	-0.3	0.4	-0.7	2.6	0.6	1.2	0.2	17.3	-0.1	0.8	-0.1	8.4	-0.6	-0.4	0.0
C50	-4.6	-0.4	1.4	-0.9	4.2	0.5	1.6	0.3	17.5	-0.2	0.3	0.1	9.0	-0.6	0.6	0.0
C51	-5.2	-0.5	0.6	-0.7	3.6	0.4	1.4	0.2	16.9	-0.2	0.6	-0.1	8.4	-0.6	-0.5	0.2

Table III.2. Seasonal average precipitation for 51 Canadian farms in Neutral (N) years and deviations from Neutral in El Niño (EN), Strong El Niño (SEN), and El Viejo (EV) years.

Farm	DJF				MAM				JJA				SON			
	N	EN	SEN	EV	N	EN	SEN	EV	N	EN	SEN	EV	N	EN	SEN	EV
	mm	----- deviation (%) -----			mm	----- deviation (%) -----			mm	----- deviation (%) -----			mm	----- deviation (%) -----		
C1	457	-20	18	7	242	-3	-8	12	115	-1	12	11	368	-20	-23	1
C2	703	-20	0	22	370	16	-11	22	188	-2	-26	17	531	-11	-50	12
C3	89	-26	-21	10	74	36	-22	5	161	46	42	52	100	-26	-1	15
C4	46	-9	-52	53	81	-2	1	4	215	6	11	10	88	-13	-34	-19
C5	58	-24	-47	29	77	13	-8	-2	228	10	35	14	87	-15	-10	-7
C6	60	-40	-26	36	108	-14	-13	-14	216	12	-15	13	107	-22	-47	-21
C7	54	-24	-33	24	125	-23	-35	-11	149	14	-13	13	86	-25	-41	-10
C8	54	-24	-33	24	125	-23	-35	-11	149	14	-13	13	86	-25	-41	-10
C9	35	-41	13	31	103	-24	-27	-21	174	30	2	24	85	-23	-54	-6
C10	58	-24	-47	29	77	13	-8	-2	228	10	35	14	87	-15	-10	-7
C11	58	-24	-47	29	77	13	-8	-2	228	10	35	14	87	-15	-10	-7
C12	50	-23	-18	26	97	-38	-49	-23	113	43	32	11	78	-31	-42	-19
C13	50	-23	-18	26	97	-38	-49	-23	113	43	32	11	78	-31	-42	-19
C14	58	-28	-41	15	77	12	-16	8	202	24	8	19	70	-7	50	30
C15	45	-18	-23	15	93	-27	-32	-11	115	24	29	22	77	-32	-40	-23
C16	50	-36	-42	10	71	4	-30	-8	203	0	67	8	69	-15	25	19
C17	51	-16	-36	14	77	6	0	-6	174	14	10	5	59	-20	45	21
C18	55	-6	-41	37	89	-8	23	3	138	29	-19	25	71	-20	-52	7
C19	55	-6	-41	37	89	-8	23	3	138	29	-19	25	71	-20	-52	7
C20	51	-16	-36	14	77	6	0	-6	174	14	10	5	59	-20	45	21
C21	55	-6	-41	37	89	-8	23	3	138	29	-19	25	71	-20	-52	7
C22	48	3	-28	11	86	-15	-5	-12	176	24	32	22	74	6	53	2
C23	48	3	-28	11	86	-15	-5	-12	176	24	32	22	74	6	53	2
C24	53	-36	-18	16	90	21	40	15	164	2	42	14	99	-37	-14	-27
C25	44	-16	-30	24	87	0	14	-1	150	14	39	21	74	-23	7	-15
C26	57	-1	-50	-9	83	-4	10	-7	155	16	98	32	88	-6	-11	1
C27	57	-1	-50	-9	83	-4	10	-7	155	16	98	32	88	-6	-11	1
C28	53	-36	-18	16	90	21	40	15	164	2	42	14	99	-37	-14	-27
C29	47	-19	10	31	95	13	-5	7	168	-16	-20	9	82	-31	18	-12
C30	59	-6	-25	11	89	32	24	5	184	-2	60	6	110	-38	-42	-27
C31	62	9	-1	28	88	43	47	20	193	19	27	20	120	-24	-19	4
C32	57	-20	-36	7	106	-1	-7	-12	199	6	12	8	87	-17	38	10
C33	57	-15	-16	6	115	-8	-6	-13	209	2	4	0	123	-25	-3	2
C34	57	-20	-36	7	106	-1	-7	-12	199	6	12	8	87	-17	38	10
C35	68	-12	-35	3	124	-9	-7	6	241	-7	-13	-9	112	-15	3	-4
C36	59	4	-31	16	133	-6	-38	23	208	18	-7	-3	102	-6	77	16
C37	52	-2	-10	6	116	6	4	9	228	-1	17	4	101	4	17	0

Table III.2 (continued). Seasonal average precipitation for 51 Canadian farms in Neutral (N) years and deviations from Neutral in El Niño (EN), Strong El Niño (SEN), and El Viejo (EV) years.

Farm	DJF				MAM				JJA				SON			
	N	EN	SEN	EV	N	EN	SEN	EV	N	EN	SEN	EV	N	EN	SEN	EV
	mm	----- deviation (%) -----			mm	----- deviation (%) -----			mm	----- deviation (%) -----			mm	----- deviation (%) -----		
C38	52	-2	-10	6	116	6	4	9	228	-1	17	4	101	4	17	0
C39	59	-22	-34	5	113	12	-31	3	217	17	3	2	106	-10	89	8
C40	180	-17	-16	18	229	-8	20	-2	280	-4	14	-19	232	-19	2	-15
C41	180	-17	-16	18	229	-8	20	-2	280	-4	14	-19	232	-19	2	-15
C42	196	-11	24	14	212	-24	48	2	284	-9	-30	-8	268	-2	-12	-16
C43	294	-6	6	4	270	-20	38	-1	294	-15	-18	-13	312	-4	-9	-17
C44	294	-6	6	4	270	-20	38	-1	294	-15	-18	-13	312	-4	-9	-17
C45	348	-8	-8	-2	329	-19	-8	-8	295	-17	14	-12	317	-5	-22	-16
C46	348	-8	-8	-2	329	-19	-8	-8	295	-17	14	-12	317	-5	-22	-16
C47	348	-8	-8	-2	329	-19	-8	-8	295	-17	14	-12	317	-5	-22	-16
C48	293	-13	-6	-3	247	-16	10	3	267	-13	0	-15	291	0	-14	-16
C49	293	-13	-6	-3	247	-16	10	3	267	-13	0	-15	291	0	-14	-16
C50	297	-2	-12	9	257	-16	18	-25	271	-14	-5	-26	314	-15	-45	-6
C51	350	-13	-11	6	286	-11	12	-7	277	16	52	-1	330	-1	-4	0

Table III.3. Seasonal average air temperatures for 66 U.S. farms in Neutral (N) years and deviations from Neutral in El Niño (EN), Strong El Niño (SEN), and El Viejo (EV) years.

Farm	DJF				MAM				JJA				SON			
	N	EN	SEN	EV	N	EN	SEN	EV	N	EN	SEN	EV	N	EN	SEN	EV
	°C	---- deviation (°C) ----			°C	---- deviation (°C) ----			°C	---- deviation (°C) ----			°C	---- deviation (°C) ----		
U1	-0.8	0.8	1.3	0.7	10.7	0.2	0.7	-0.1	21.4	-0.8	0.1	-0.6	10.6	0.6	-0.9	0.4
U2	1.7	1.0	1.1	1.3	11.0	0.5	0.5	0.5	21.0	0.3	0.4	0.6	11.3	0.9	0.0	0.9
U3	-2.7	1.1	0.8	0.9	7.9	0.2	0.1	-0.3	17.8	-0.4	0.7	0.0	7.5	0.4	-0.5	-0.1
U4	-4.9	0.1	-0.5	0.0	7.4	-0.4	-0.5	-0.1	19.4	0.1	0.1	-0.4	7.9	0.4	-0.1	-0.4
U5	8.4	-0.1	-0.4	-0.2	15.4	0.5	0.5	0.3	24.4	-0.1	0.0	-0.3	17.2	0.3	-0.6	-0.3
U6	9.1	-0.4	-0.5	-0.6	13.5	0.3	0.2	0.5	21.4	0.1	-0.1	-0.1	16.1	0.2	-0.4	-0.2
U7	-9.7	2.5	3.3	-0.3	6.1	1.2	1.0	-0.5	19.7	0.2	0.9	-0.1	7.1	0.2	-0.9	-0.5
U8	-3.0	2.1	2.4	0.6	9.4	0.3	-0.2	-0.3	22.2	-0.3	1.6	-0.4	10.1	0.2	-0.5	-0.6
U9	-6.0	2.1	1.8	0.7	7.4	0.4	-1.8	-0.3	19.8	1.0	0.9	-0.1	7.8	0.3	-1.2	-0.4
U10	-10.3	1.9	3.6	-0.2	5.5	1.0	0.1	0.0	19.9	0.6	1.4	0.1	7.1	0.3	-1.1	-0.5
U11	0.0	-0.2	0.6	1.2	11.8	-0.5	-1.8	0.5	24.3	0.2	0.2	-0.4	12.3	0.2	-0.7	-0.2
U12	1.3	-0.4	-0.4	0.8	11.2	-0.3	-2.1	0.4	22.7	0.4	0.0	-0.3	12.5	-0.1	-1.0	-0.1
U13	-1.3	0.3	0.9	1.1	10.6	-0.1	-1.0	0.6	23.5	0.4	1.0	-0.2	12.0	0.0	-1.0	-0.5
U14	-1.4	0.9	1.5	1.5	11.6	0.2	-1.1	0.2	24.6	0.4	1.2	-0.3	12.8	-0.1	-1.1	-0.4
U15	-3.7	1.8	1.5	1.2	11.0	1.0	-0.9	0.0	23.6	0.3	1.3	-0.3	12.2	-0.1	-0.8	-0.3
U16	-4.4	1.2	2.2	1.1	9.3	0.0	-1.1	0.1	22.6	0.6	0.8	0.2	10.4	-0.2	-1.7	-0.6
U17	-8.8	1.8	2.6	0.7	8.0	1.3	-0.3	0.0	21.5	1.0	1.4	0.2	9.1	0.1	-0.6	-0.3
U18	-9.8	1.6	2.9	0.9	7.4	1.6	-0.3	-0.4	20.9	1.1	1.4	0.1	8.9	0.3	-0.6	-0.1
U19	-0.6	1.4	0.9	1.6	13.5	0.5	-1.8	-0.1	26.2	0.2	-0.1	-0.9	14.9	-0.3	-1.2	-0.6
U20	2.6	0.6	1.5	1.8	15.6	0.3	-1.0	0.0	26.3	0.3	-0.3	-0.9	16.9	-0.4	-0.6	-0.4
U21	-2.2	1.3	2.4	2.0	12.7	0.8	-0.7	0.3	24.4	0.2	1.2	-0.4	13.9	-0.1	-0.5	0.0
U22	0.2	0.3	1.3	1.9	13.2	0.4	-1.1	0.0	23.7	0.2	0.5	-0.5	14.3	-0.4	-0.7	0.1
U23	2.6	0.2	1.4	1.8	15.0	0.6	-1.1	-0.2	25.4	0.3	0.1	-0.8	16.0	-0.3	-0.7	-0.1
U24	-18.4	0.3	0.3	0.5	3.3	0.0	0.1	0.4	17.4	0.0	0.3	0.2	5.1	0.1	0.5	0.1
U25	-11.0	1.2	2.5	0.0	6.2	1.3	0.2	-0.5	19.7	1.3	1.2	0.1	7.5	0.2	-0.4	0.0
U26	-10.0	1.2	2.9	-0.2	5.0	0.9	-0.3	-0.7	18.1	0.8	1.2	-0.1	7.5	0.0	-0.5	0.0
U27	-8.1	1.1	2.3	0.2	3.9	0.7	-0.3	-0.7	16.3	0.8	1.8	-0.2	7.1	0.2	0.3	0.7
U28	-6.3	0.8	3.2	0.8	6.6	0.9	-0.3	-0.5	19.4	1.1	1.8	-0.1	9.9	-0.1	-0.1	0.2
U29	-5.3	0.9	2.5	1.2	7.5	1.4	0.4	0.0	19.9	1.5	1.7	0.7	10.1	0.2	0.3	0.9
U30	-7.7	0.8	3.2	1.0	8.4	1.6	0.2	-0.1	21.2	0.8	1.5	-0.1	10.1	-0.1	0.1	0.2
U31	-5.7	1.0	3.4	1.6	10.0	1.3	0.0	0.1	22.4	0.7	1.8	-0.1	11.7	-0.2	-0.2	0.3
U32	-4.2	0.6	3.3	1.5	9.3	1.0	0.1	-0.2	21.1	0.9	1.6	0.1	11.5	-0.3	0.1	0.2
U33	-3.1	0.2	3.4	1.9	10.6	1.3	0.5	0.3	22.4	0.6	1.3	-0.2	12.7	-0.4	0.0	0.1

Table III.3 (continued). Seasonal average air temperatures for 66 U.S. farms in Neutral (N) years and deviations from Neutral in El Niño (EN), Strong El Niño (SEN), and El Viejo (EV) years.

Farm	DJF				MAM				JJA				SON			
	N	EN	SEN	EV	N	EN	SEN	EV	N	EN	SEN	EV	N	EN	SEN	EV
	°C	---- deviation (°C) ----			°C	---- deviation (°C) ----			°C	---- deviation (°C) ----			°C	---- deviation (°C) ----		
U34	-1.5	0.4	2.9	2.2	12.6	1.0	-0.3	0.2	23.8	0.5	0.9	-0.2	13.9	-0.2	-0.1	0.1
U35	-0.1	0.2	2.2	1.6	13.1	1.5	-0.9	-0.3	24.4	1.0	0.8	-0.9	14.4	0.1	0.0	-0.2
U36	1.4	-0.3	2.7	2.1	13.8	0.6	-0.2	0.1	24.0	0.2	0.9	-0.7	14.7	-0.2	0.8	0.2
U37	2.1	-0.2	1.9	2.0	14.8	0.6	-0.8	-0.1	24.9	0.2	0.8	-0.5	15.6	-0.3	0.1	0.1
U38	3.0	-0.3	1.7	2.2	14.6	0.5	-0.6	0.2	24.3	0.4	0.5	-0.4	15.4	-0.1	0.0	0.3
U39	1.9	-0.7	2.0	1.8	12.9	0.7	0.0	-0.1	22.3	0.7	0.6	-0.2	13.9	-0.4	0.5	0.2
U40	0.6	-0.5	2.5	2.2	12.3	0.5	0.1	0.1	21.8	0.9	1.0	0.1	13.3	-0.4	0.6	0.8
U41	4.9	-0.1	-0.2	1.7	16.9	-0.4	-1.6	0.2	27.3	0.2	-0.1	-0.7	17.4	-0.4	-0.8	-0.2
U42	5.7	-0.2	-0.9	1.1	17.4	-0.4	-2.0	0.0	27.5	0.2	-0.7	-0.9	17.8	-0.4	-0.8	-0.3
U43	3.9	0.6	0.5	1.7	16.3	0.3	-1.3	0.4	26.9	0.3	-0.6	-0.5	17.5	-0.1	-1.3	-0.4
U44	6.9	-0.1	0.2	1.4	18.2	-0.3	-1.6	0.0	28.1	0.2	-1.2	-0.8	19.7	-0.4	-1.0	-0.6
U45	9.3	0.1	0.0	0.0	18.7	0.0	0.1	0.0	27.9	0.0	0.1	0.1	19.5	0.0	0.0	0.0
U46	9.3	0.0	0.1	2.0	19.5	-0.1	-1.4	0.5	27.7	0.5	-0.7	-0.2	20.1	0.1	-0.6	0.4
U47	13.8	-0.7	-1.1	1.3	23.2	-1.0	-1.0	-0.5	29.1	-0.1	-1.0	-0.7	23.4	-0.3	-0.9	-0.2
U48	11.7	-0.6	-0.3	1.2	20.8	-0.6	-1.2	-0.3	28.6	-0.3	-0.8	-0.7	22.2	-0.6	-0.9	-0.3
U49	10.9	-0.5	0.3	1.8	20.2	-0.2	-1.1	0.1	27.8	-0.2	-0.3	-0.5	21.3	-0.2	-0.6	0.1
U50	11.4	-0.1	0.1	-0.1	19.7	0.0	0.1	0.0	27.6	-0.1	-0.3	0.0	20.1	-0.1	0.1	0.1
U51	5.9	-0.2	0.9	1.9	17.3	0.4	-1.6	0.0	26.5	0.4	-0.5	-0.5	17.6	0.2	-0.4	0.1
U52	5.4	0.1	1.0	2.0	17.0	0.5	-1.3	-0.1	26.5	0.5	0.7	-0.2	17.4	0.2	-0.4	0.2
U53	9.2	-1.4	0.9	1.3	18.9	0.0	-1.0	-0.5	26.6	0.0	-0.1	-0.3	19.3	0.0	0.2	0.1
U54	7.6	-1.0	1.2	1.6	17.5	0.1	-0.4	0.2	26.3	0.1	0.5	-0.6	18.2	-0.2	0.3	0.1
U55	12.1	-0.8	0.8	1.5	19.9	0.2	-0.5	0.0	27.3	-0.1	0.4	-0.2	21.4	0.0	0.5	0.0
U56	16.2	-0.6	0.9	1.5	22.2	-0.2	-0.8	0.4	27.9	0.1	-0.1	-0.4	24.1	-0.2	0.2	0.0
U57	-2.8	0.3	3.1	1.9	9.2	1.0	0.8	0.2	20.5	0.5	1.2	0.1	11.8	-0.1	0.1	0.7
U58	-3.2	0.1	2.2	0.6	7.9	1.4	0.8	0.0	20.4	0.5	1.4	-0.1	11.3	0.0	0.0	1.1
U59	-7.8	0.4	1.6	0.0	6.1	0.9	1.0	-0.7	19.3	0.2	1.5	-0.1	8.8	-0.1	0.1	0.7
U60	-4.8	0.0	2.3	0.7	7.3	0.7	0.4	-0.5	19.2	0.5	1.1	0.0	9.8	-0.6	-0.2	0.7
U61	-1.4	-0.1	2.4	1.4	10.8	0.5	0.0	0.1	22.4	0.8	1.1	0.2	12.8	-0.3	-0.2	0.7
U62	2.3	-0.3	2.4	1.2	12.0	0.1	0.5	-0.2	23.1	0.4	0.9	-0.2	15.4	-0.5	0.3	-0.1
U63	3.4	-0.6	1.8	1.7	14.4	0.4	0.2	-0.1	24.6	0.5	0.6	-0.1	15.9	-0.4	0.1	0.3
U64	5.3	-0.6	1.2	1.8	15.6	0.6	0.2	0.3	25.0	0.6	0.2	0.1	17.0	-0.3	-0.1	0.2
U65	5.8	-0.9	1.2	1.7	16.6	-0.1	-0.5	0.1	26.2	0.2	0.1	-0.4	17.2	-0.6	0.1	-0.1
U66	7.3	-0.9	0.9	1.8	17.4	0.0	-0.4	-0.3	26.2	0.2	0.1	-0.4	18.1	-0.4	-0.2	0.1

Table III.4. Seasonal average precipitation for 66 U.S. farms in Neutral (N) years and deviations from Neutral in El Niño (EN), Strong El Niño (SEN), and El Viejo (EV) years.

Farm	DJF				MAM				JJA				SON			
	N	EN	SEN	EV	N	EN	SEN	EV	N	EN	SEN	EV	N	EN	SEN	EV
	mm	----- deviation (%) -----			mm	----- deviation (%) -----			mm	----- deviation (%) -----			mm	----- deviation (%) -----		
U1	82	-13	27	-2	63	-40	-23	-19	27	21	-18	26	65	-48	-15	-18
U2	151	-24	-10	8	113	-27	-19	-14	53	35	21	41	108	-46	-13	-6
U3	98	-31	-29	23	108	-9	-46	-16	92	12	25	10	89	-34	-17	14
U4	75	-40	15	-7	95	-13	-27	-10	73	-10	39	-4	72	-40	33	23
U5	282	-33	35	-45	107	-42	81	-21	9	-41	0	59	116	-40	76	-3
U6	246	-47	49	-42	118	-49	63	-40	2	29	200	200	71	-5	151	15
U7	27	-25	-1	19	87	-8	-22	4	139	-10	-12	22	60	-18	-10	-21
U8	56	-28	-12	16	147	6	-18	-14	114	1	-30	9	92	-20	40	12
U9	40	-28	-28	7	125	-10	-22	-3	132	-13	-19	11	76	-14	18	2
U10	32	-16	-13	1	135	1	-27	6	208	-4	-28	-16	77	-16	75	-4
U11	22	22	6	-6	84	-8	50	-27	143	-20	-44	-9	48	23	37	21
U12	28	13	54	-20	115	-2	18	-1	222	-22	-29	-3	89	16	15	-9
U13	33	-5	65	-15	182	-11	9	-31	210	-3	-19	6	78	22	89	6
U14	37	-3	43	-25	193	-14	11	-21	245	-22	-43	-11	95	20	67	16
U15	53	-30	59	17	249	-15	15	-12	280	-1	-26	-21	165	-4	88	12
U16	35	19	-6	-17	157	27	39	-3	241	-8	3	-22	86	27	127	0
U17	50	-21	46	-22	191	-5	-2	-7	289	-23	-13	-26	137	-7	67	6
U18	71	-33	39	-24	202	-7	41	-6	368	-26	-35	-24	150	11	84	40
U19	81	-6	58	-23	223	14	43	-3	271	-1	-25	14	219	-34	24	0
U20	153	2	24	18	326	-12	49	-15	285	7	-8	10	285	-5	36	8
U21	107	-27	51	20	289	-10	52	-18	360	-17	-27	-16	279	-4	10	-23
U22	168	0	42	2	331	-24	48	-11	290	0	-35	0	288	3	14	-4
U23	231	5	46	17	339	-6	60	-8	243	18	-4	4	277	-1	41	17
U24	51	-7	-60	-17	112	50	-10	11	290	-15	19	2	146	-6	36	3
U25	71	-27	-8	-11	178	-3	-6	4	312	-10	5	-1	187	-33	16	9
U26	114	-20	29	-4	183	15	8	11	296	-7	1	6	223	-6	28	2
U27	175	-17	-5	12	154	14	42	29	245	3	12	-11	238	-2	-15	-4
U28	104	-21	50	10	180	12	58	17	308	-27	-33	-23	209	-8	7	2
U29	116	-25	47	24	189	-15	50	16	251	-16	-21	-7	234	-13	-10	-14
U30	82	-23	51	6	239	-9	36	-1	376	-20	-31	-25	203	-13	35	4
U31	111	-15	32	26	240	13	49	13	320	-6	-29	-8	225	-10	10	5
U32	150	-27	-6	19	239	-7	20	9	289	-19	-9	-6	217	-4	6	2
U33	184	-24	-7	22	299	-15	-3	-4	319	-22	-7	-10	209	-19	2	26

Table III.4 (continued). Seasonal average precipitation for 66 U.S. farms in Neutral (N) years and deviations from Neutral in El Niño (EN), Strong El Niño (SEN), and El Viejo (EV) years.

Farm	DJF				MAM				JJA				SON			
	N	EN	SEN	EV	N	EN	SEN	EV	N	EN	SEN	EV	N	EN	SEN	EV
	mm	----- deviation (%) -----			mm	----- deviation (%) -----			mm	----- deviation (%) -----			mm	----- deviation (%) -----		
U34	203	-13	21	4	329	-22	24	-13	292	-15	9	-11	246	-21	-11	0
U35	221	-15	36	2	322	-5	79	-13	305	-15	-36	-5	255	-13	5	2
U36	293	-9	-5	35	358	-17	49	6	357	-2	-25	-3	299	-16	-29	-9
U37	308	-4	42	23	391	-14	65	-9	325	-7	-32	11	298	1	-6	18
U38	332	-9	25	22	420	-18	58	-16	295	-6	-17	20	280	3	15	3
U39	273	-8	-18	5	280	-4	33	11	328	-14	1	-5	250	-18	-6	7
U40	258	-12	-1	10	323	-23	30	3	386	-18	-8	-1	269	-8	-1	4
U41	48	10	77	-21	126	-2	31	13	223	-8	-35	-7	149	1	2	-5
U42	53	31	126	-14	159	-7	-11	-25	204	-16	-61	3	185	-11	-21	-29
U43	116	14	40	-2	297	-4	25	-20	223	-12	2	18	248	-1	35	5
U44	203	19	33	14	314	-6	15	3	195	-23	43	3	253	15	36	18
U45	286	-2	45	12	307	-4	20	6	244	-8	21	25	272	5	55	7
U46	261	4	25	14	278	-12	43	11	222	-12	85	22	289	-14	49	0
U47	100	43	24	-7	136	33	-43	29	194	-2	54	0	222	5	45	2
U48	225	17	24	-2	243	13	37	23	250	-6	102	11	337	-7	41	-11
U49	291	32	57	17	291	-1	76	15	463	19	2	-10	358	-9	58	-24
U50	355	29	54	5	380	3	46	-24	452	5	-10	2	329	-3	61	6
U51	291	10	64	26	366	-12	27	-7	286	-28	-12	35	294	10	54	4
U52	327	7	76	29	387	-6	52	-4	286	-23	-17	18	274	-9	50	3
U53	407	3	31	-10	407	-15	32	-19	536	-4	-10	-17	295	13	8	19
U54	346	0	22	1	352	-4	24	-4	326	-11	-19	6	225	2	33	13
U55	284	46	18	-16	297	9	52	-20	621	-2	-19	-8	250	43	15	-7
U56	178	24	68	-30	215	0	24	-9	559	-8	-1	11	248	35	17	-3
U57	179	-19	-16	23	266	-9	18	-9	297	13	-4	-5	236	-12	2	0
U58	192	-6	-22	16	201	-6	50	14	240	3	-21	11	258	-8	-13	-9
U59	193	-15	2	11	204	-3	49	18	296	-3	-22	0	264	-1	8	-4
U60	187	-8	-10	-2	222	-6	27	9	287	-9	-16	-4	216	9	5	4
U61	227	-15	8	-6	253	-1	59	7	296	-19	-26	12	241	17	10	-1
U62	291	0	-3	-21	278	-14	28	-5	338	-37	1	6	232	-3	32	3
U63	268	0	-6	-9	289	-20	20	-10	356	-23	-33	-4	278	-21	12	-12
U64	281	6	10	-6	270	-7	30	16	408	-13	-35	-4	253	-11	-5	0
U65	319	-7	26	-3	312	-12	24	-1	355	-6	-19	7	216	21	14	30
U66	277	-2	32	-13	277	1	35	10	418	-4	-14	10	217	22	5	1

Table III.5. Seasonal average air temperatures for 23 Mexican farms in Neutral (N) years and deviations from Neutral in El Niño (EN), Strong El Niño (SEN), and El Viejo (EV) years.

Farm	DJF				MAM				JJA				SON			
	N	EN	SEN	EV	N	EN	SEN	EV	N	EN	SEN	EV	N	EN	SEN	EV
	°C	---- deviation (°C) ----			°C	---- deviation (°C) ----			°C	---- deviation (°C) ----			°C	---- deviation (°C) ----		
M1	14.5	1.6	1.4	1.5	20.5	0.8	0.3	0.2	31.6	-0.2	1.3	0.6	23.6	0.7	1.3	0.6
M2	17.2	0.7	0.7	0.4	23.4	0.1	1.2	0.3	31.6	-0.3	0.1	0.2	25.7	-0.2	-0.1	0.3
M3	17.7	0.7	0.7	0.6	22.7	0.0	1.4	0.1	30.1	-0.2	0.6	0.4	25.8	0.2	0.7	0.6
M4	19.5	0.5	0.0	0.9	23.3	1.0	0.5	0.8	29.0	0.5	-0.5	1.0	26.1	0.6	-0.4	0.7
M5	24.2	0.4	0.5	0.8	26.4	0.9	0.1	0.5	29.9	0.2	0.1	0.5	28.9	0.0	-0.1	0.5
M6	12.5	0.3	0.5	-0.1	18.7	0.1	0.5	-0.3	22.0	-0.3	0.4	0.7	17.7	0.1	-0.4	0.6
M7	12.3	-0.1	-0.5	-0.2	18.3	0.5	0.0	0.0	20.1	-0.1	0.1	0.5	16.6	0.2	-1.0	0.0
M8	10.8	0.2	0.6	-0.1	17.1	0.6	0.8	0.2	19.4	0.7	0.2	1.6	15.5	0.3	-0.9	0.2
M9	18.2	0.6	0.8	0.8	22.9	0.6	0.4	0.4	23.2	-0.3	0.0	0.0	21.6	0.0	0.9	0.1
M10	15.6	-0.6	0.7	0.4	21.0	-0.3	0.0	0.9	20.5	-0.3	0.3	1.0	18.4	-0.4	-0.1	0.0
M11	27.6	-0.5	0.1	0.4	32.3	0.3	0.7	0.6	29.7	0.4	-1.4	0.4	29.0	-0.1	-1.2	0.1
M12	14.3	2.1	1.0	1.2	19.6	1.2	0.9	0.8	20.4	0.6	0.7	0.4	17.8	1.0	0.4	0.6
M13	14.5	0.4	-0.4	-1.5	24.0	1.0	-2.0	0.3	29.6	0.3	0.5	1.0	23.0	0.6	-1.7	-0.4
M14	14.2	1.5	0.6	-0.9	23.6	1.3	0.6	0.6	28.8	0.7	1.9	1.3	22.5	0.7	0.4	0.3
M15	22.7	-1.7	-2.2	-2.3	27.2	-3.0	-3.6	-2.4	24.3	-3.3	-3.8	-1.9	23.4	0.2	-1.0	-3.0
M16	14.9	1.3	0.5	-1.6	23.5	0.7	1.0	0.3	28.6	0.4	1.2	0.8	24.2	0.6	0.8	-0.5
M17	13.3	-0.1	0.2	1.4	17.8	0.2	-0.5	1.1	17.7	0.1	-0.2	0.8	15.6	-0.2	-0.7	0.3
M18	13.8	-0.2	0.4	0.4	18.3	0.0	0.0	0.2	18.4	-0.4	-0.2	0.0	16.8	-0.4	-0.3	0.1
M19	22.3	0.9	0.1	0.0	27.0	0.3	-0.4	-0.1	27.5	0.0	-0.2	0.2	25.7	0.0	-0.6	0.1
M20	16.6	-0.3	0.3	0.2	21.0	0.0	-0.4	0.1	19.8	-0.3	-1.0	0.2	18.3	-0.3	-0.8	-0.2
M21	22.4	0.7	-0.2	-0.3	27.2	0.4	-0.6	0.2	27.3	-0.4	-0.8	0.0	25.6	0.0	-0.9	-0.2
M22	21.5	0.5	-0.2	-0.1	25.8	0.5	-1.0	0.4	25.6	0.2	-0.3	0.6	23.8	0.0	-1.0	-0.1
M23	22.2	1.1	1.1	1.2	26.1	0.0	0.4	0.5	26.4	0.8	-0.3	1.1	24.0	0.2	-0.6	1.0

Table III.6. Seasonal average precipitation for 23 Mexican farms in Neutral (N) years and deviations from Neutral in El Niño (EN), Strong El Niño (SEN), and El Viejo (EV) years.

Farm	DJF				MAM				JJA				SON			
	N	EN	SEN	EV	N	EN	SEN	EV	N	EN	SEN	EV	N	EN	SEN	EV
	mm	----- deviation (%) -----			mm	----- deviation (%) -----			mm	----- deviation (%) -----			mm	----- deviation (%) -----		
M1	28	27	-36	296	7	-49	4	202	16	73	-57	288	21	-15	-14	147
M2	57	-21	-35	91	13	-52	0	97	163	10	17	-20	89	-14	-12	25
M3	85	-50	-35	83	13	41	31	333	377	1	-7	-3	154	21	-7	64
M4	62	61	-48	55	2	84	434	1243	378	14	6	-22	228	11	-15	29
M5	53	164	93	68	2	619	2447	3241	772	38	-4	16	428	35	-16	64
M6	46	3	-70	-28	16	43	84	417	256	22	11	20	156	-16	18	60
M7	39	27	-53	-36	33	82	46	23	217	43	37	35	113	-5	16	37
M8	45	-11	-56	-6	27	1	81	70	200	54	38	9	99	71	33	42
M9	43	7	-39	8	27	59	199	65	581	-2	-5	-15	218	-8	-12	-7
M10	45	-39	-56	-4	62	-22	38	-33	491	-1	-4	50	197	23	-3	35
M11	59	-80	-89	-87	17	71	40	154	468	10	-11	-31	191	4	-25	-17
M12	46	39	-43	-3	66	25	46	-26	367	18	-1	36	140	10	31	50
M13	46	-19	-65	138	179	-52	-33	-70	170	-63	19	-17	150	-19	-5	-16
M14	75	16	-40	77	225	-5	-22	-13	285	-7	8	96	356	-9	3	-15
M15	23	-73	-43	-35	93	1	-12	-72	483	9	22	12	195	67	26	11
M16	92	39	6	147	130	126	21	-66	153	-18	-6	80	172	27	27	-19
M17	30	-36	-45	-37	102	-4	2	-35	331	6	4	11	148	-4	2	-5
M18	26	-57	-11	70	140	-30	14	-50	267	-22	7	34	138	7	31	50
M19	39	-14	49	4	87	21	32	-68	866	-9	5	2	495	-36	-17	-58
M20	18	-78	-30	-12	145	-4	8	-44	371	14	-12	16	186	-10	-11	4
M21	347	13	12	4	217	-5	-24	-41	861	-15	3	4	866	4	-11	-17
M22	38	-30	49	122	98	-51	-14	-38	449	15	-6	35	237	6	-2	-3
M23	50	102	21	158	126	-5	-49	-19	344	47	5	51	275	16	26	17

C. ENSO effects on crop yields

C. 1 Continental Summary for Corn and Wheat

Corn

The following four maps (Figs. III.3- III.6) show the EPIC-simulated impacts of the various ENSO-states on the continental distribution of dryland corn yields. The first figure of this set shows dryland corn yields under Neutral conditions; the other three figures show deviations from Neutral yield under EN, SEN and EV conditions.

Potential yields under Neutral conditions throughout Canada are in the 4-6 Mg ha^{-1} range (Fig.III.3). Highest potential yields in North America are shown in the Appalachian region of the U.S., although for reasons of topography and economics corn production is much less important there than in the adjacent Corn Belt and Southeast. Yields are lower at the western and northern edges of the Corn Belt. In only two locations in Mexico do potential yields under typical dryland management exceed 6 Mg ha^{-1}.

In the sections that follow, yields on the individual farms are related to the geographic distribution of ENSO-driven climatic anomalies, but a few of the most obvious effects seen in Figs. III.4 - III.6 are highlighted and their relation to climatic anomalies described in the foregoing section (Figs. III.1a-f and III.2 a-f) are noted here.

EN conditions (Fig. III.4) affect corn yields in Canada only modestly with yield deviations from Neutral in the range of +/- 1 Mg ha^{-1}. Most of the U.S. shows yield decreases under EN of up 2 Mg ha^{-1} with a greater loss near the Texas Panhandle. These effects are attributable to higher temperatures and diminished precipitation in both winter and summer. Modest yield increases occur on portions of the Gulf Coast and at the eastern edges of the Great Lakes. These effects are associated with lower temperatures and higher winter precipitation. Increases up to 2 Mg ha^{-1} occur in the North Central region favored, perhaps, by higher temperatures. EN is most beneficial on the Gulf Coast at the Texas/Mexico border where yields increase by as much as 4 Mg ha^{-1} due to good precipitation. Throughout the remainder of Mexico, yields increase or decrease by less than 1 Mg ha^{-1}. Since at many locations in Mexico simulated potential yields are low (because of assumptions regarding technology of dryland farming there), these changes can be quite significant to the local economy.

SEN (Fig III.5) lowers corn yields slightly in Canada where higher temperatures and slightly lower precipitation occur. Most dryland corn yields in Mexico are within ±1 Mg ha^{-1} of the Neutral yield, but a few large gains and losses are also noted. The complexity of the Mexican terrain and the complex distributions of ENSO effects also require interpretation on the scale of the individual farm. Yields in the Southeast and Gulf Coast are improved with a warmer winter and slightly cooler summer. Most farms bordering the Corn Belt on the west and north show increases of up to 1 Mg ha^{-1} and some show yields up to 3 Mg ha^{-1}. The causes for these effects are not evident in the climate maps (Figs. III.1e-f and III.2e-f) and are adduced in the records of the individual farms (Tables III.7-9).

EV (Fig. III.6) reduces corn yields modestly in western Canada and increases them modestly in the east. Yields in the U.S. are reduced in most of the corn-growing region where winter temperatures are elevated and summer temperatures unchanged or slightly lower. Farms within a region extending from the Southeast through the Mississippi Delta and extending into Oklahoma and Central Kansas experience modest yield increases associated with increased winter precipitation, while the Upper Corn Belt and the North Central states lose yield because of higher temperatures and reduced summer precipitation. Yields in Mexico, where temperature effects are scattered, winter precipitation is improved and summer precipitation is lowered, range from modestly positive to modestly negative.

Wheat

Wheat is grown under rainfed conditions in the Prairie Provinces of Canada, in the northern and western U.S. Great Plains and in the western Corn Belt states. It is also grown in central and southern Mexico. In Canada most wheat is spring sown; in the U.S. wheat is mostly winter sown except in the northern tier of states where spring sown wheat dominates. In Mexico dryland wheat is grown in summer and irrigated wheat is grown in winter.

Potential yields of wheat are highest in Canada (Fig. III.7). In much of the Great Plains (west of the 100th meridian) yields range from 1-2 Mg ha^{-1}. In Kansas and the more easterly states, potential yields are higher (2-3 Mg ha^{-1}). Corn and soybeans are more profitable in the eastern portions of the Plains States and the Prairie States to their east, so actual wheat production in this region is limited. Yields in eastern Washington and the Central Valley of California range from 1-3 Mg ha^{-1}. Potential wheat yields in Mexico under rainfed conditions range from 1-3 Mg ha^{-1}.

Wheat yields are reduced in most U.S. and many Canadian locations under EN conditions (Fig. III.8) by as much as 1 Mg ha^{-1} below Neutral, although many farms in Canada do show modest gains. Losses appear most closely related to higher winter temperatures in the major wheat producing regions. Lower summer precipitation contributes to the loss of yield in the Northern Great Plains. Mexican yields vary in the range of $\pm$ 0.5 Mg ha^{-1}.

Under SEN conditions (Fig. III.9) wheat yields in Canada are either reduced or increased slightly on most farms although losses greater than 0.5 Mg ha^{-1} occur in southwestern Saskatchewan. Yields in the southerly and central portion of the traditional U.S. winter wheat belt (Nebraska to northern Texas) increase by as much as 0.5 Mg ha^{-1}. Where losses of yield occur, as in the northern Great Plains, they are slight. Yields in Mexico vary from significantly improved to moderately reduced. Winter precipitation is good in the southern US portions of of the wheat-growing region. Conditions are good in the Prairie Provinces in the SEN summer. Northern Mexico gets more precipitation in winter, but the opposite in summer. Except in the far south, Mexico is warmer in winter and summer under SEN conditions. The much warmer winter in Canada and the slightly warmer summer do not appear to offset the improved moisture situation in the Prairie Provinces.

EV (Fig. III.10) creates a different pattern in Canada where, except at the eastern edge of the wheat belt, most farms show greater than Neutral yields. The cooler year in Canada coupled with increased summer precipitation may account for the better yields there. Yields in the western and northern Great Plains are down by as much as 0.5 Mg ha^{-1}. In the eastern portion of the Plains states and Cornbelt, in California and part of the Pacific Northwest yields are up by 0.5 Mg ha^{-1}. The warm winter and cool summer of the U.S Midwest under EV conditions may account for the better yields in that region since winter and summer precipitation anomalies are not striking. Yields are mostly improved in Mexico.

C. 2 Canada (Canola, wheat, barley, corn, and potatoes)

In the Prairie Provinces, yields of barley simulated for 30 years of Neutral weather varied 2.6 times from 1.9 to 4.9 Mg ha^{-1} (Table III.7 a). Correspondingly, yields of wheat varied threefold from 1.4 to 4.2 Mg ha^{-1} (Table III.7 c). Canola yields (Table III.7 b) ranged from 1.2 to 3.4 Mg ha^{-1} — within the range of variation of cereal crops.

Under the EN condition yields both increased and decreased with respect to the Neutral state. Yields decreased more often in cereal crops than in the oilseed crop. Yield increases in barley did not surpass 0.48 Mg ha^{-1} while yield reductions reached -0.96 Mg ha^{-1}. Smaller yield variations were simulated for wheat (0.34 and -0.56 Mg ha^{-1}). The yield variations for canola ranged from 0.43 to -0.64 Mg ha^{-1} with more yield increases than reductions (20 vs. 17). Barley yields under the SEN condition deviated more widely from those of the Neutral condition (from 0.64 to -1.63 Mg ha^{-1}). Wheat yield deviations under SEN exhibited similar behavior (0.37 Mg ha^{-1} and -0.99 Mg ha^{-1}). Canola yield deviations from Neutral also increased under the SEN condition but overall there were more yield decreases than increases, a result opposite to the two simulated cereal crops. Under the EV scenario, the response of the three crops modeled was consistent with two thirds or more of the farms showing yield increases. For barley, yield deviations ranged from –0.17 to 0.85 Mg ha^{-1} with 27% of the farms (10 farms) showing a yield increase of at least 0.15 Mg ha^{-1}. The range in yield deviations observed for wheat under EV was much narrower (-0.02 – 0.46 Mg ha^{-1}) than for barley with 30% of the farms (11 farms) showing yield increases of at least 0.2 Mg ha^{-1}. Canola yield deviations under EV ranged from –0.57 to 0.70 Mg ha^{-1} including 38% of the farms with at least a 0.1 Mg ha^{-1} yield increase.

Corn was simulated on five farms in British Columbia, Ontario and Quebec (Table III.7d). In general, there was little variability in yield (5.2 - 6.0 Mg ha^{-1}). These yields fall within the range reported by Statistics Canada. Corn yields under EN decreased in two out of five farms. Of interest is the differential response observed between the two British Columbia farms where in the C1 farm (Vancouver station) corn yields decreased by 0.3 Mg ha^{-1} while in the C2 farm (Chilliwack station) yields increased slightly by 0.1 Mg ha^{-1}. Overall, Vancouver is drier than Chilliwack (Table III.2) and the latter station shows a 16% increase in precipitation during the spring months of EN years. This is also detected in the changes in water stress days for the two farms (Table III.7d). SEN conditions reduced corn yield in four out of five cases; while EV conditions reduced yield in British Columbia but raised it in central Canada (Ontario and Quebec).

Potato was the main crop simulated in Atlantic Canada (New Brunswick, Nova Scotia, and Prince Edward Island). As with corn, potato yields in Neutral years did not vary much across the region (5.5 - 6.4 Mg ha^{-1}, dry mass basis[4]) (Table III.7e). Yields under EN decreased consistently across the region by as much as 1.0 Mg ha^{-1}, although most of the decreases were much smaller. Yields decreased under the SEN scenario in all but in the two Nova Scotia farms where a ~0.2 Mg ha^{-1} yield increase was simulated. The response of potato to EV conditions was consistent across Canada with yield-differences ranging varying from near 0 to 0.3 Mg ha^{-1}.

We also examined the following hypothesis: do ENSO scenarios impact yield variability? Figs. III.11-13 depict the relationship between the coefficient of variation of yield and yield itself for barley, canola, and wheat under the four ENSO conditions. In general, yield variability decreases as yields increase. In cereal crops, the relationship between yield and yield variability was well described by quadratic polynomials. In canola the relationship between yields and yield variability was more complex and required a third-order polynomial for acceptable fits. The canola simulations, however, were the ones where a particular ENSO state most influenced the yield variability relationship (Fig. III.12). Of the three ENSO states used to simulate yields, SEN induced greater variability at low yield levels.

Another hypothesis examined in this section pertains to the general regional relationship between water stress days and yield for a given ENSO scenario. Figs. III.14, III.15 and III.16 depict the relationships between yield changes (barley, canola, and wheat) and changes from number of Neutral water stress days associated with EN, SEN, and EV. Visual examination of these figures suggests clear and differential crop responses to the three ENSO conditions. The differential yield response of barley under EN (Fig. III.14) associates clearly with water stress days (i.e., up the 52% of the variation in the data was explained with the quadratic equation fitted). SEN induced a more extended linear response but the explanatory power of the linear function increased by 20% (R^2 = 0.72) with respect to the EN condition. The quadratic function of the EV condition describes well the yield increases associated with decreases in water stress days. Wheat behaved in a manner similar to barley (Fig. III.16) but the mathematical functions for wheat under EV had low explanatory power. Canola exhibited somewhat a similar behavior except for a different pattern under the EN state where decreases in water stress augmented yields (Fig. III.15).

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[4] The fraction of water in yield is 0.8, therefore to convert these values to field yields the yield values should be multiplied by a factor of 5.

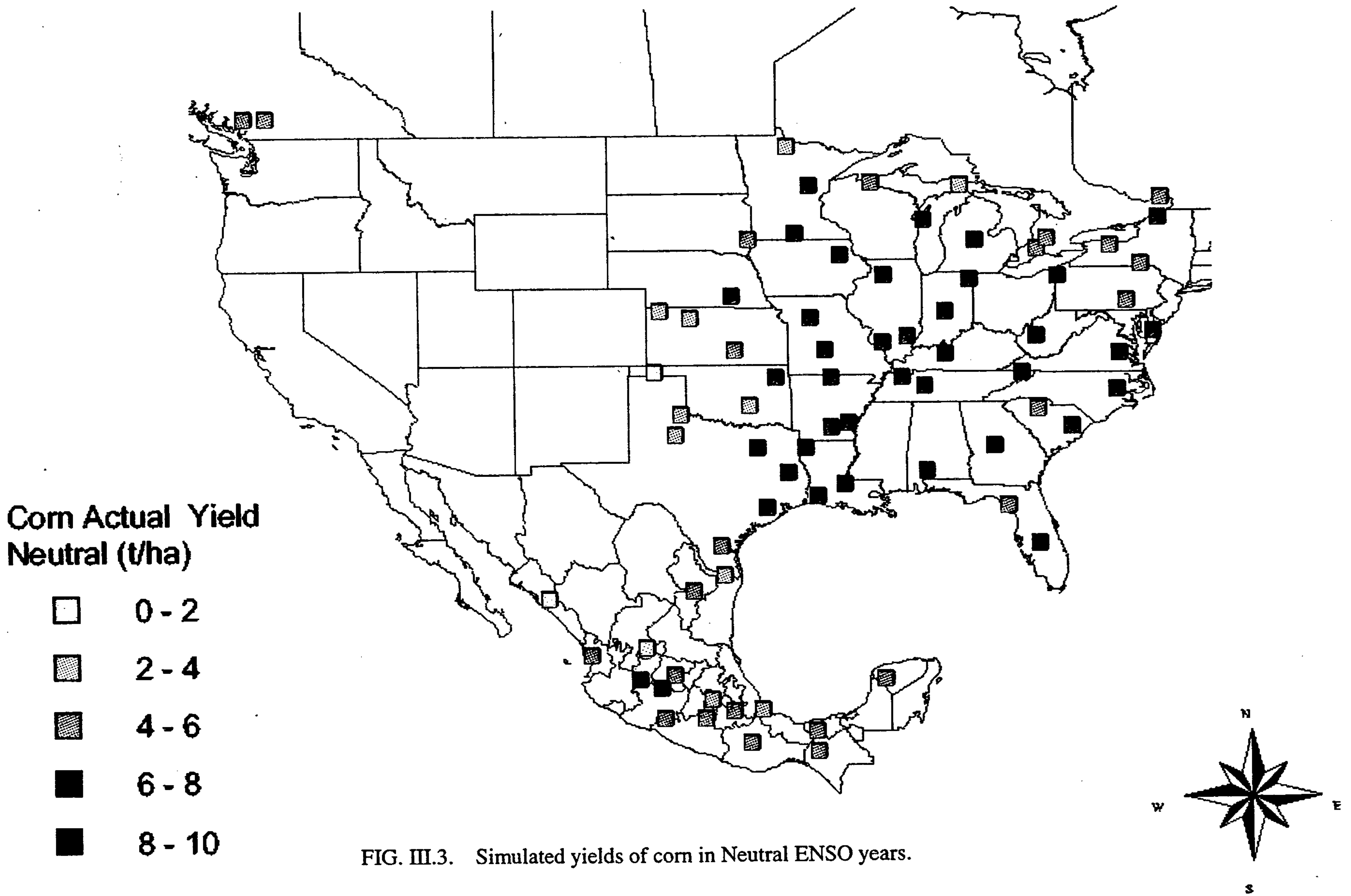


FIG. III.3. Simulated yields of corn in Neutral ENSO years.

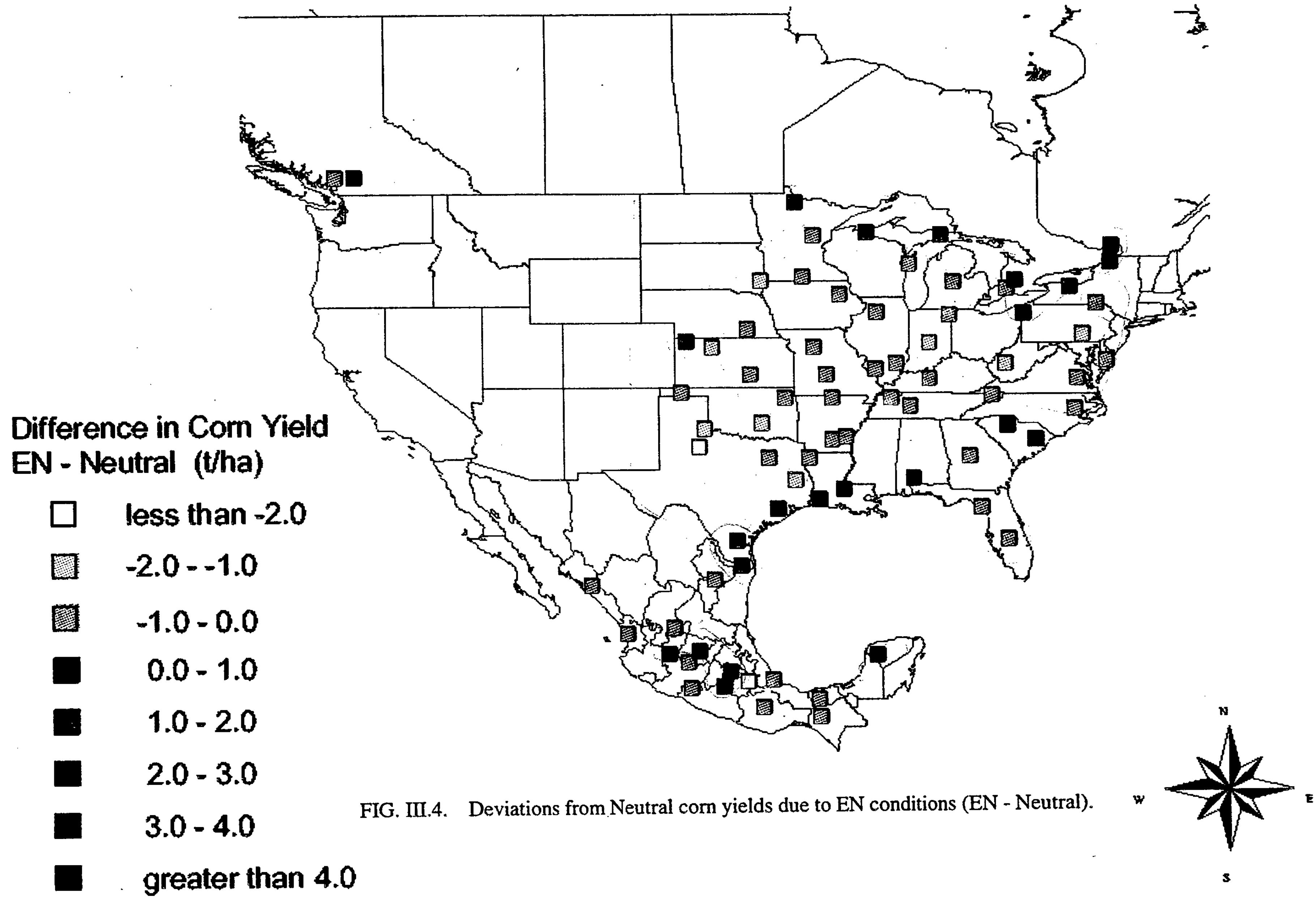


FIG. III.4. Deviations from Neutral corn yields due to EN conditions (EN - Neutral).

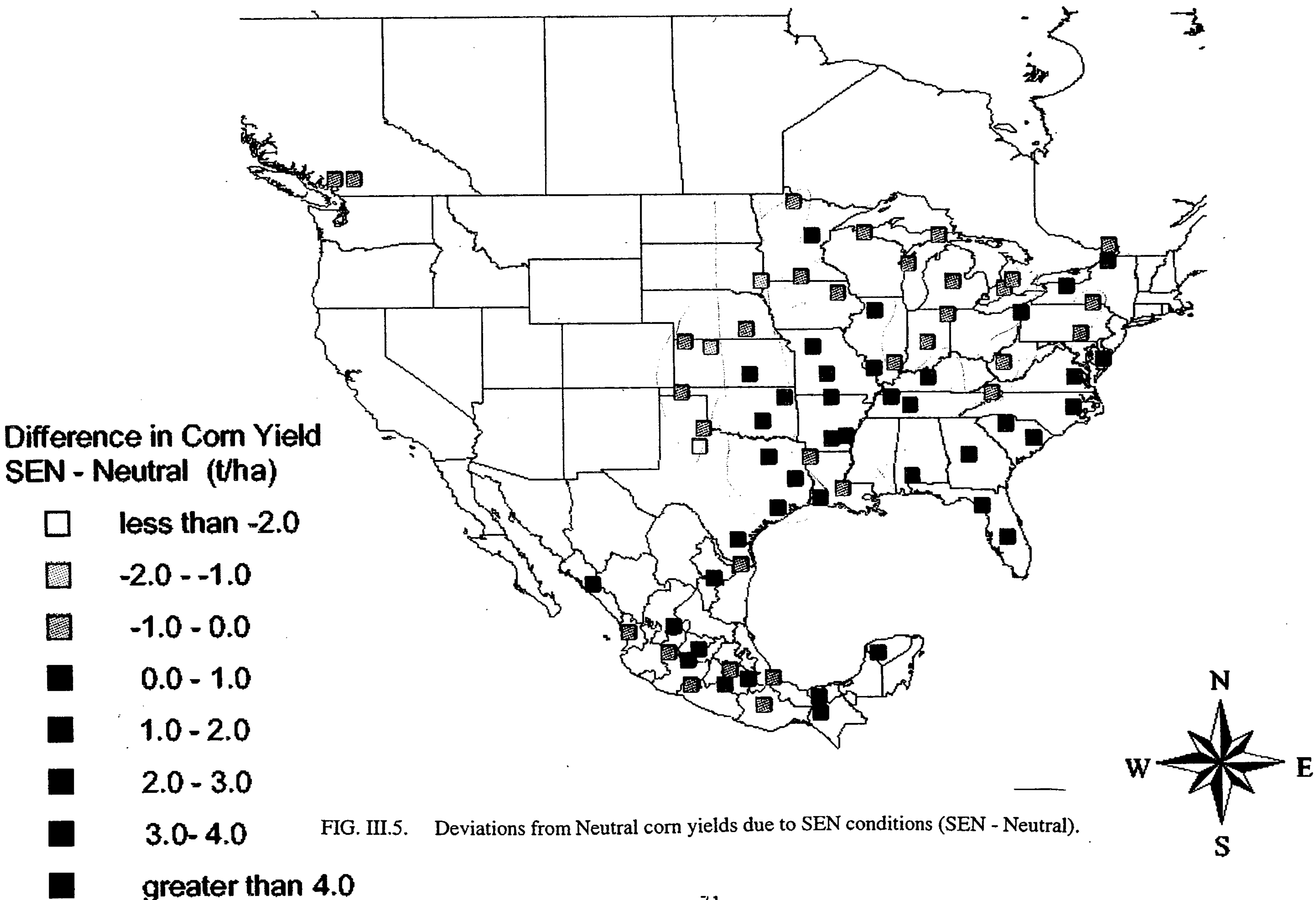


FIG. III.5. Deviations from Neutral corn yields due to SEN conditions (SEN - Neutral).

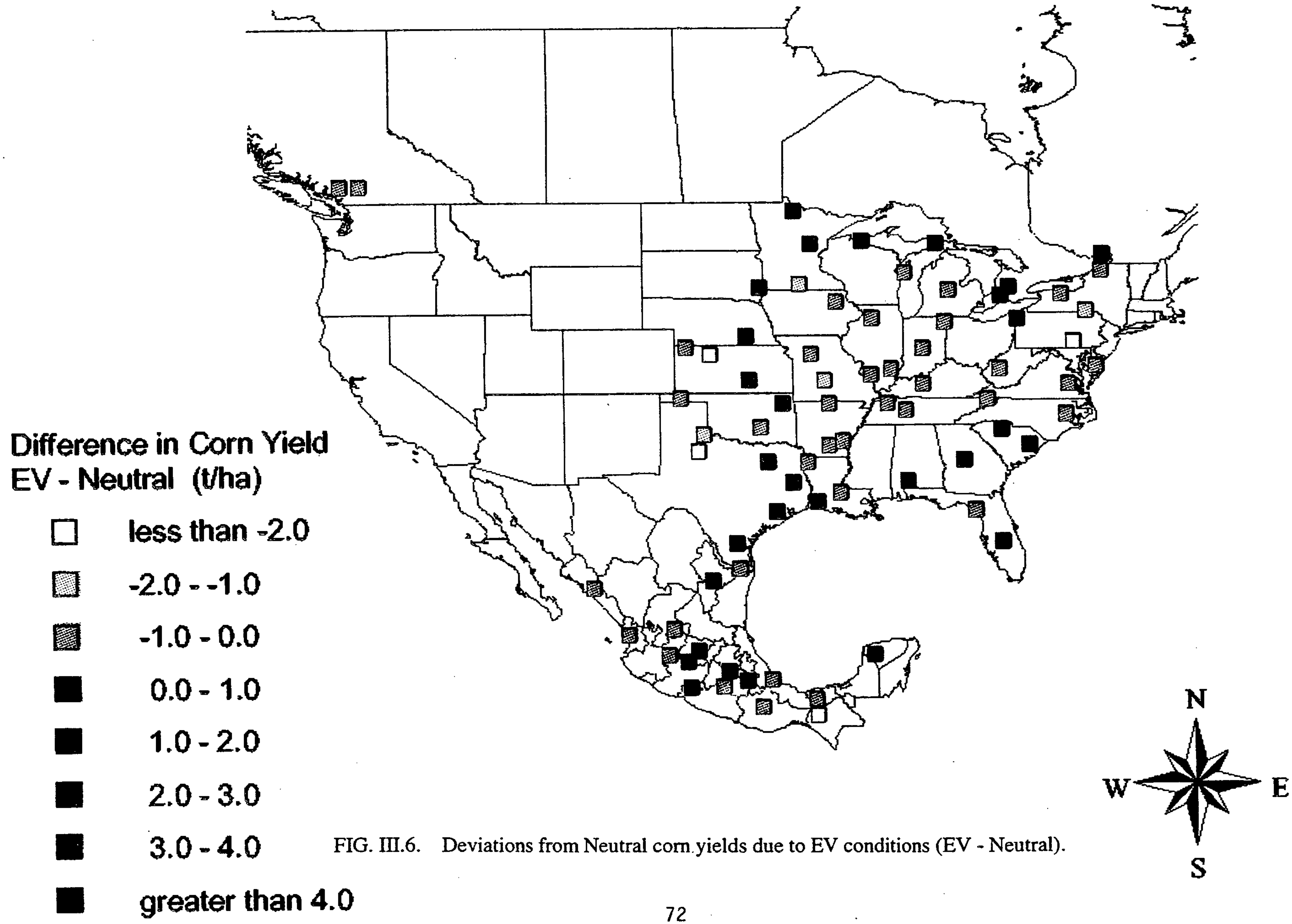


FIG. III.6. Deviations from Neutral corn yields due to EV conditions (EV - Neutral).

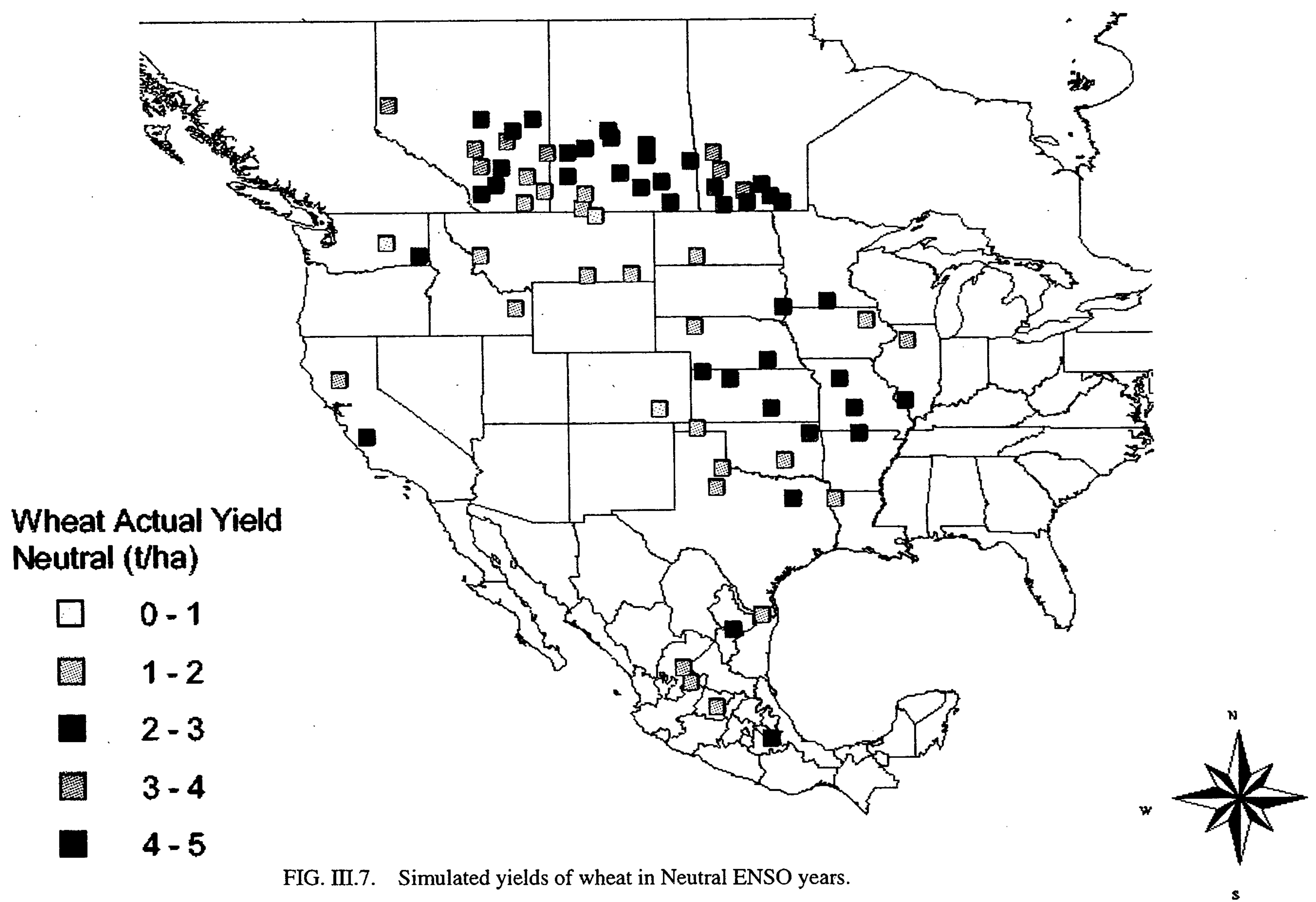


FIG. III.7. Simulated yields of wheat in Neutral ENSO years.

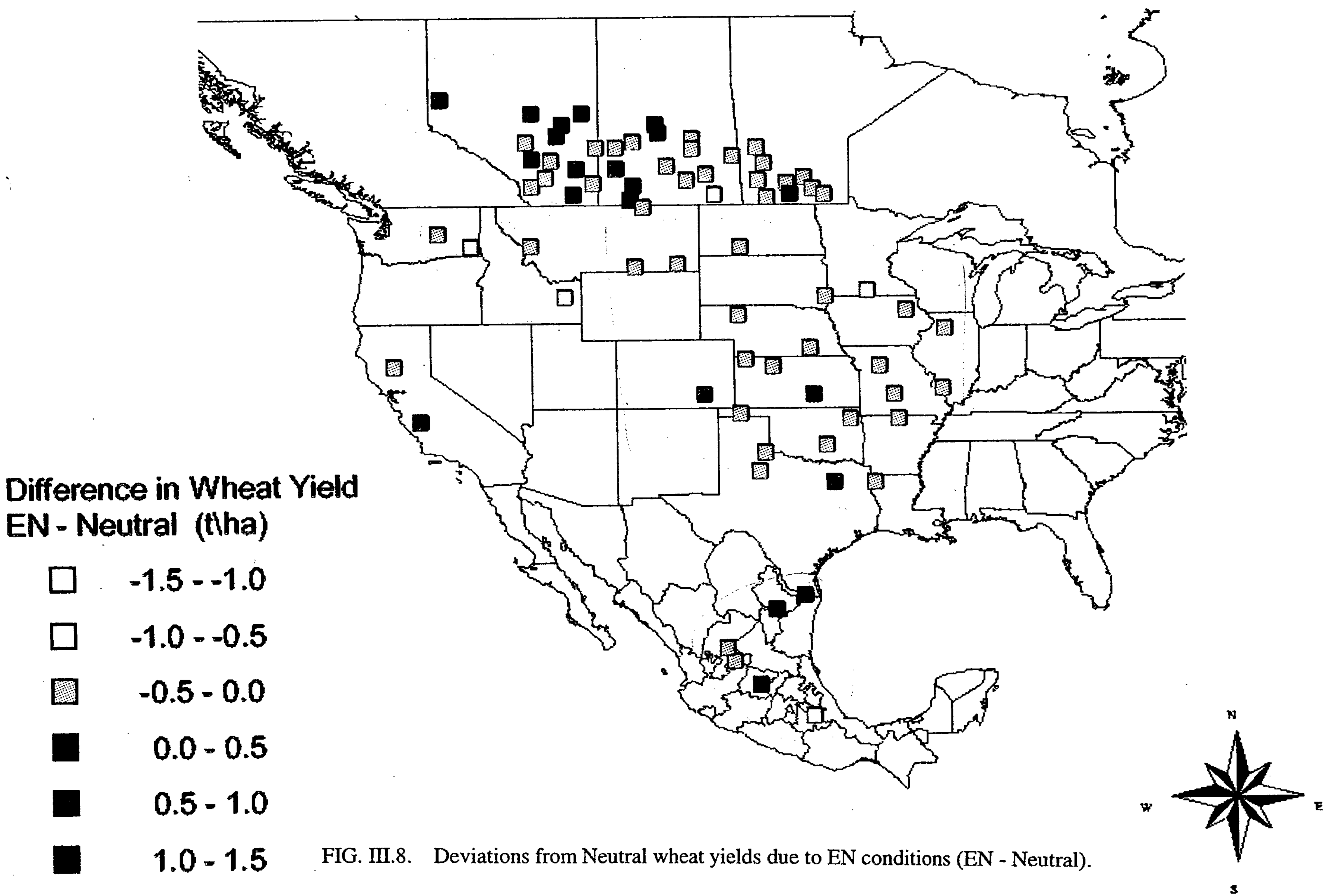


FIG. III.8. Deviations from Neutral wheat yields due to EN conditions (EN - Neutral).

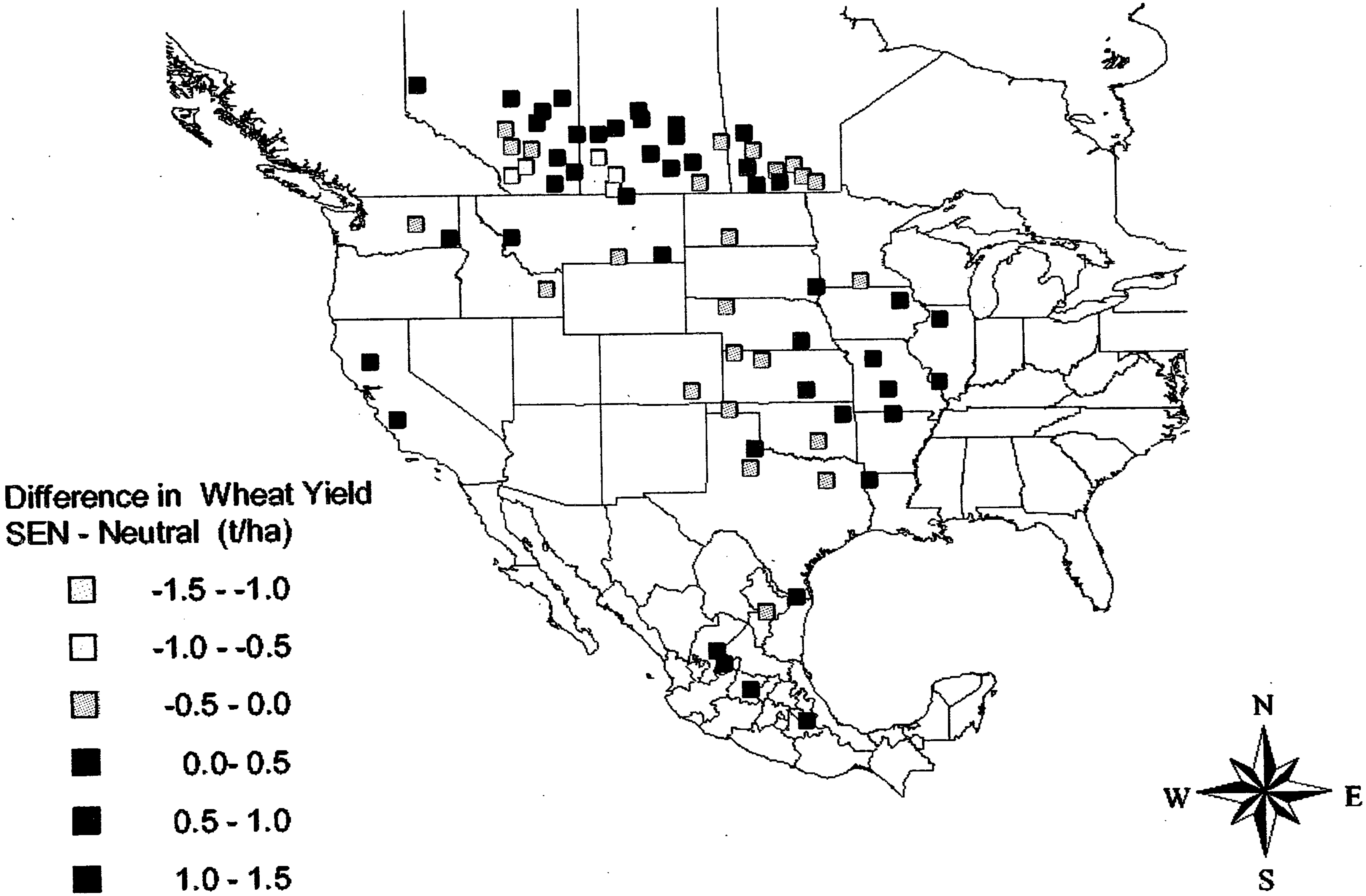


FIG. III.9. Deviations from Neutral wheat yields due to SEN conditions (SEN - Neutral).

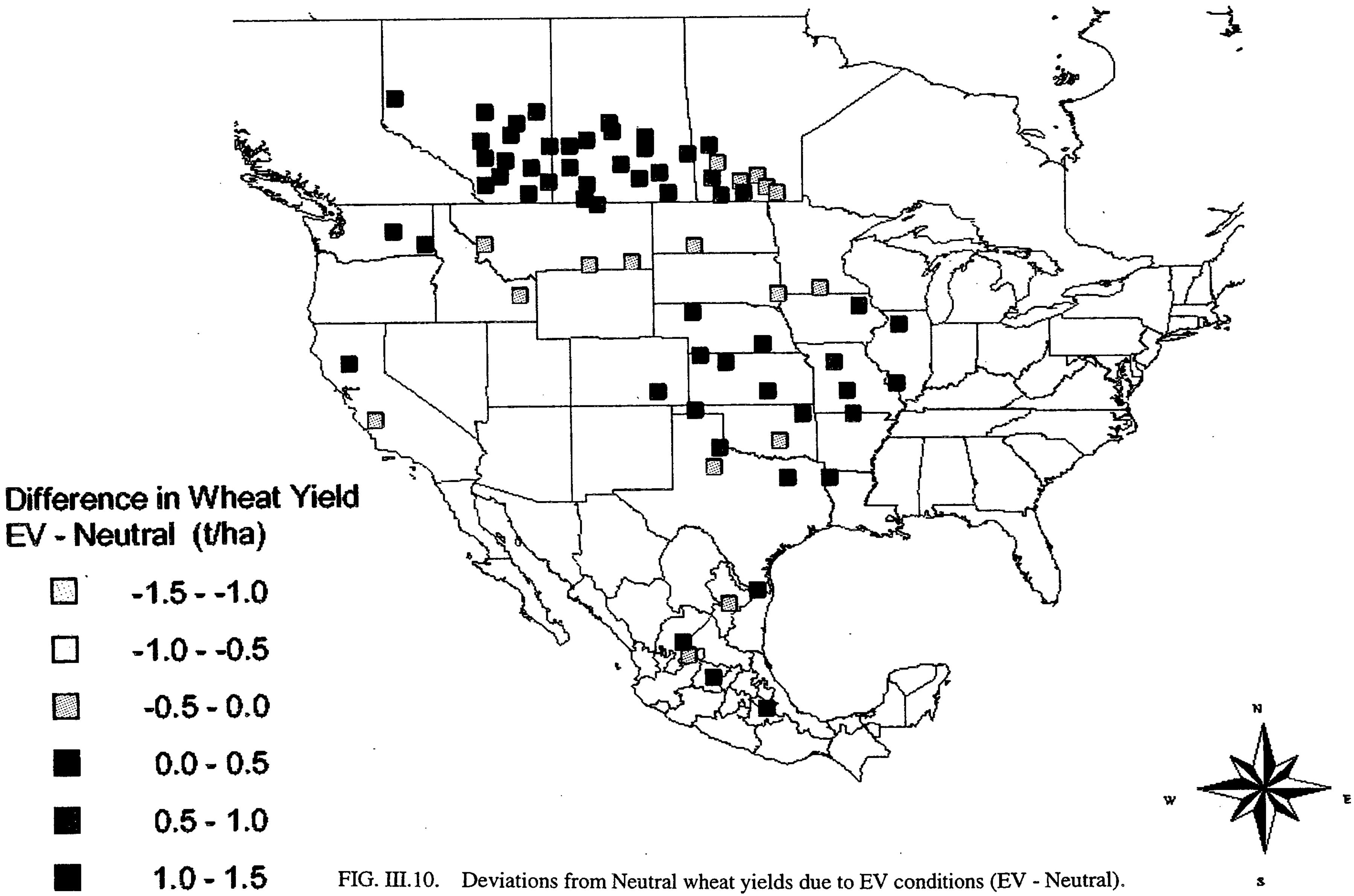


FIG. III.10. Deviations from Neutral wheat yields due to EV conditions (EV - Neutral).

Table III.7 a. Yields of barley in Canada, stress days under Neutral conditions and deviations from Neutral due to EN, SEN and EV.

Farm	Crop yields								Stress days							
			Deviation from N						Temperature				Water			
	N		EN		SEN		EV			Deviation from N				Deviation from N		
	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev	N	EN	SEN	EV	N	EN	SEN	EV
	Mg ha^{-1}								d				d			
C3	3.96	0.26	0.10	-0.05	-0.03	-0.08	-0.12	-0.05	20	2	-1	0	19	-6	-4	-2
C4	4.00	0.43	-0.37	0.00	-0.33	0.00	0.01	-0.04	18	-5	-3	0	8	-2	-1	0
C5	3.85	0.40	0.38	0.13	0.16	-0.07	0.11	-0.11	16	-1	-2	0	12	3	-5	-2
C6	4.51	0.25	0.09	0.08	-0.46	0.30	-0.02	-0.02	23	-4	-5	0	16	-1	10	-2
C7	3.25	1.14	-0.71	-0.13	-1.23	-0.35	0.43	-0.21	16	-5	-3	2	32	6	15	-1
C8	3.49	1.10	-0.78	0.02	-1.63	-0.32	0.45	-0.29	16	-5	-3	2	29	7	18	-5
C9	4.11	0.47	-0.16	0.23	-0.41	0.35	-0.01	0.06	20	-3	-1	2	26	1	7	-4
C10	4.32	0.30	0.08	0.05	0.09	0.02	0.04	0.00	19	-2	-1	1	8	0	-2	0
C11	4.91	0.24	0.07	-0.01	0.03	-0.03	-0.06	-0.01	21	-2	-1	0	14	-1	-2	0
C12	1.86	0.81	0.48	0.26	0.27	0.21	0.30	0.27	11	-4	-1	2	39	-3	1	-2
C13	2.24	0.88	0.27	0.23	0.09	0.20	0.29	0.25	12	-5	-2	1	36	-1	3	-2
C14	3.90	0.30	0.08	0.02	-0.01	0.02	-0.01	0.03	13	-3	-1	-2	8	-3	-2	-3
C15	2.03	0.91	-0.42	-0.12	0.30	0.23	0.39	0.25	11	-4	0	1	37	2	1	-3
C16	4.34	0.31	-0.24	0.27	0.12	-0.05	0.03	-0.09	19	-5	-3	-1	14	8	-8	-3
C17	3.78	0.53	-0.12	0.20	0.09	-0.08	0.12	-0.22	12	-3	1	-2	19	3	-3	-11
C18	3.12	0.94	0.28	0.08	-0.80	-0.07	0.59	-0.22	14	-5	2	-3	34	-6	7	-16
C19	2.38	1.02	0.44	0.15	-0.79	-0.25	0.85	0.11	13	-4	1	2	42	-5	6	-13
C20	3.89	0.68	-0.21	0.20	0.07	-0.13	0.18	-0.32	13	-4	0	-1	22	3	-2	-10
C21	2.80	1.02	0.39	0.11	-0.82	-0.21	0.75	-0.02	13	-4	1	2	38	-5	6	-13
C22	3.38	0.34	0.04	0.06	0.04	0.00	0.04	0.01	14	-5	0	-1	13	-4	-6	-4
C23	3.93	0.33	0.11	0.00	0.10	-0.06	0.11	-0.03	16	-5	0	0	16	-5	-7	-5
C24	3.67	0.70	-0.89	0.32	0.20	-0.35	0.09	-0.03	12	-4	3	0	21	10	-9	-2
C25	3.27	0.94	-0.07	-0.05	0.64	-0.40	0.46	-0.20	11	-3	3	1	30	0	-17	-9
C26	4.36	0.20	0.05	0.06	0.16	0.00	0.07	0.13	15	-3	2	0	15	-1	-5	-2
C27	4.05	0.28	-0.03	0.18	0.15	-0.06	0.09	0.09	14	-3	2	0	17	0	-9	-6
C28	4.06	0.55	-0.72	0.30	0.10	-0.23	0.07	-0.04	12	-4	3	0	19	9	-8	-3
C29	3.72	0.92	-0.96	-0.07	-0.03	0.12	0.14	-0.06	12	-4	3	0	24	6	-2	-4
C30	3.89	0.23	-0.02	0.03	0.03	0.07	0.03	0.01	13	-4	3	-2	9	2	-3	-2
C31	4.54	0.16	-0.04	0.05	0.04	-0.03	0.06	0.02	15	-3	2	-1	15	-3	-4	-3
C32	4.49	0.26	-0.12	0.24	0.07	0.03	0.09	-0.01	14	-3	2	-1	11	3	-2	-2
C33	4.37	0.23	-0.04	-0.01	-0.17	0.02	-0.05	0.05	14	-2	5	-1	9	2	1	0
C34	4.03	0.27	0.01	0.17	0.10	-0.05	0.11	-0.04	10	-2	3	-1	11	1	-3	-4
C35	4.38	0.24	0.05	-0.04	0.00	0.06	-0.05	-0.02	11	-2	3	-1	6	2	3	0
C36	3.94	0.29	0.02	0.00	-0.04	-0.02	-0.08	-0.06	9	-2	1	-2	9	-4	0	-2
C37	4.06	0.30	-0.05	0.01	-0.07	0.04	-0.10	0.04	11	-3	3	0	9	-2	-1	0
C38	4.34	0.18	-0.01	-0.02	0.01	0.00	0.00	-0.02	11	-3	3	0	10	-1	-2	-1
C39	3.95	0.33	0.03	-0.09	-0.04	0.01	-0.17	0.04	12	-3	1	-2	10	-2	-1	0

Table III.7 b. Yields of canola in Canada, stress days under Neutral conditions and deviations from Neutral due to EN, SEN and EV.

Farm	Crop yields								Stress days							
			Deviation from N						Temperature				Water			
	N		EN		SEN		EV			Deviation from N				Deviation from N		
	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev	N	EN	SEN	EV	N	EN	SEN	EV
	Mg ha^{-1}								d				d			
C3	1.99	0.14	-0.18	-0.03	-0.30	-0.03	-0.30	-0.04	31	5	5	5	12	-6	-4	-4
C4	2.62	0.16	0.05	0.02	-0.30	-0.02	-0.21	-0.02	31	-4	-1	0	5	0	-1	1
C5	2.62	0.20	0.06	0.00	-0.12	-0.01	-0.42	-0.07	27	1	1	3	8	1	-4	-2
C6	2.34	0.14	0.13	0.02	-0.27	0.14	-0.13	-0.02	34	-3	-4	2	9	0	6	-2
C7	1.89	0.57	-0.24	-0.06	-0.59	-0.21	0.20	-0.04	19	-5	-3	4	38	5	11	-2
C8	2.11	0.65	-0.35	-0.10	-0.81	-0.24	0.29	-0.07	20	-5	-3	4	35	7	14	-4
C9	2.18	0.37	0.43	0.09	0.02	0.01	0.09	-0.09	36	-8	-10	-1	24	-1	7	-7
C10	2.85	0.15	-0.06	0.01	-0.16	0.04	-0.51	-0.02	29	0	2	3	4	-1	-1	0
C11	2.96	0.18	-0.05	0.00	-0.17	0.00	-0.57	-0.03	30	1	1	2	8	-2	-2	-1
C12	1.23	0.33	0.19	0.15	0.05	0.15	0.02	0.03	20	-11	-7	-4	44	-3	0	-2
C13	1.36	0.29	0.14	0.22	-0.02	0.22	0.05	0.13	20	-10	-7	-4	42	-2	1	-2
C14	2.84	0.16	0.16	0.02	0.08	0.02	0.02	0.01	28	-6	-3	-4	5	-2	-1	-1
C15	1.25	0.34	-0.09	0.05	0.18	0.28	0.13	0.09	12	-4	1	2	42	1	-1	-2
C16	2.56	0.18	0.24	0.22	0.37	0.00	0.00	-0.02	33	-7	-4	-3	9	9	-6	-2
C17	2.82	0.44	-0.12	0.14	-0.07	0.02	0.29	-0.20	20	-5	1	0	25	3	-3	-11
C18	1.80	0.48	0.23	0.13	-0.34	0.00	0.54	-0.03	19	-7	0	-1	41	-3	2	-14
C19	1.38	0.42	0.26	0.15	-0.28	0.02	0.67	0.17	18	-6	0	3	48	-2	2	-12
C20	2.76	0.48	-0.15	0.12	-0.06	0.01	0.39	-0.18	19	-4	1	0	28	3	-3	-9
C21	1.60	0.46	0.29	0.16	-0.31	0.00	0.70	0.10	19	-6	0	4	44	-3	2	-12
C22	2.63	0.31	0.27	-0.14	0.16	-0.15	0.03	-0.16	24	-5	0	2	15	-6	-8	-9
C23	2.82	0.36	0.35	-0.16	0.20	-0.18	0.08	-0.18	25	-4	-1	2	18	-6	-7	-9
C24	2.45	0.51	-0.64	-0.02	0.33	-0.16	0.15	-0.04	17	-6	1	-1	28	8	-13	-3
C25	1.98	0.51	0.04	-0.05	0.75	-0.02	0.49	0.07	15	-4	2	1	35	0	-16	-7
C26	3.07	0.18	0.25	0.07	0.26	-0.04	0.05	0.05	23	-2	2	3	21	-1	-12	-8
C27	2.78	0.35	0.27	0.06	0.37	-0.20	0.17	-0.11	23	-3	2	3	24	-2	-17	-12
C28	2.71	0.48	-0.63	0.02	0.29	-0.15	0.17	-0.07	17	-6	1	-1	25	9	-11	-3
C29	2.31	0.60	-0.53	-0.14	-0.16	0.07	0.32	-0.03	16	-6	1	0	29	6	-1	-4
C30	3.09	0.14	0.01	0.05	-0.01	0.00	-0.01	0.00	21	-5	1	1	10	3	-5	-2
C31	3.29	0.15	0.07	0.03	0.00	0.01	0.15	-0.01	23	-4	-1	1	15	-3	-5	-2
C32	3.35	0.21	-0.13	0.20	-0.05	-0.03	0.12	-0.04	20	-5	0	1	14	3	-4	-2
C33	3.40	0.12	-0.02	0.04	-0.21	0.00	0.01	0.00	22	-5	0	0	9	1	-1	1
C34	3.15	0.20	-0.06	0.17	-0.04	-0.05	0.08	-0.02	18	-4	0	0	13	3	-4	-3
C35	3.37	0.14	-0.07	0.02	-0.20	0.03	0.01	-0.02	15	-3	2	-1	7	2	2	1
C36	2.97	0.29	0.04	-0.04	-0.09	-0.02	0.03	-0.14	13	-3	1	-1	10	-4	-1	-2
C37	3.12	0.27	-0.04	-0.05	-0.13	-0.02	0.04	-0.05	15	-4	2	1	12	0	-3	0
C38	3.23	0.15	-0.02	0.04	-0.09	-0.02	0.07	-0.02	14	-4	3	1	12	0	-3	-1
C39	3.01	0.28	0.06	-0.01	-0.07	0.05	0.01	0.01	17	-5	0	-1	16	-5	-4	0

Table III.7 c. Yields of wheat in Canada, stress days under Neutral conditions and deviations from Neutral due to EN, SEN and EV.

Farm	Crop yields								Stress days							
			Deviation from N						Temperature				Water			
	N		EN		SEN		EV			Deviation from N				Deviation from N		
	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev	N	EN	SEN	EV	N	EN	SEN	EV
	Mg ha⁻¹								d				d			
C3	3.06	0.26	0.34	-0.03	0.37	-0.07	0.22	-0.07	14	0	-2	0	19	-6	-6	-4
C4	3.28	0.28	-0.26	-0.01	-0.11	0.01	0.09	-0.01	11	-3	-2	0	6	-1	-1	0
C5	2.79	0.35	0.34	0.08	0.27	-0.09	0.33	-0.13	10	-2	-2	-1	11	3	-7	-4
C6	3.56	0.28	0.06	0.05	-0.37	0.27	0.11	-0.07	16	-4	-2	0	14	0	14	-3
C7	2.26	0.86	-0.48	-0.21	-0.84	-0.36	0.28	-0.16	14	-3	-1	0	36	5	13	-1
C8	2.37	0.89	-0.48	-0.13	-0.99	-0.34	0.18	-0.24	13	-3	0	-1	32	7	19	-4
C9	2.77	0.46	-0.14	0.12	-0.37	0.12	0.19	0.02	16	-3	0	1	27	2	10	-4
C10	3.22	0.28	0.12	0.00	0.17	0.00	0.27	-0.02	12	-2	-1	0	6	0	-3	-1
C11	4.16	0.22	0.10	-0.01	0.14	-0.04	0.11	-0.03	15	-3	-1	-1	11	0	-4	0
C12	1.36	0.55	0.30	0.18	0.15	0.17	0.17	0.12	10	-3	-1	0	38	-2	5	2
C13	1.55	0.54	0.23	0.21	0.04	0.16	0.19	0.17	11	-3	-1	1	36	0	6	2
C14	2.75	0.23	0.15	0.00	0.09	0.02	0.16	0.08	9	-4	-2	-3	7	-3	-3	-5
C15	1.52	0.59	-0.28	-0.03	0.17	0.29	0.25	0.19	11	-2	1	0	38	1	1	-1
C16	3.16	0.31	-0.35	0.22	0.06	-0.06	0.15	-0.08	12	-3	-4	-1	11	12	-9	-5
C17	2.42	0.53	-0.02	0.05	0.10	-0.03	0.29	-0.26	9	-3	0	-3	21	3	-3	-12
C18	2.05	0.64	0.18	0.07	-0.54	-0.18	0.22	-0.03	9	-4	6	-4	35	-7	8	-16
C19	1.66	0.65	0.33	0.16	-0.53	-0.19	0.46	0.24	12	-3	3	0	45	-5	6	-13
C20	2.44	0.59	-0.04	0.10	0.12	0.00	0.29	-0.25	10	-4	0	-3	25	3	-2	-13
C21	1.93	0.67	0.27	0.11	-0.58	-0.21	0.32	0.13	12	-3	4	0	41	-7	6	-13
C22	2.43	0.32	0.10	-0.02	0.19	-0.04	0.19	-0.05	11	-6	-1	-1	16	-6	-9	-7
C23	2.67	0.31	0.08	-0.01	0.17	-0.05	0.19	-0.05	11	-5	-1	-1	16	-5	-9	-7
C24	2.29	0.59	-0.34	0.10	0.26	-0.19	0.05	-0.07	11	-2	1	-2	24	8	-11	-3
C25	2.22	0.70	-0.06	-0.10	0.32	-0.20	0.14	-0.07	10	-2	0	-1	33	-1	-17	-9
C26	3.00	0.22	0.00	0.06	0.19	0.05	0.18	0.07	12	-5	1	-2	14	0	-7	-4
C27	2.66	0.31	-0.10	0.16	0.23	-0.08	0.21	-0.03	11	-5	0	-2	18	-1	-12	-8
C28	2.61	0.53	-0.35	0.12	0.16	-0.13	0.03	-0.08	11	-2	2	-2	20	10	-8	-2
C29	2.45	0.69	-0.56	-0.16	-0.01	0.08	0.05	0.00	12	-1	3	-2	25	6	-1	-4
C30	2.75	0.19	-0.06	0.03	0.00	0.06	0.04	0.01	9	-3	3	-2	6	3	-2	-2
C31	3.24	0.22	-0.03	0.01	0.03	0.00	0.07	-0.01	12	-2	2	-3	11	-4	-5	-5
C32	2.97	0.31	-0.10	0.13	0.03	0.00	0.11	-0.08	9	-2	2	-2	10	3	-1	-4
C33	3.02	0.23	-0.05	0.05	-0.05	0.01	-0.02	0.05	10	-2	8	-1	3	3	1	0
C34	2.70	0.25	-0.09	0.13	0.06	-0.05	0.11	-0.05	7	-1	2	-2	9	2	-2	-4
C35	3.03	0.21	-0.05	0.08	-0.06	0.12	-0.01	-0.01	7	-1	4	-1	3	2	4	0
C36	2.63	0.33	0.05	-0.08	0.01	-0.07	0.11	-0.16	7	-1	2	-2	9	-5	-2	-4
C37	2.87	0.21	-0.02	-0.02	-0.03	0.04	-0.01	0.00	10	-2	3	0	9	-2	-2	0
C38	2.97	0.24	-0.01	0.01	-0.01	0.00	-0.02	-0.01	7	-1	3	-1	6	-2	-2	-2
C39	2.77	0.22	0.00	-0.02	-0.02	0.06	-0.01	0.08	10	-3	0	-2	12	-3	-3	0

Table III.7 d. Yields of corn in Canada, stress days under Neutral conditions and deviations from Neutral due to EN, SEN and EV.

Farm	Crop yields								Stress days							
			Deviation from N						Temperature				Water			
	N		EN		SEN		EV			Deviation from N				Deviation from N		
	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev	N	EN	SEN	EV	N	EN	SEN	EV
	Mg ha^{-1}								d				d			
C1	5.63	0.08	-0.26	0.08	-0.36	0.11	-0.43	0.07	2	1	1	0	36	6	6	6
C2	5.75	0.13	0.05	0.03	-0.09	0.08	-0.13	0.02	3	-1	7	-1	31	4	3	2
C40	5.67	0.23	-0.25	0.02	-0.34	-0.01	0.11	-0.01	4	0	-2	3	15	-2	-4	0
C41	5.58	0.24	0.21	0.01	-0.29	-0.03	0.10	0.00	5	0	-3	-3	15	-2	-3	0
C42	5.98	0.43	0.13	0.04	0.00	-0.09	0.05	-0.15	2	0	0	0	26	2	-3	2

Table III.7 e. Yields of potato in Canada, stress days under Neutral conditions and deviations from Neutral due to EN, SEN and EV.

Farm	Crop yields								Stress days							
			Deviation from N						Temperature				Water			
	N		EN		SEN		EV			Deviation from N				Deviation from N		
	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev	N	EN	SEN	EV	N	EN	SEN	EV
	Mg ha^{-1}								d				d			
C43	5.54	0.63	-0.04	0.00	-0.34	0.05	0.29	-0.11	2	1	1	1	29	3	1	-2
C44	5.53	0.63	-0.02	0.01	-0.33	0.07	0.30	-0.10	2	1	1	1	28	3	1	-1
C45	6.01	0.38	-0.16	0.00	-0.05	0.05	0.21	-0.02	3	1	-1	0	26	4	4	1
C46	6.00	0.38	-0.11	-0.01	-0.07	0.04	0.22	-0.04	1	0	0	0	27	3	2	2
C47	6.01	0.38	-0.96	0.00	-0.05	0.04	0.20	0.00	3	5	-1	1	29	0	1	0
C48	6.29	0.28	-0.15	0.06	-0.19	-0.02	0.10	0.05	4	0	-1	0	16	1	0	0
C49	6.29	0.28	-0.15	0.06	-0.18	-0.01	0.10	0.05	5	0	-1	0	16	1	0	0
C50	5.83	0.42	0.05	-0.07	0.12	0.01	0.14	-0.10	8	0	-1	0	14	1	-4	-1
C51	6.01	0.39	0.02	-0.02	0.25	0.01	-0.01	-0.02	3	0	-1	1	16	0	-2	-1

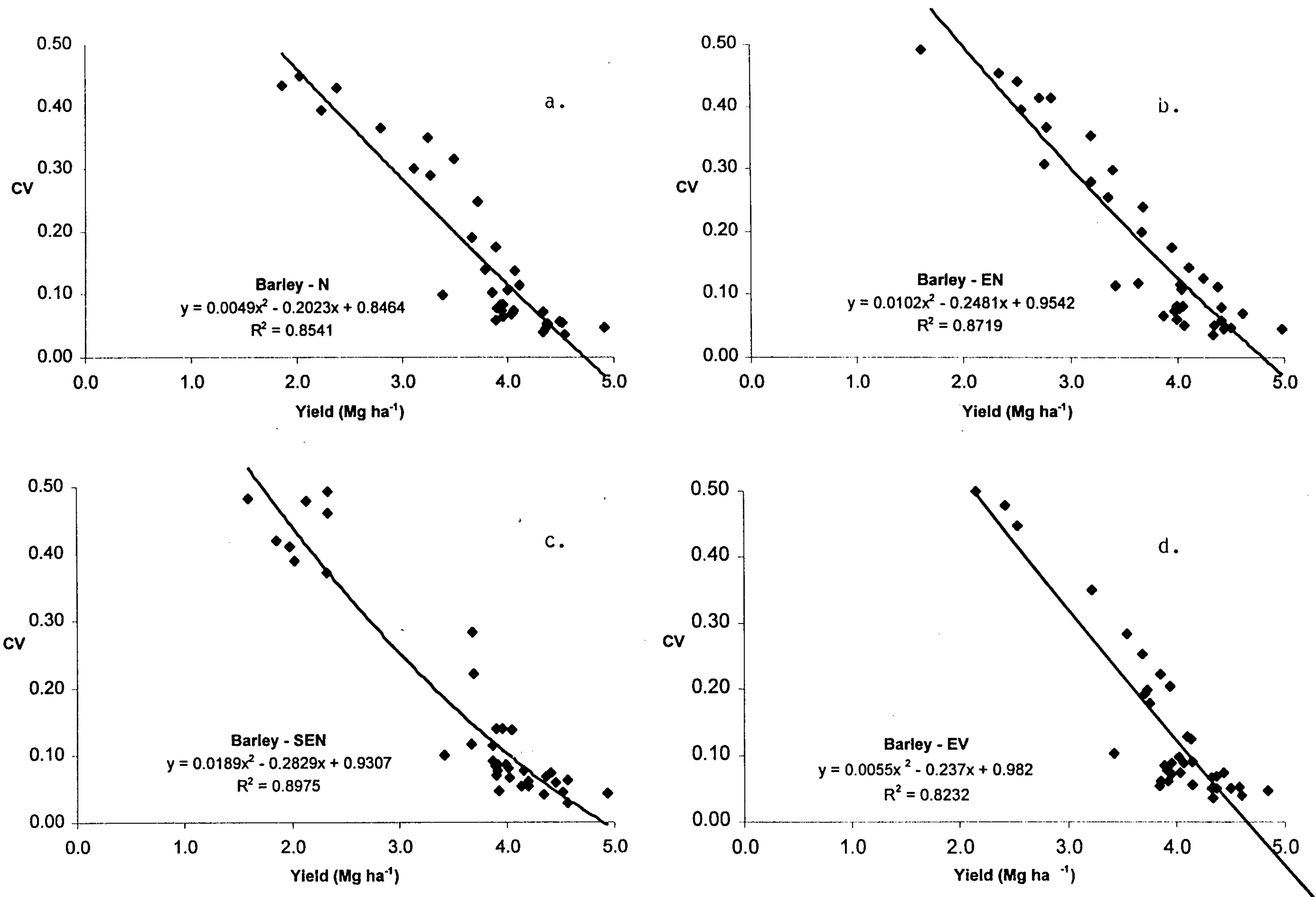


Fig.III.11. Coefficient of variation (CV, expressed as fraction) as a function of barley yield simulated for Canada under the four ENSO conditions: N, neutral; EN, El Niño; SEN, Strong El Niño and EV, El Viejo.

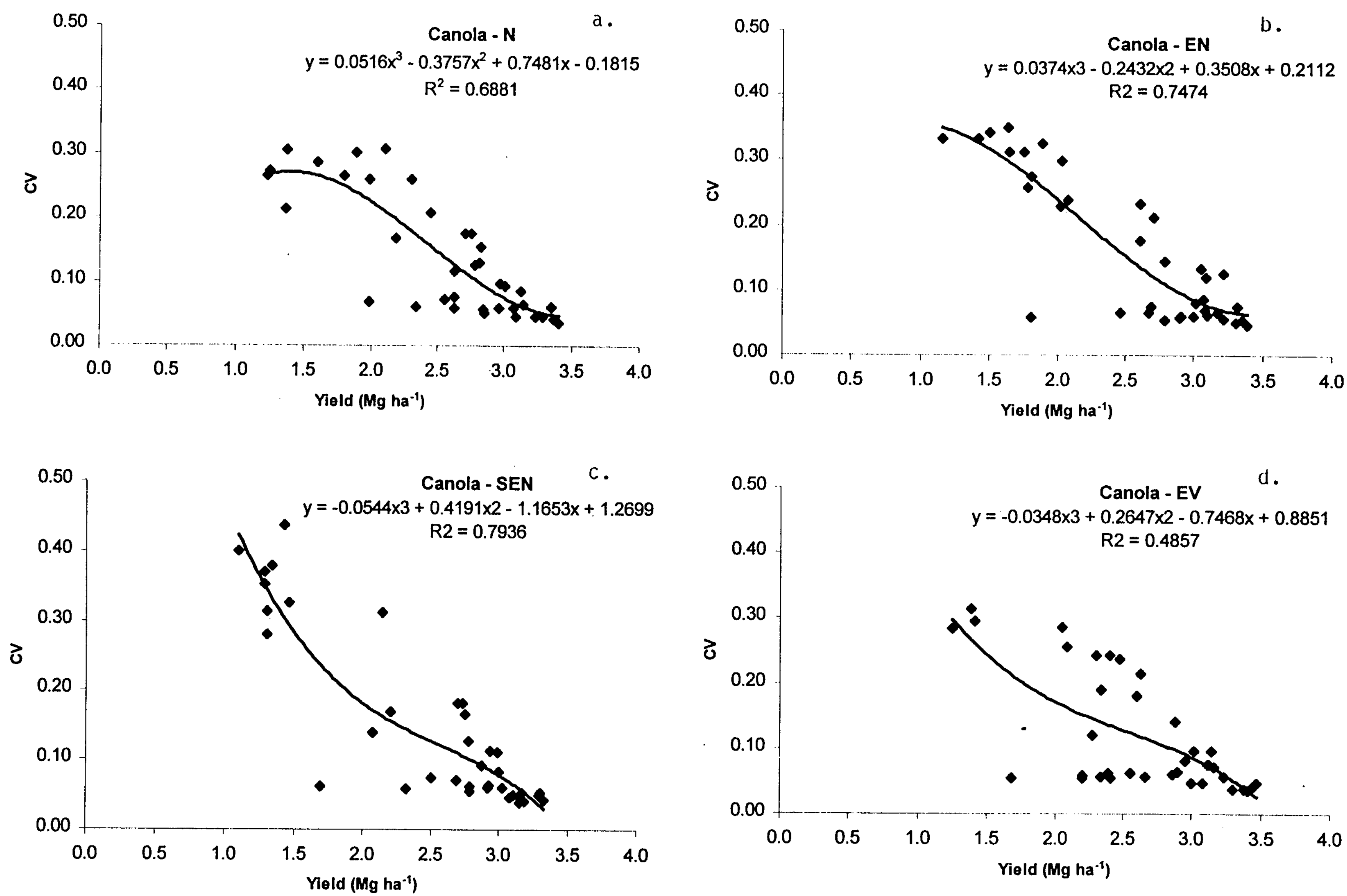


Fig. III.12. Coefficient of variation (CV, expressed as fraction) as a function of canola yield simulated for Canada under the four ENSO conditions: N, neutral; EN, El Niño; SEN, Strong El Niño; and EV, El Viejo.

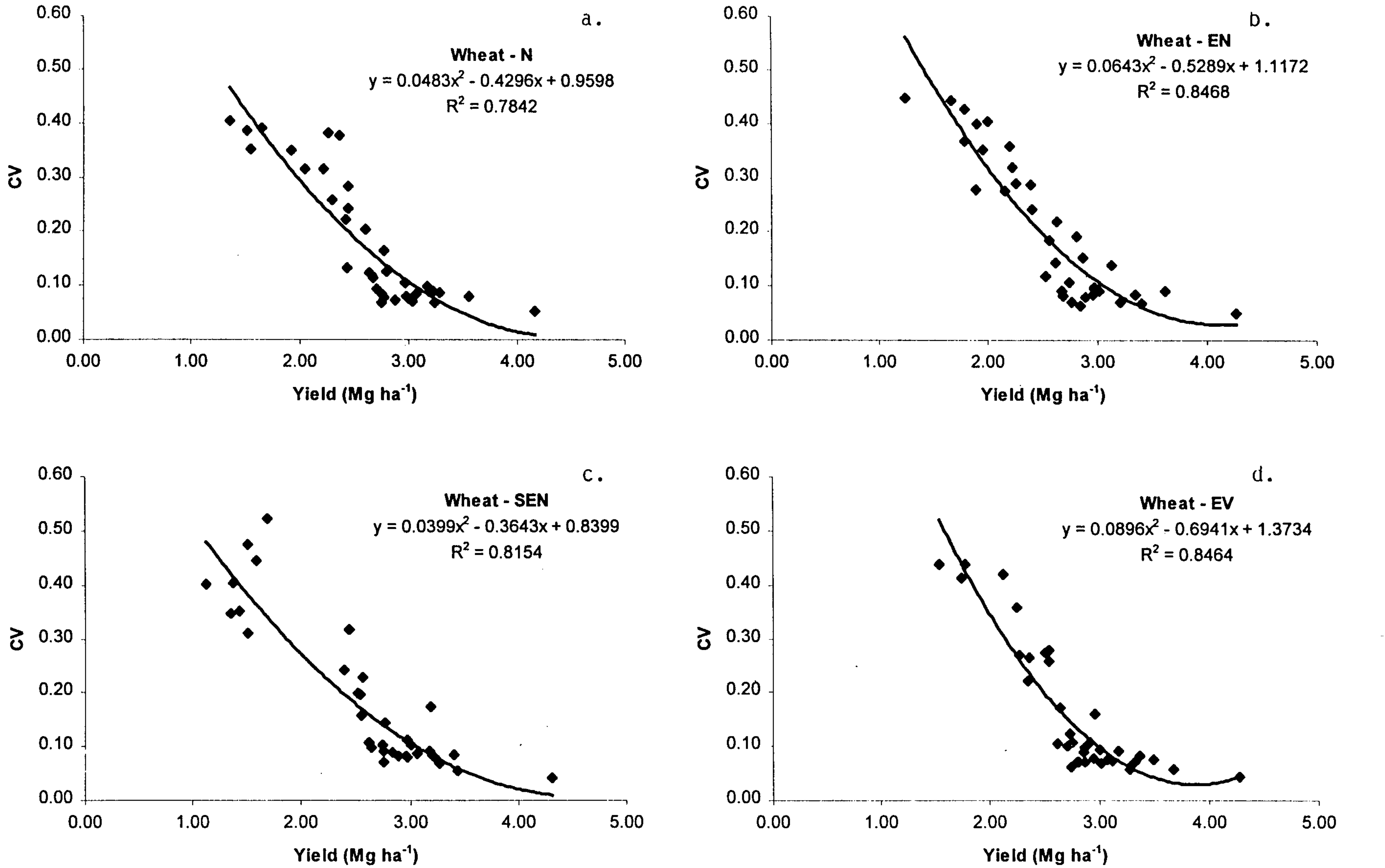


Fig. III.13. Coefficient of variation (CV, expressed as fraction) as a function of wheat yield simulated for Canada under the four ENSO conditions: N, neutral; EN, El Niño; and SEN, Strong El Niño; EV; El Viejo.

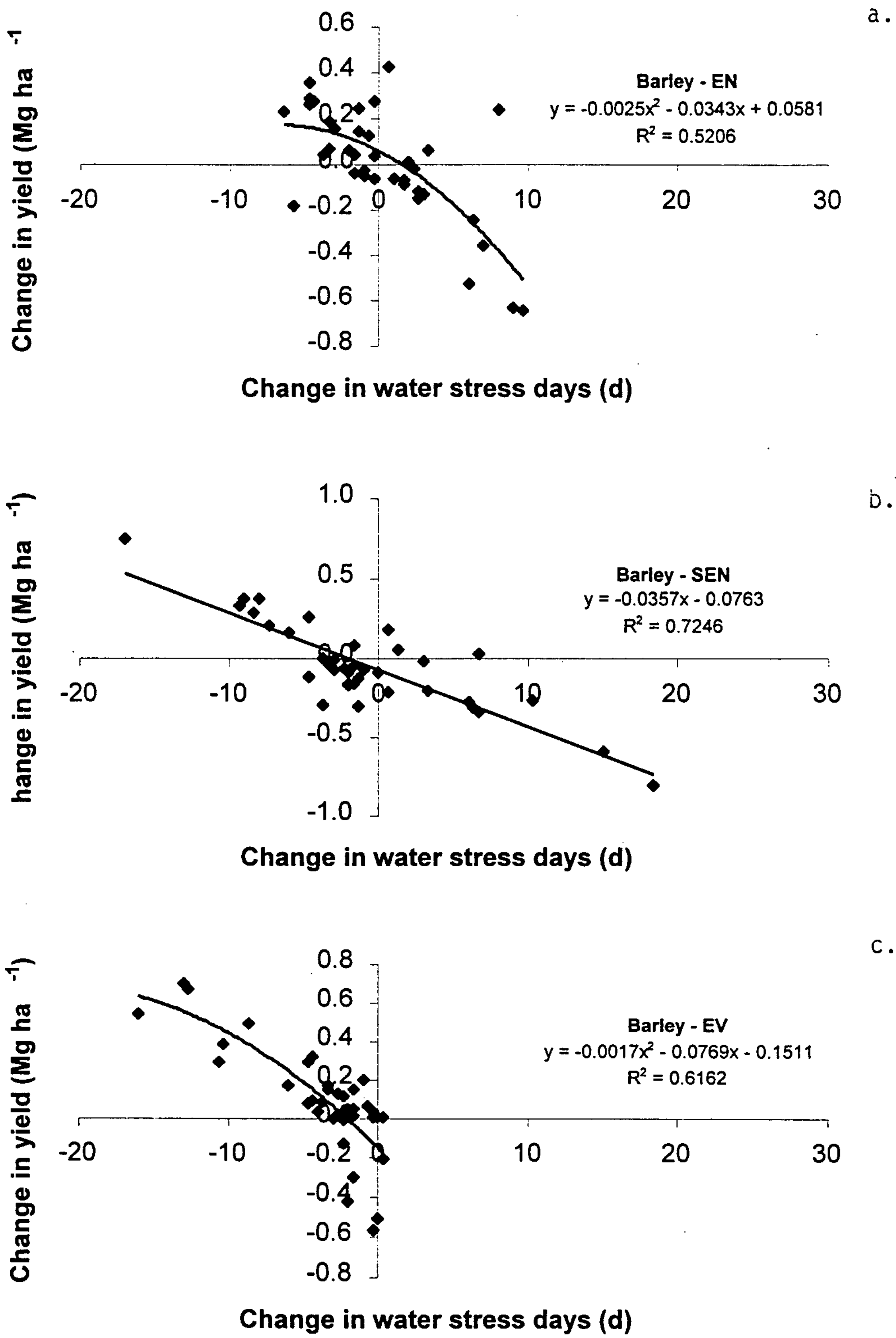
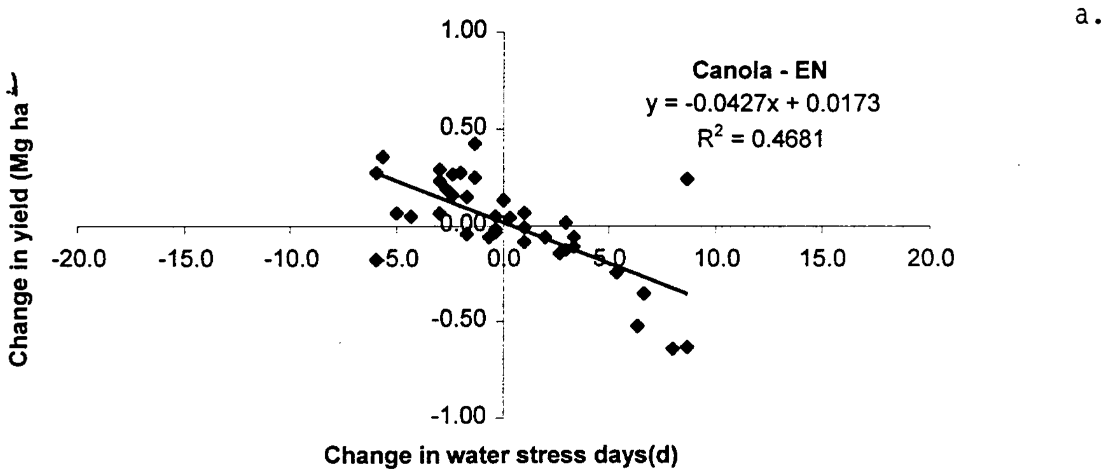
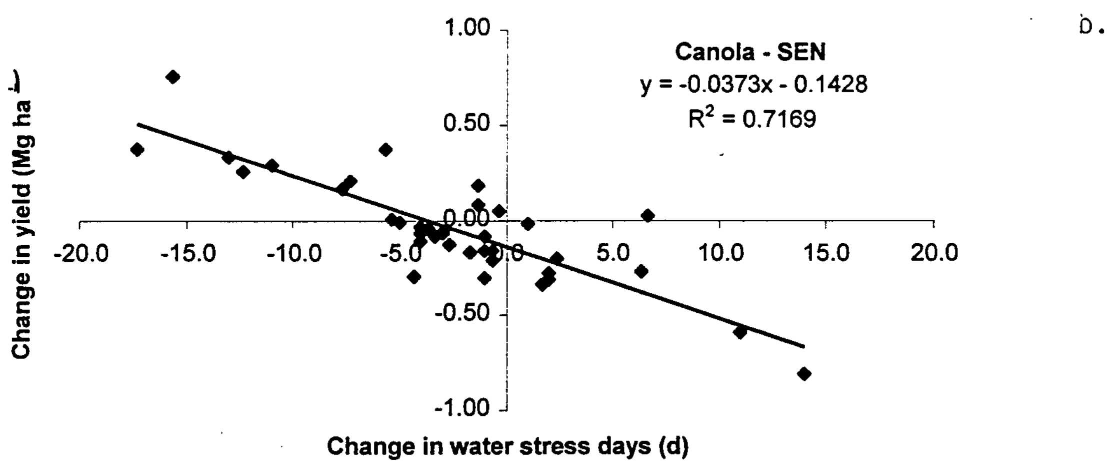


Fig. III.14. Deviations of Canadian barley yields from Neutral under a) EN, b) SEN, c) SEN as a function of change in water stress days.





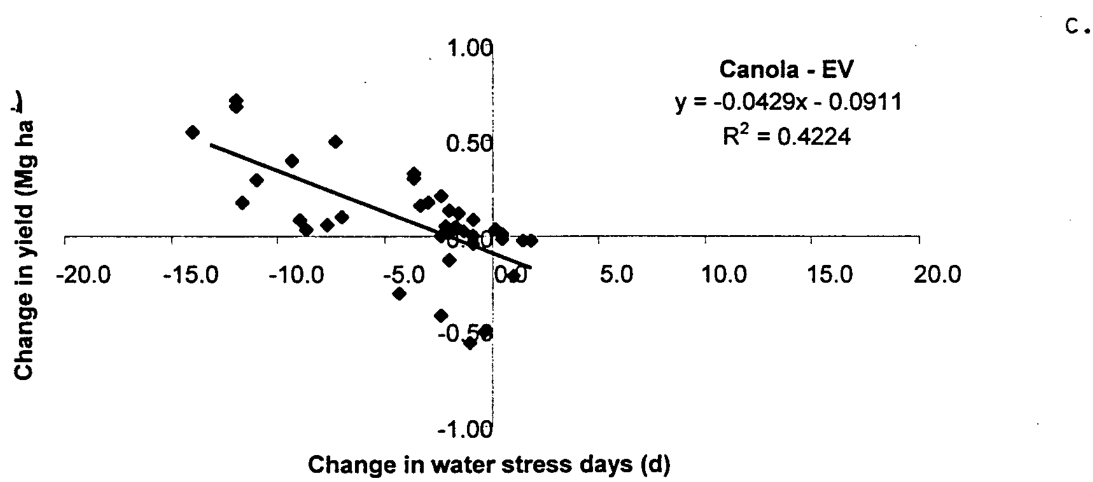


Fig. III.15. Variations of Canadian canola yields under a) EN, b) SEN, c) EV as a function of change in water stress days.

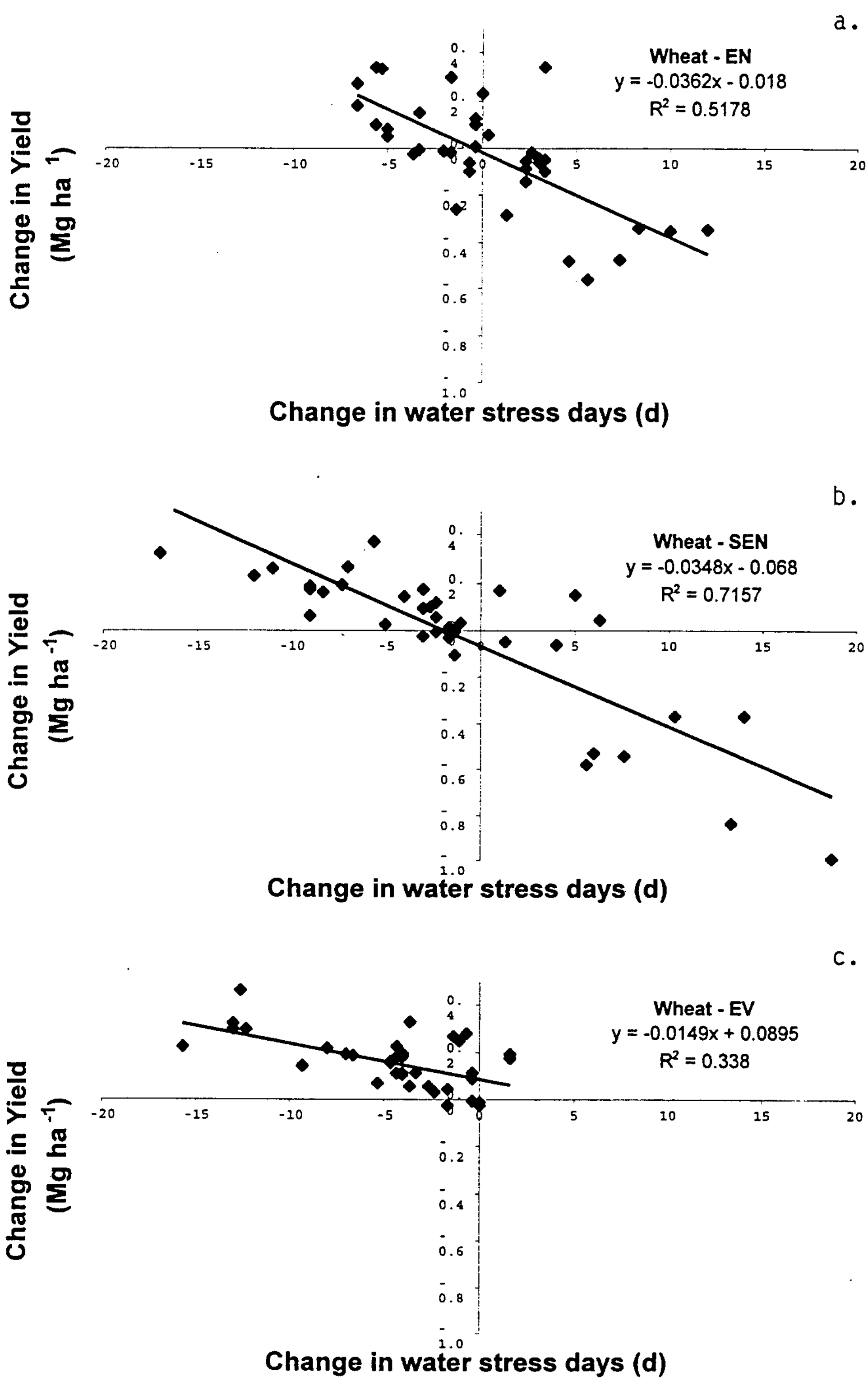


Fig. III.16. Deviations of Canadian spring wheat yields under a) EN, b) SEN, c) EV as a function of change in water stress days.

C.3 United States

Simulated average corn yields for the Corn Belt (Midwest and Central United States including the Ohio Valley) ranged from 6.5 to 8.9 Mg ha^{-1} under Neutral conditions (Table III.8 a). Farms located to the north of the Corn Belt (farms U24, 27) and to the West (U12, 13, 14, 15, 17, 19) have lower yields because of extremes in temperatures and/or less precipitation. Corn yields in the southern Great Plains (U41-46) ranged from 2.7 to 8.4 Mg ha^{-1} showing the potential for high levels of production; yield variability is high in this region. Simulated farm yields for the mid Atlantic and southeastern U.S. ranged from 5.0 to 7.8 Mg ha^{-1} (U53-56, 61-65) with the high yields occurring among those farms located in the Atlantic Coastal Plain (U62, 63, 64, 66).

EN conditions decreased yields with respect to Neutral in much of the central U.S. and Corn Belt (U17, 21, 22, 23, 29-37). These decreases were quite variable, however, ranging from -0.01 to -1.83 Mg ha^{-1}. Farms to the north of the Corn Belt (U24, 26, 27) show increased corn yields with respect to neutral. The EN climate also decreased yields for farms in the semi arid western Great Plains (U12, 14) where Neutral yields are, in any case, low. Corn yields decrease with respect to Neutral on farms located in the southern Great Plains (U41-46). Yields decrease as much as 2.2 Mg ha^{-1} in this region. Farms in the eastern half of the United States showed more variability in their yield response to EN with 8 farms decreasing by as much as 1.25 Mg ha^{-1}; 6 farms show increasing yields in this region.

SEN climate increased yields on farms located in a narrow band stretching from Southern Kansas into the Great Lakes region (U20, 19, 15, 17, 25, 24, 26, 27). Farms to the east of this region (U18, 21, 22, 29-35) within the Corn Belt and located to the west (U12-14) in the western Great Plains decreased yields under the SEN climate. In the southeastern U.S., the SEN climate increased yields on farms U53-54, 56, 65-66 located from southern Alabama to the Carolinas. Corn yields also increased for a set of farms in eastern and southern Texas (U44, 46, 47, 48, 49). Corn yields in the mid Atlantic and northeast generally decreased under the SEN climate (U39, 40, 58-64).

The EV climate increased corn yields within a region extending from the southeastern into the mid Atlantic states (U53, 54-56, 61, 62, 65, 66) with the maximum increase from Neutral of 1.28 Mg ha-1 for farm U65. The EV climate also increased corn yields in a large area in the central portion of the US. This region includes the Southern Plains (U43, 44, 46-48) and extends into eastern Kansas and Missouri (U19, 20-23, 35, 51, 52). With the Corn Belt, corn yields primarily decreased with a mean decrease of -0.40 Mg ha^{-1} from Neutral for farms U17, 18, 30, 34, 33, 32, 29. However, the EV climate increased yields for farms U31 and U35 in Illinois U57 in Ohio. Corn yields also decreased for farms in the western Great Plains (U12-14, 41, 42).

Under Neutral conditions, winter wheat yields ranged from 0.62 to 2.19 Mg ha^{-1} in the Pacific Northwest and from 0.58 to 2.83 in the Great Plains and Midwest (which includes all farms east of the Rocky Mountains) (Table III.8 b). For the Great Plains, the most productive farms were located within an area stretching from Iowa to western Nebraska and Kansas. Yields for the two California farms (U5, 6) were 1.92 and 2.52 Mg ha^{-1}.

The EN condition decreased yields on most farms with the decreases ranging from -0.01 to -0.90 Mg ha^{-1}. Yields decreased for all farms in the Pacific Northwest and for all but three farms in the Great Plains/Midwest. The greatest losses occur on farms U2 and U4 located in the Pacific Northwest with decreases of -0.90 and -0.61 Mg ha-1 respectively. California farm yields were insensitive to the EN climate with farm U5 decreasing yield by 0.06 Mg ha^{-1} and farm U6 increasing yield by 0.04 Mg ha^{-1}.

In general, wheat yields benefited from the SEN climate with 21 farms increasing and 10 farms decreasing yields. Farms in the central Great Plains and Corn Belt (farms U19 – 23, 30, 31, 35) increase yields with the increases ranging from 0.15 to 0.66 Mg ha^{-1}. Farms in the northern Great Plains (U8-10) decreased wheat yields under the SEN climate. Wheat yields for farms U5 and U6 in California showed more sensitivity and variability under the SEN climate than under the EN climate with farm U5 increasing yield by 0.08 Mg ha-1 and U6 decreasing yield –0.10 Mg ha^{-1}. Farms in the Pacific Northwest were also variable in their response to SEN climate with yield changes from Neutral ranging from –0.47 (U4) to 0.08 Mg ha^{-1} (U2).

A pattern similar to SEN emerges under EV conditions with farms in the eastern Great Plains and Corn Belt increasing wheat yields while farms in the western and northern Great Plains decrease yields. Wheat yield response to the EV climate differs from SEN for farms in the central Great Plains with most farms (U11-14, 16, 42) decreasing yields. The EV climate has a variable impact on wheat yields in the Pacific Northwest with two farms increasing yield (U2, 3) and two farms decreasing yield (U1, 4).

Figs.III.17 (a-d) and III.18 (a-d) show the relationship between mean yield and coefficient of variation for corn and winter wheat, respectively, under each of the four ENSO conditions. Yield variability increases as mean crop yields decrease for all of these cases. This relationship appears to be stronger for corn than for wheat. Yield variability in corn increases under the El Niño climate. This is most evident for farms with mean yields less than 4.0 Mg ha^{-1}; however, a slight increase in variability is observed for the farms with higher yields as well. Corn farms under the Strong El Niño and El Viejo conditions increase variability for the lower productivity sites; on the higher production farms, variability appears to be unchanged with respect to Neutral. Wheat yields tend to be less variable than corn yields. Wheat yield variability is relatively unchanged under both El Niño and El Viejo climates; the greatest increase in variability occurs under the Strong El Niño conditions.

The relationship of yields and water stress days for the three ENSO states is examined in Figs. III.19 (a-c) and 20 (a-c) for corn and wheat, respectively. For all cases, increases in water stress days indicate decreases in crop yield. This relationship is stronger for corn than for wheat and does not appear to change dramatically with ENSO condition. This suggests the importance of precipitation in determining yield differences under all ENSO conditions. The relationship between yields and water stress days is stronger for corn than for wheat under EN, SEN, and EV conditions alike.

Table III.8 a. Yields of dryland corn in the United States, stress days under Neutral conditions and deviations from Neutral due to EN, SEN and EV.

Farm	Crop yields								Temperature				Water			
	N		Deviation from N							Deviation from N				Deviation from N		
			EN		SEN		EV									
	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev	N	EN	SEN	EV	N	EN	SEN	EV
	Mg ha^{-1}								d				d			
U12	1.57	1.17	-0.75	-0.42	-0.98	-0.43	-0.06	0.00	15	-1	11	-1	42	7	-1	-2
U13	2.10	1.60	0.11	0.29	-0.86	-0.55	-0.26	0.19	16	-5	3	2	45	-1	-4	5
U14	3.30	1.99	-1.77	-0.68	-2.54	-1.17	-1.43	-0.38	11	-4	5	1	35	8	4	7
U15	6.44	1.47	-0.90	0.19	0.04	-1.02	-0.30	-0.05	12	-3	2	2	12	4	-3	5
U17	5.26	2.03	-1.83	-0.15	1.01	-1.42	-1.49	0.13	20	-9	2	5	24	8	-10	8
U18	7.70	0.38	-0.66	0.06	-1.01	0.09	-0.37	0.17	23	-9	-2	3	5	4	5	5
U19	5.48	1.73	-0.75	0.48	0.06	-0.36	1.04	-0.39	8	-2	5	1	19	0	0	-4
U20	7.22	0.41	-0.26	-0.01	0.05	-0.10	0.43	0.00	8	-1	1	-1	3	0	0	0
U21	7.43	0.39	-0.13	0.16	-0.13	-0.04	0.39	0.02	10	-2	1	1	3	1	0	0
U22	7.40	1.38	-0.10	-0.44	-1.50	0.26	0.39	-0.18	11	-2	2	1	14	-1	8	-2
U23	7.22	0.35	-0.06	0.01	-0.09	-0.02	0.45	0.01	7	-1	1	0	2	-1	0	0
U24	3.05	0.68	0.02	0.01	0.12	0.28	-0.06	0.24	35	-1	1	2	5	1	0	2
U25	7.09	0.54	-0.41	0.68	0.08	-0.13	0.02	0.03	36	-11	-1	4	10	2	-3	-2
U26	5.59	0.35	1.13	0.17	0.60	0.01	-0.60	0.03	42	-3	-1	0	5	0	0	0
U27	2.20	0.28	1.61	0.14	2.11	0.07	0.00	0.03	53	-6	-8	-1	3	-1	-1	-1
U28	7.05	0.41	-0.05	0.05	-0.39	0.02	-0.26	0.02	34	-5	-11	4	7	1	3	3
U29	6.64	0.45	-0.69	0.28	-0.61	-0.03	-0.16	0.11	28	-12	-7	-6	10	2	1	2
U30	7.72	0.38	-0.54	0.14	-0.96	0.32	-0.36	0.31	22	-7	-4	3	4	2	4	4
U31	7.38	0.39	-0.50	0.05	-0.73	0.03	0.11	0.01	16	-3	-5	2	4	-1	0	-1
U32	7.44	0.69	-0.71	0.25	-0.69	0.10	-0.11	-0.06	25	-7	-13	0	13	0	1	0
U33	7.05	0.87	-1.21	0.57	-0.90	0.11	-0.11	0.08	11	-3	-4	1	12	6	2	1
U34	7.36	1.06	-0.55	-0.06	-0.69	-0.29	-0.25	-0.20	10	-3	0	2	11	2	1	5
U35	7.59	0.48	-0.52	0.07	-0.68	0.12	0.40	0.06	11	-4	0	3	4	2	4	2
U36	8.54	0.38	-0.36	0.21	-0.62	0.24	0.13	-0.05	8	0	1	0	3	1	3	-1
U37	8.13	0.34	-0.01	0.05	-0.59	-0.04	0.29	0.01	6	0	0	0	2	-1	-1	-1
U38	8.08	0.30	-0.32	0.09	-0.73	0.01	0.11	0.03	6	0	0	1	2	1	2	0
U39	8.93	0.44	-0.96	0.25	-0.35	0.27	-0.22	0.24	12	-3	0	2	9	4	-1	1
U40	8.59	0.42	-1.00	0.53	-0.18	0.19	-0.10	0.04	15	-4	-4	-1	4	6	-1	1
U41	2.76	1.62	-1.21	-0.03	-1.91	-0.74	-0.83	0.35	11	1	7	0	36	4	8	3
U42	3.40	2.22	-2.21	-0.96	-2.53	-1.14	-2.28	-1.37	10	0	8	0	30	8	13	13
U43	2.89	1.98	-1.03	-0.51	-0.76	-0.03	0.36	0.16	5	-1	1	-1	28	4	4	0
U44	8.36	0.41	-0.07	0.05	0.29	0.02	0.17	0.00	19	1	7	0	2	2	-1	0
U45	6.74	0.33	-0.31	0.01	-0.14	0.07	-0.06	-0.02	5	0	0	1	5	4	-1	-2

Table III.8 a. (continued). Yields of dryland corn in the United States, stress days under Neutral conditions and deviations from Neutral due to EN, SEN and EV.

Farm	Crop yields								Temperature				Water			
	N		Deviation from N: EN		SEN		EV		N	Deviation from N			N	Deviation from N		
	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev		EN	SEN	EV		EN	SEN	EV
	Mg ha^{-1}								d				d			
U46	6.87	0.87	-1.00	0.26	0.63	-0.34	0.02	0.13	13	0	6	-1	13	7	-6	-2
U47	4.44	1.63	1.31	-0.98	1.81	-1.27	1.14	-0.94	13	4	3	2	12	-10	-11	-7
U48	7.85	0.40	0.19	0.21	0.53	-0.02	0.43	0.01	19	2	4	1	4	0	-2	-2
U49	7.09	0.32	0.10	0.05	0.07	-0.03	0.26	0.04	5	0	2	-1	1	0	0	0
U50	6.30	0.29	0.09	-0.04	-0.12	-0.06	-0.07	-0.01	5	0	-1	0	1	0	0	0
U51	6.72	0.46	-0.44	0.13	-0.03	0.15	0.42	-0.10	4	-1	0	0	7	4	1	-3
U52	7.41	0.36	-0.28	-0.01	-0.50	-0.08	0.18	0.03	5	-1	0	-1	1	1	0	1
U53	6.82	0.39	0.06	-0.03	0.03	-0.12	0.38	0.00	8	0	3	1	2	1	-1	0
U54	6.31	0.62	-0.09	0.22	0.14	-0.21	0.62	-0.04	9	-1	3	1	9	2	1	-3
U55	6.00	0.51	-0.10	-0.01	-0.09	0.03	0.15	0.01	4	-1	0	0	8	2	1	0
U56	6.94	0.43	-0.29	0.34	0.14	-0.05	0.40	-0.11	3	0	1	0	2	4	1	0
U57	7.41	0.42	0.29	0.06	0.38	0.09	0.09	0.18	27	-1	-1	-2	10	-2	-3	3
U58	4.95	1.20	0.23	-0.34	-0.75	-0.07	1.03	-0.71	19	-2	-3	1	18	-3	2	-6
U59	6.35	0.50	0.01	-0.06	-0.42	0.24	0.15	0.21	30	-1	-6	1	8	0	6	1
U60	4.99	1.71	-0.40	-0.13	-1.04	-0.13	-0.50	-0.16	29	-2	-2	1	20	1	6	4
U61	5.00	1.56	-1.25	-0.12	-2.45	-0.04	-0.48	-0.16	14	-5	-5	-3	22	7	13	4
U62	7.83	0.33	-0.44	0.19	-0.42	0.09	0.16	0.05	12	-2	-3	0	3	6	1	0
U63	7.37	0.34	-0.31	0.01	-0.17	-0.02	0.02	0.05	7	0	-1	0	2	1	3	1
U64	7.35	0.34	-0.24	0.03	-0.02	0.01	0.04	0.10	6	0	0	0	2	1	1	0
U65	5.17	0.68	0.01	0.03	0.33	-0.11	1.28	-0.12	9	0	2	0	23	1	-2	-4
U66	7.69	0.40	0.13	0.01	0.16	0.01	0.30	0.00	11	1	3	1	1	0	0	0

Table III.8 b. Yields of winter wheat in the United States, stress days under Neutral conditions and deviations from Neutral due to EN, SEN and EV.

Farm	Crop yields								Temperature				Water			
	N		Deviation from N						N	Deviation from N			N	Deviation from N		
			EN		SEN		EV			EN	SEN	EV		EN	SEN	EV
	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev								
	Mg ha^{-1}								d				d			
U1	0.62	0.21	-0.15	-0.05	0.02	-0.01	-0.07	-0.06	68	-55	5	-20	60	-46	2	-5
U2	2.19	0.65	-0.90	-0.19	0.08	0.04	0.11	0.17	45	10	-12	-8	30	29	0	0
U3	1.63	0.49	-0.17	-0.03	-0.48	0.01	0.02	-0.09	0	0	0	0	29	24	34	-3
U4	1.53	0.65	-0.61	-0.23	-0.47	-0.30	-0.40	-0.15	0	0	0	0	50	16	-4	2
U5	1.92	0.34	-0.06	0.03	0.08	-0.01	0.01	0.11	23	1	0	3	3	-1	-1	-1
U6	2.52	0.29	0.04	0.00	-0.10	0.10	0.17	0.24	23	3	-2	5	3	0	-1	0
U7	0.96	0.42	-0.01	0.03	0.01	0.06	0.04	-0.02	0	0	0	0	46	13	16	-6
U8	1.49	0.47	0.00	-0.07	-0.19	-0.09	-0.08	0.06	0	11	22	0	53	9	3	5
U9	1.59	0.39	-0.07	0.09	-0.25	0.07	0.08	0.04	0	0	0	0	43	7	12	-9
U10	1.45	0.33	-0.02	-0.03	-0.04	0.00	-0.05	0.00	0	0	0	0	35	4	5	3
U11	0.58	0.20	0.02	0.00	0.35	0.16	-0.28	-0.07	4	0	11	-4	4	3	31	-4
U12	1.09	0.31	-0.02	0.02	0.09	0.14	-0.03	-0.01	69	-9	-39	-7	58	-5	3	-10
U13	2.08	0.51	-0.34	-0.04	0.21	0.00	-0.26	-0.03	15	-11	-4	6	23	0	-6	11
U14	2.04	0.60	-0.29	-0.01	0.18	-0.05	-0.16	-0.17	11	7	32	13	17	4	-1	12
U15	2.25	0.46	-0.20	0.03	0.05	-0.08	0.07	0.03	0	4	0	0	15	0	-5	0
U16	1.44	0.30	-0.01	0.05	0.36	0.03	-0.12	0.11	0	0	0	0	30	-8	-11	17
U17	2.47	0.41	-0.40	0.10	-0.08	0.04	0.03	0.05	0	0	0	0	17	6	0	-1
U18	2.83	0.47	-0.70	0.03	-0.14	0.00	-0.09	0.03	0	0	0	0	20	0	1	0
U19	2.34	0.58	0.02	0.03	0.25	-0.12	0.09	-0.13	75	2	-3	1	9	1	0	-1
U20	2.65	0.50	-0.03	0.02	0.33	0.00	0.12	0.04	75	-2	-13	-12	6	-1	-3	-3
U21	2.77	0.42	-0.37	0.10	0.66	0.00	0.08	0.12	4	4	46	22	13	0	-2	-1
U22	2.18	0.25	-0.14	0.06	0.13	0.07	0.08	0.02	65	-24	12	11	12	0	-2	-4
U23	2.06	0.39	-0.02	-0.02	0.21	-0.07	0.10	0.04	72	2	-16	-12	5	0	-2	-1
U30	1.98	0.43	-0.11	0.00	0.15	0.07	0.11	0.03	0	0	0	0	18	1	-2	1
U31	1.82	0.44	-0.15	0.05	0.39	0.13	0.11	0.05	0	0	18	0	14	0	-5	-1
U35	2.04	0.56	-0.13	-0.01	0.46	-0.10	0.23	-0.01	68	-5	-8	12	8	0	-4	-2
U41	1.47	0.51	0.00	-0.07	0.19	-0.11	0.09	0.19	50	-7	1	-9	61	-3	-22	-3
U42	1.70	0.53	-0.03	-0.06	-0.25	-0.07	-0.22	-0.08	58	-6	1	-10	36	-1	5	21
U43	1.80	0.38	-0.02	0.00	-0.12	0.01	-0.07	0.11	60	-5	-36	-16	11	-1	-6	2
U44	2.78	0.65	0.05	-0.01	0.08	-0.02	-0.07	0.01	46	-1	-12	-8	2	-1	-1	-1
U45	1.84	0.28	0.00	0.01	0.07	-0.01	0.04	0.00	0	0	0	0	1	0	0	0

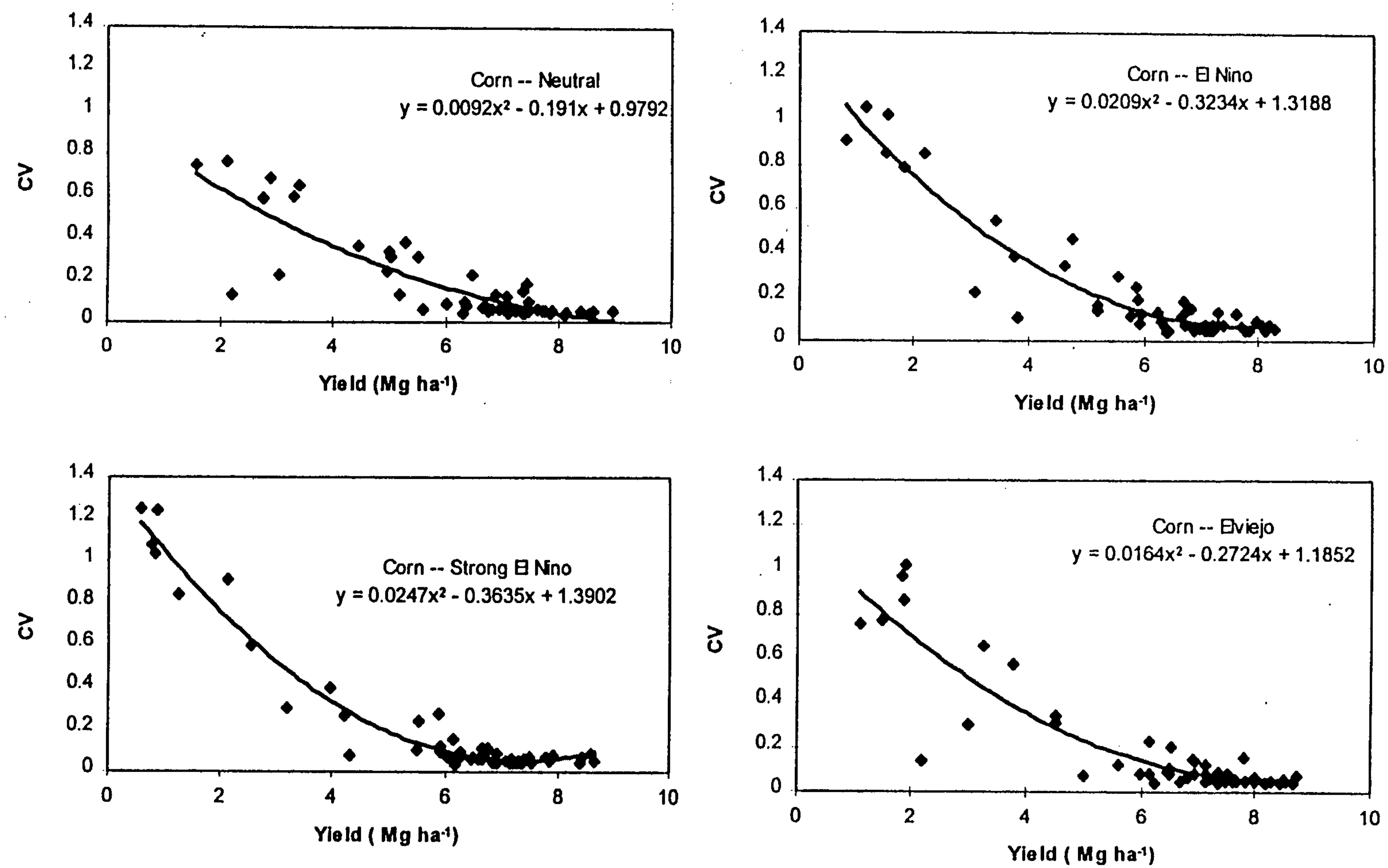


Fig. III.17 Coefficient of variation (CV expressed as a fraction) as a function of corn yield simulated under (a) Neutral, (b) El Niño, (c) Strong El Niño and (d) El Viejo ENSO scenarios.

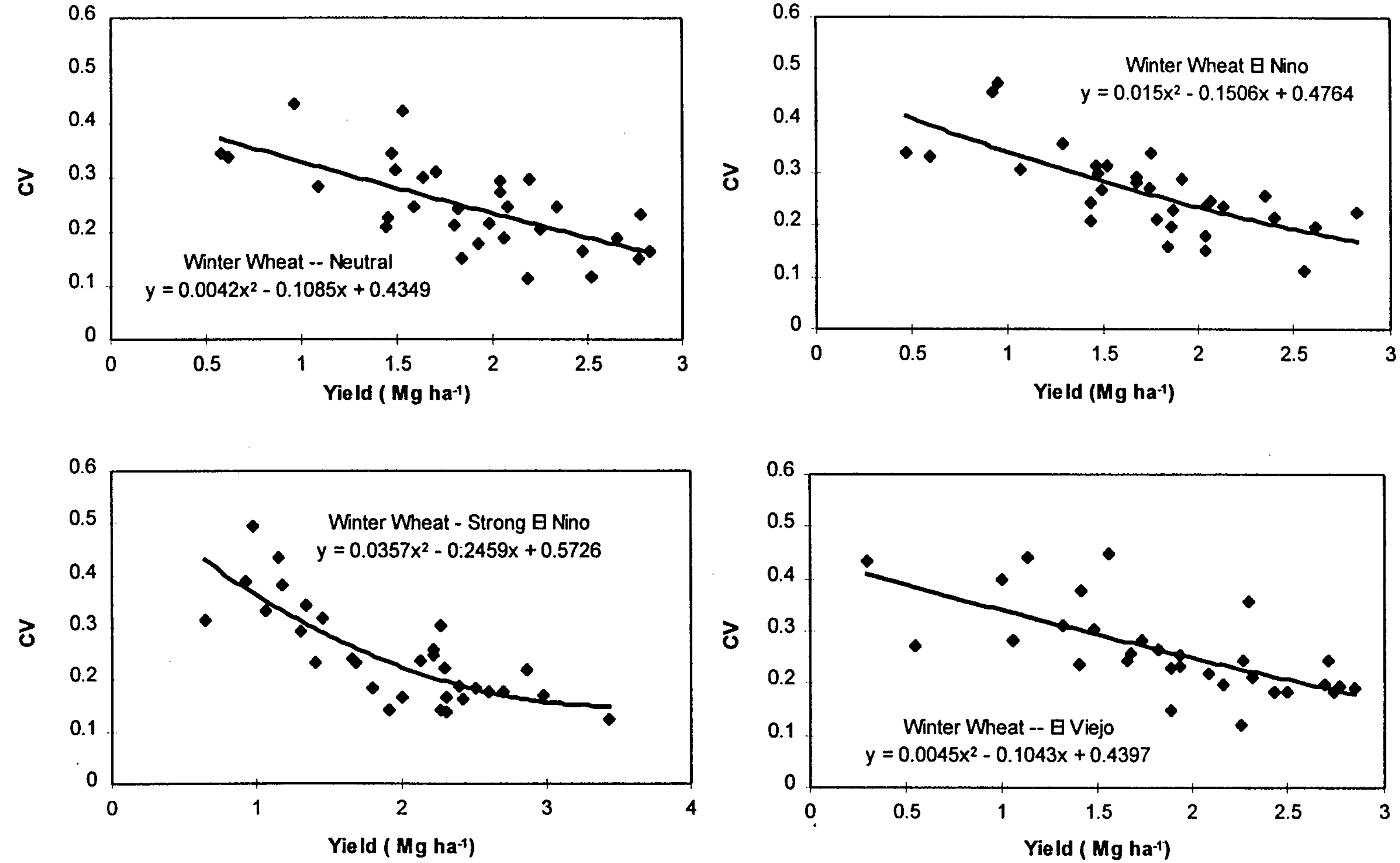


Fig. III.18 (a-b) Coefficient of variation (CV expressed as a fraction) as a function of winter wheat yield simulated under (a) Neutral, (b) El Niño, (c) Strong El Niño and (d) El Viejo ENSO scenarios.

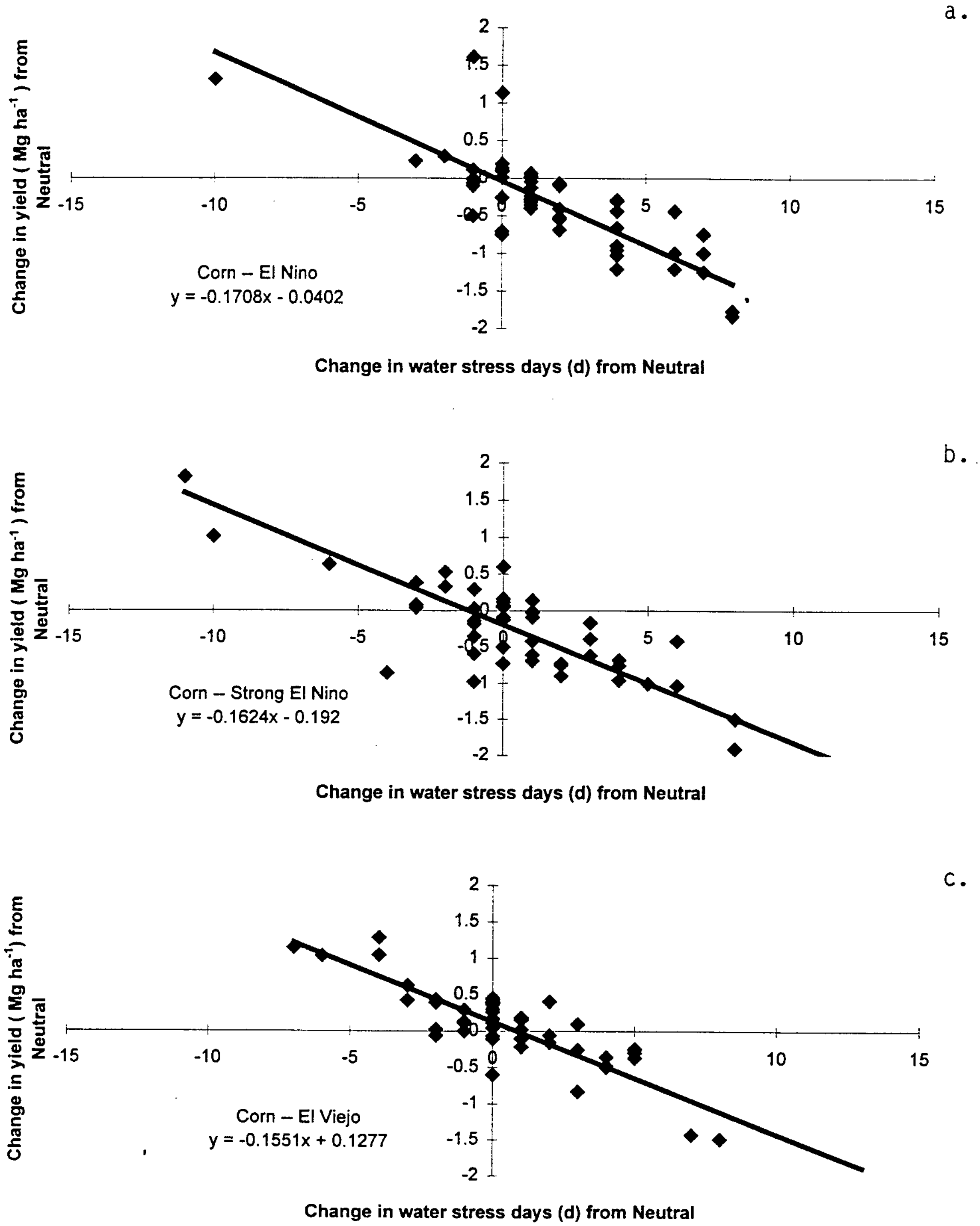


Fig. III.19 U.S. corn yields as a function of change from Neutral water stress days under (a) El Niño, (b) Strong El Niño, and (c) El Viejo ENSO scenarios .

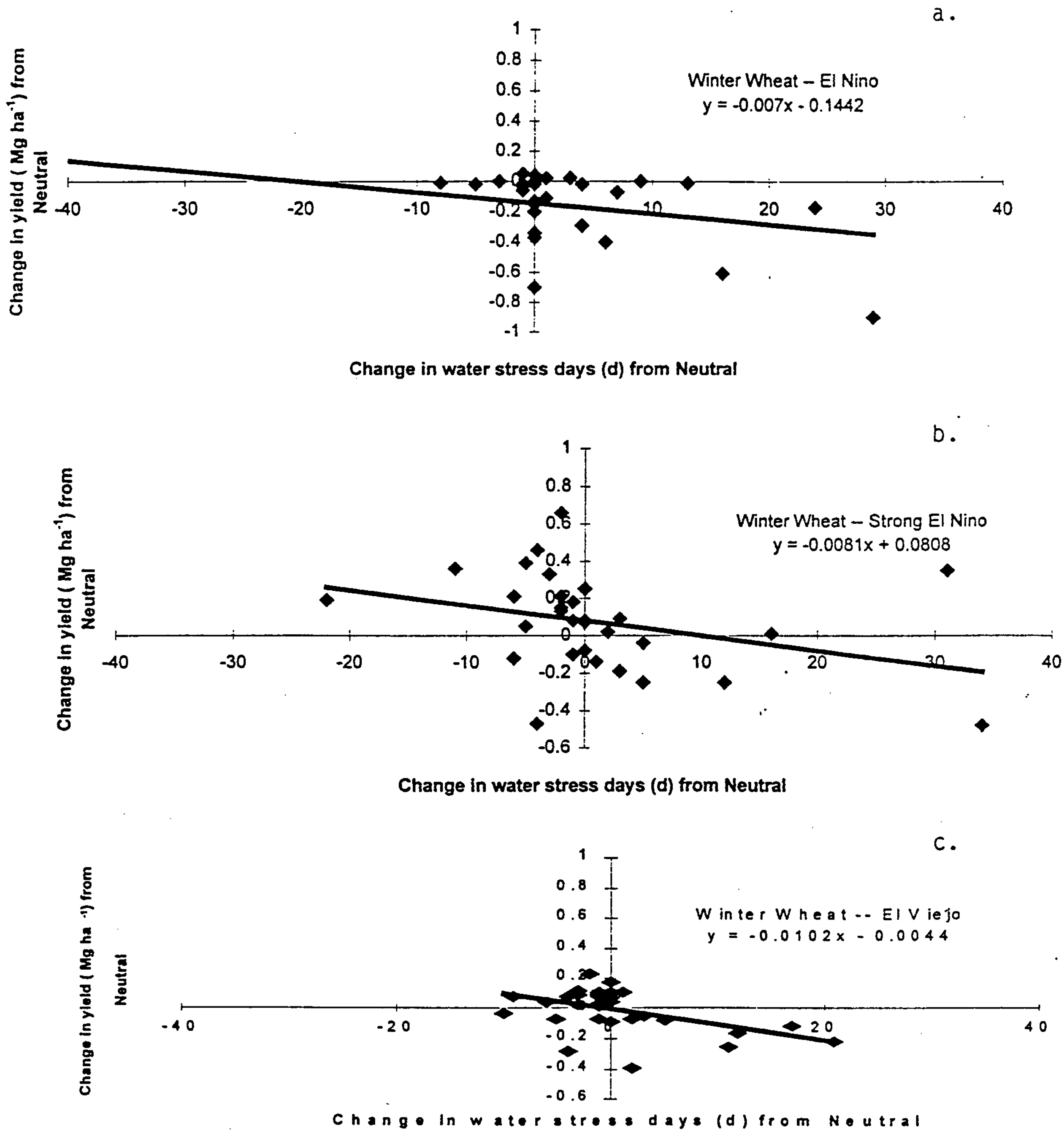


Fig. III.20 U.S. winter wheat yields as a function of change from Neutral water stress days under (a) El Niño, (b) Strong El Niño, and (c) El Viejo ENSO scenarios

C. 4 Mexico

Dryland Corn. Corn yields simulated across 17 dryland farms varied more (CV: 20.6%) than those simulated across 11 irrigated farms (CV: 6.8%) (Tables III 9 a-b).

Average corn yield was 0.5 Mg ha^{-1} greater under EN than under Neutral conditions; SEN, however, reduced average yield by 2.2 Mg ha^{-1}. Reductions in corn yield were strongly related to increases in number of water stress days. Water stress days occur when the crop is exposed to intense evaporative demand and/or when precipitation is insufficient to meet crop needs. Loss of yield increases with number of water stress days. The dependency of yield on stress day was greater under EN than under SEN and EV conditions (Fig. III.21). During EN events dryland corn lost 97 kg ha^{-1} of yield for each day of water stress; 54 and 26 kg ha^{-1} were lost under SEN and EV conditions although the relationship between stress days and yield is very weak for EV.

Farm M22, located in Chiapas in the Humid Tropics, suffered the greatest reduction in yield (-2.52 Mg ha^{-1}) under SEN conditions. The loss is related to the 34 days of water stress resulting from a 49 percent reduction in rainfall during the spring months (Table III.6). The opposite occurred on farm M16, located in Tamaulipas State within the Dry Tropics. Corn yield increased by 4.41 Mg ha^{-1} under EN conditions. This is attributable to significant increases in precipitation during the first months of the crop growing season: rainfall increased by 39% in winter and by 126% in spring. In general, the country average yield of dryland corn was 4.56 Mg ha^{-1} under Neutral conditions, with a potential reduction of 130 kg ha^{-1} during SEN events.

Irrigated Corn. Under Neutral conditions the countrywide yield of irrigated corn was 7.33 Mg ha^{-1}. EN reduces yields by 360 kg ha^{-1}. Highest yields occur on Farm M15 in Morelos State (Temperate region). That yield can be reduced by 2.98 and 1.03 Mg ha^{-1} under EN and SEN conditions (Table III.9 b.). As irrigation minimizes water stress, the irrigated crop responds primarily to changes in air temperature –particularly high temperatures and early frosts. Air temperature affects the demand for irrigation water. The greatest increment in water demand was for farm M4 located in Sinaloa State in the Dry Tropics: 207 mm of additional water was required under EN conditions associated with an 0.6 °C increase of air temperature. However, water savings are also possible; irrigation requirement was reduced by 184 mm on Farm M15 in Morelos State because of a reduction of air temperature.

Dryland Bean. Yields of dryland bean (Table III.9c) under Neutral conditions ranged from 0.86 Mg ha^{-1} in the semiarid environment of Zacatecas (Farm M8) to 2.2 Mg ha^{-1} in the dry tropical environment of Nayarit State (Farm M5). Farm M11 located in Guerrero State (Dry Tropic) shows the greatest yield reduction, 590 kg ha^{-1}, occurring under the SEN condition. This effect was related to a 31% decrease in precipitation and the consequent 15 days of water stress during the summer growing season (Table III.6). Although variations in crop yield were detected among farms, the country average change in crop yield was insignificant for all ENSO conditions.

The negative effect of stress days can be observed in Fig. III.22, which indicates the dryland bean crop more sensitive to SEN than either to EN or EV conditions. Under EV conditions yield can be reduced by 11 kg ha^{-1} for each day of water stress.

Irrigated Bean. Beans are grown under irrigation in Mexico in different seasons of the year depending on location. In the Semiarid Northwest (farms M2 and M7) they are grown from November to May; in the Semiarid and Temperate region (farms M7, M8, M12 and M18) from March to October; and in the Southeastern Dry Tropical region (farm M20) from February to early June.

Under Neutral ENSO conditions, irrigated beans yielded an average of 2.3 Mg/ha (Table III 9d). Yield deviations from Neutral in all three ENSO states were more often positive than negative but trivial in either case despite the occurrence of as many as 11 temperature stress days.

Dryland Wheat: Dryland wheat is sown in Mexico as a summer crop. The average wheat yield of studied production systems was 1.77 Mg ha^{-1} under Neutral conditions. In the Northern Semiarid zone yields were reduced (on Farms M7 and M8) under EN conditions and on Farm M14 farm under EV and SEN (Table III 9e). However, the most significant yield reduction (0.77 Mg ha^{-1}) was simulated under EN conditions for Farm M18 located in the Temperate region. Crop yield reductions of about 70 kg ha^{-1} can be expected for every stress day under EN and SEN events (Fig. III.23).

Irrigated Wheat: Wheat is grown under irrigation in Mexico during the winter season. The ten irrigated wheat production systems modeled averaged 3.93 Mg ha^{-1} of grain under Neutral conditions. On average, yields increased by 0.04 Mg ha^{-1} under EN and by 0.06 Mg ha^{-1} under SEN. However, the largest anomaly is a 0.20 Mg ha^{-1} reduction under droughty EV situations. Seven of eleven farms experienced wheat yield reduction under EV (Table III 9f).

Table III.9 a. Yields of dryland corn in Mexico, stress days under Neutral conditions and deviations from Neutral due to EN, SEN and EV.

Farm	Crop yields								Stress days							
			Deviation from N						Temperature				Water			
	N		EN		SEN		EV			Deviation from N				Deviation from N		
	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev	N	EN	SEN	EV	N	EN	SEN	EV
	Mg ha^{-1}								d				d			
M4	1.91	0.41	-0.07	0.06	-0.05	0.03	0.03	0.12	0	0	0	0	2	0	2	-1
M5	4.78	0.33	-0.20	0.05	-0.19	0.13	-0.02	0.08	6	-1	-1	-1	1	0	0	2
M7	1.25	0.10	-0.06	0.01	-0.03	0.00	0.85	0.15	15	-2	-1	-7	1	0	0	0
M9	6.24	0.62	0.06	-0.03	-0.62	0.47	-0.11	0.06	3	0	2	1	1	0	7	0
M10	7.16	0.39	-0.13	0.06	0.11	-0.08	0.23	-0.01	19	-3	-1	3	4	0	-2	-1
M11	4.92	0.66	-0.51	0.04	0.44	0.12	-0.11	-0.01	2	-1	2	0	4	5	9	5
M12	5.70	0.36	0.11	0.01	0.18	0.03	0.09	-0.03	18	6	5	3	2	-1	-1	-1
M14	5.13	1.02	-0.79	0.40	0.12	-0.19	0.04	0.26	5	-1	-4	-2	14	6	-6	2
M15	4.50	1.44	0.08	-0.36	-0.88	-0.08	0.69	-0.27	0	4	0	0	17	17	2	-9
M16	3.24	2.32	4.41	-1.17	-0.72	-0.31	-0.40	0.16	4	1	1	1	37	-22	3	-1
M17	3.61	1.35	0.44	0.11	0.71	-0.04	-0.52	-0.12	25	2	-2	6	71	-4	0	-5
M18	5.09	1.78	-2.04	0.04	1.10	-0.54	0.26	-0.14	13	-4	-2	1	64	29	-27	-11
M19	3.43	0.19	-0.02	-0.01	-0.10	0.00	-0.06	0.00	2	0	0	0	1	0	0	0
M20	4.95	1.10	-0.17	-0.09	-0.02	-0.04	-0.21	-0.08	6	-1	-4	1	2	0	2	4
M21	5.99	0.38	-0.08	0.04	-0.34	-0.01	0.17	-0.06	3	0	2	0	2	1	2	-1
M22	4.99	2.09	-0.67	-0.35	-2.52	-0.50	0.77	0.01	2	0	0	-1	32	2	6	-1
M23	4.60	1.42	0.13	-0.48	0.63	-0.96	0.27	-0.02	1	0	0	1	21	-8	-14	-5

Table III.9 b. Yields of irrigated corn in Mexico, stress days under Neutral conditions and deviations from Neutral due to EN, SEN and EV.

	Crop yields								Stress days							
			Deviation from N						Temperature				Water			
	N		EN		SEN		EV			Deviation from N				Deviation from N		
Farm	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev	N	EN	SEN	EV	N	EN	SEN	EV
	Mg ha^{-1}								d				d			
M2	6.56	0.6	-0.13	-0.03	-0.19	-0.03	0.32	0.03	11	0	-2	-1	6	0	8	1
M3	8.29	0.44	-0.52	-0.16	-0.21	0.3	-0.21	0.12	16	8	7	8	3	2	-1	2
M6	7.48	0.4	0.07	0.00	-0.01	0.23	0.12	-0.02	10	-1	-1	0	1	0	0	0
M7	6.85	0.25	-0.05	-0.03	0.00	0.00	0.04	-0.02	27	2	-1	3	1	0	0	0
M10	9.34	0.5	0.04	-0.06	0.02	0.09	0.92	-0.03	13	-3	0	6	2	0	0	0
M12	9.07	0.66	0.07	0.12	0.08	0.10	0.08	0.14	14	9	6	7	1	0	0	0
M14	6.61	0.56	-0.05	0.00	-0.55	0.28	0.18	0.24	5	-1	-4	-3	1	0	0	0
M15	9.97	0.76	-2.98	0.04	-1.03	-0.18	-1.03	-0.27	5	0	-2	-3	1	-1	0	0
M16	4.79	0.34	0.15	-0.02	0.73	-0.01	0.31	0.04	8	0	-1	1	1	0	0	0
M18	5.52	0.43	-0.31	-0.08	-0.05	0.00	0.08	0.02	5	0	-1	0	4	5	-1	-1
M20	6.16	0.58	-0.25	-0.10	0.32	0.13	-0.05	-0.10	6	-1	-4	1	1	0	0	0

Table III.9 c. Yields of dryland beans in Mexico, stress days under Neutral conditions and deviations from Neutral due to EN, SEN and EV.

Farm	Crop yields								Stress days							
			Deviation from N						Temperature				Water			
	N		EN		SEN		EV			Deviation from N				Deviation from N		
	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev	N	EN	SEN	EV	N	EN	SEN	EV
	Mg ha^{-1}								d				d			
M5	2.20	0.09	0.02	0.01	0.01	0.00	0.08	0.01	3	0	0	-1	2	-1	0	0
M6	1.64	0.34	0.06	0.14	0.21	0.13	-0.07	0.09	15	-1	3	2	70	5	-10	1
M7	0.70	0.12	0.04	-0.02	0.09	-0.01	0.05	-0.03	20	1	1	5	14	-3	-5	-8
M8	0.86	0.14	0.00	0.02	0.07	-0.01	-0.14	-0.01	21	6	-2	8	13	-9	-1	-8
M11	1.76	0.21	0.11	-0.09	-0.59	0.09	0.07	-0.06	2	-1	1	-1	7	-2	8	-1
M12	1.80	0.06	0.00	0.01	-0.01	0.02	-0.05	0.00	34	14	12	6	1	0	0	0
M16	0.92	0.18	0.00	0.00	0.10	0.02	0.03	0.00	6	0	-1	7	1	0	0	0
M17	0.99	0.05	0.00	0.00	0.08	0.01	-0.04	0.05	71	1	-11	23	1	0	0	0
M18	1.47	0.25	-0.24	0.06	0.23	-0.01	0.02	-0.02	19	-5	2	-1	17	20	-4	-2
M19	0.70	0.04	-0.01	0.00	-0.01	-0.01	-0.01	-0.01	1	0	0	0	1	0	0	0
M20	0.96	0.04	0.00	0.00	0.01	0.00	0.02	0.00	28	-3	-8	1	1	0	0	0
M21	1.19	0.06	0.01	0.00	-0.04	-0.01	0.02	0.00	1	0	1	0	1	0	0	0
M22	1.43	0.07	0.05	-0.01	0.09	0.03	0.01	0.02	6	3	-3	1	14	-11	2	-4

Table III.9 d. Yields of irrigated beans in Mexico, stress days under Neutral conditions and deviations from Neutral due to EN, SEN and EV.

Farm	Crop yields								Stress days							
			Deviation from N						Temperature				Water			
	N		EN		SEN		EV			Deviation from N				Deviation from N		
	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev	N	EN	SEN	EV	N	EN	SEN	EV
	Mg ha^{-1}								d				d			
M2	1.88	0.18	-0.06	-0.02	-0.01	-0.01	0.02	0.01	4	0	0	7	0	0	0	0
M7	2.79	0.17	-0.01	-0.02	-0.04	0.02	0.05	-0.02	26	5	3	3	4	0	1	-1
M8	2.67	0.11	0.05	0.01	-0.05	0.03	0.05	0.00	16	8	11	3	3	1	8	0
M12	2.51	0.07	0.01	0.02	0.03	0.03	0.05	0.01	28	11	9	1	9	0	0	0
M18	2.54	0.14	-0.02	0.00	0.04	0.01	0.01	0.00	29	-2	2	4	-4	3	0	0
M20	1.42	0.05	0.03	0.00	0.01	0.00	0.00	0.00	30	-1	2	1	-6	0	0	0

Table III.9 e. Yields of dryland wheat in Mexico, stress days under Neutral conditions and deviations from Neutral due to EN, SEN and EV.

	Crop yields								Stress days							
			Deviation from N						Temperature				Water			
	N		EN		SEN		EV			Deviation from N				Deviation from N		
Farm	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev	N	EN	SEN	EV	N	EN	SEN	EV
	Mg ha^{-1}								d				d			
M7	1.39	0.37	-0.06	-0.07	-0.21	0.01	0.24	-0.07	20	2	0	-6	6	-5	-5	-3
M8	1.52	0.08	-0.01	-0.01	0.03	-0.02	0.06	0.01	0	0	0	0	2	-1	-1	-1
M12	1.50	0.47	0.37	0.06	0.65	0.00	0.55	-0.03	25	-3	-5	-5	0	0	0	0
M14	2.13	0.58	0.43	0.13	-0.26	0.08	-0.40	-0.09	62	-15	-7	-6	37	-3	-1	19
M16	1.52	0.28	0.03	0.23	0.59	0.25	0.05	0.08	31	13	-3	5	23	0	-11	-10
M18	2.55	0.84	-0.77	0.00	1.06	0.02	0.34	0.01	0	0	0	0	29	9	-11	-3

Table III.9 f. Yields of irrigated wheat in Mexico, stress days under Neutral conditions and deviations from Neutral due to EN, SEN and EV.

	Crop yields								Stress days							
			Deviation from N						Temperature				Water			
	N		EN		SEN		EV			Deviation from N				Deviation from N		
Farm	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev	N	EN	SEN	EV	N	EN	SEN	EV
	Mg ha^{-1}								d				d			
M1	3.89	0.6	0.15	0.14	0.33	-0.05	-0.41	0.23	20	13	-2	14	4	-1	-2	0
M2	4.99	0.86	0.05	0.04	0.54	-0.14	-0.44	0.10	44	1	-12	5	16	1	1	6
M3	3.43	1.01	-0.38	-0.16	0.87	-0.29	-0.43	-0.13	89	1	-26	8	0	0	0	0
M7	4.01	0.58	0.10	-0.06	0.15	-0.10	0.07	-0.08	15	0	-5	6	1	0	0	0
M8	3.27	0.37	-0.04	0.01	-0.09	0.06	-0.14	0.02	11	0	2	-3	1	0	0	0
M10	4.22	0.89	0.03	0.00	-0.17	-0.14	-0.33	0.03	15	-2	-1	6	1	0	0	0
M12	5.32	0.86	0.08	-0.07	-0.03	-0.10	0.11	0.01	17	3	0	21	1	0	0	0
M13	3.13	0.44	0.11	0.01	-1.11	0.26	-0.37	0.12	23	-4	11	9	1	0	0	0
M14	3.55	0.38	0.26	0.11	0.11	0.13	0.04	0.09	60	-15	-7	-6	1	0	0	0
M16	3.54	0.55	0.01	-0.02	0.02	0.00	-0.11	0.05	36	-6	-5	2	1	0	0	0

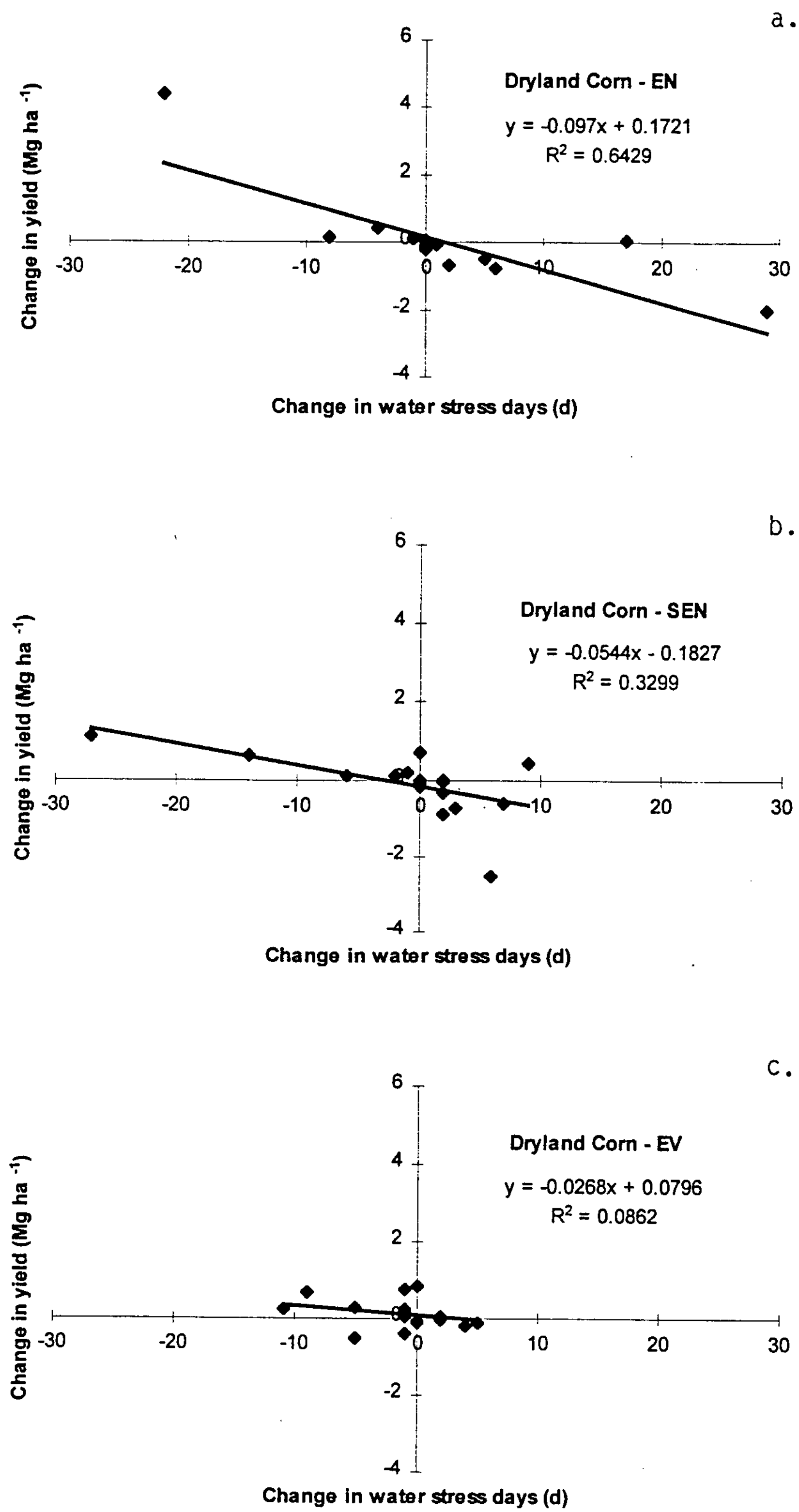


Fig. III.21. Mexican dryland corn yields as a function of change from Neutral water stress days under (a), El Niño, (b) Strong El Niño, and (c) El Viejo ENSO scenarios.

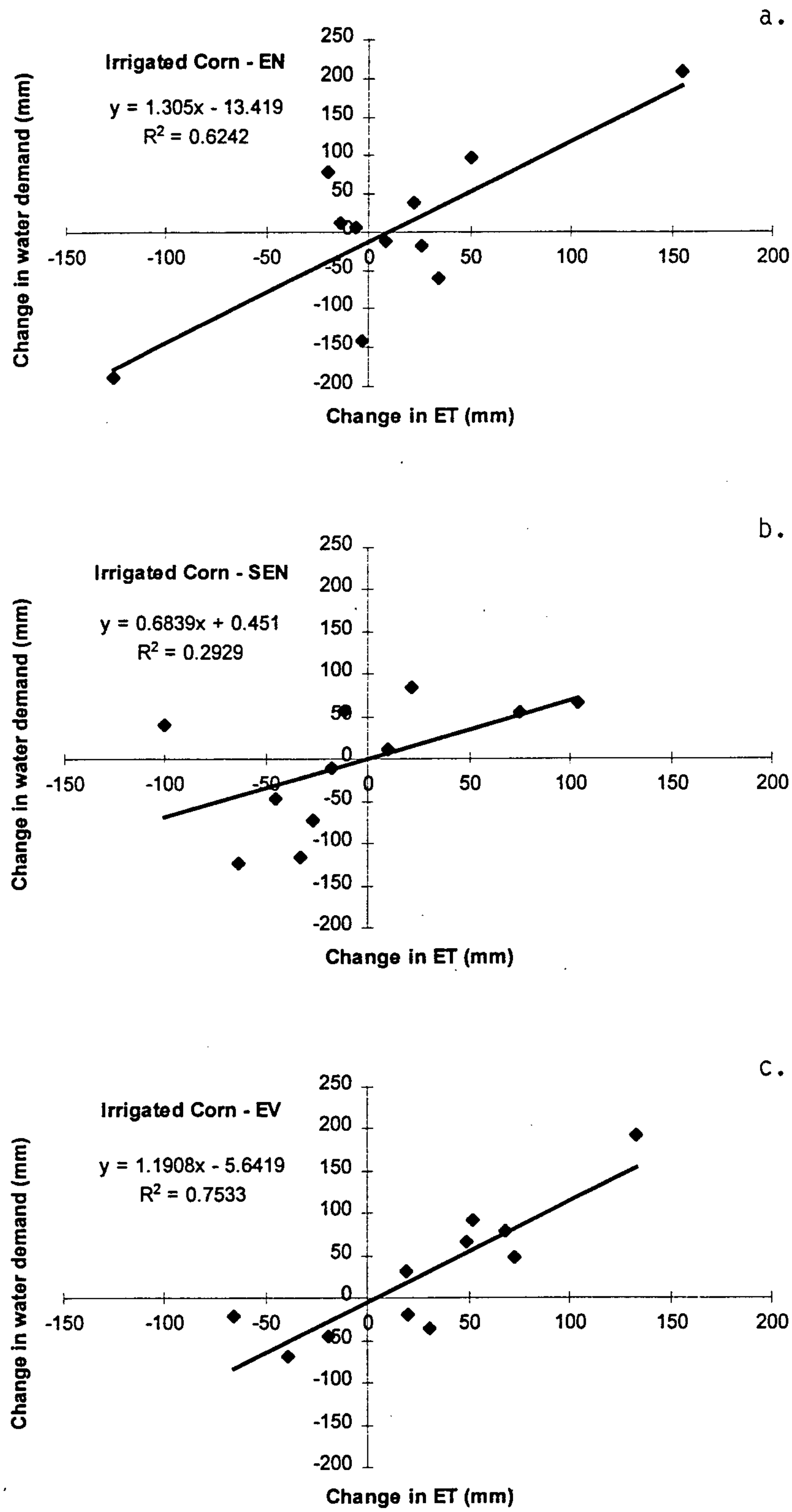


Fig. III.22. Mexican irrigated corn yields as a function of change from Neutral water stress days under (a) El Niño, (b) Strong El Niño and (c) El Viejo ENSO scenarios.

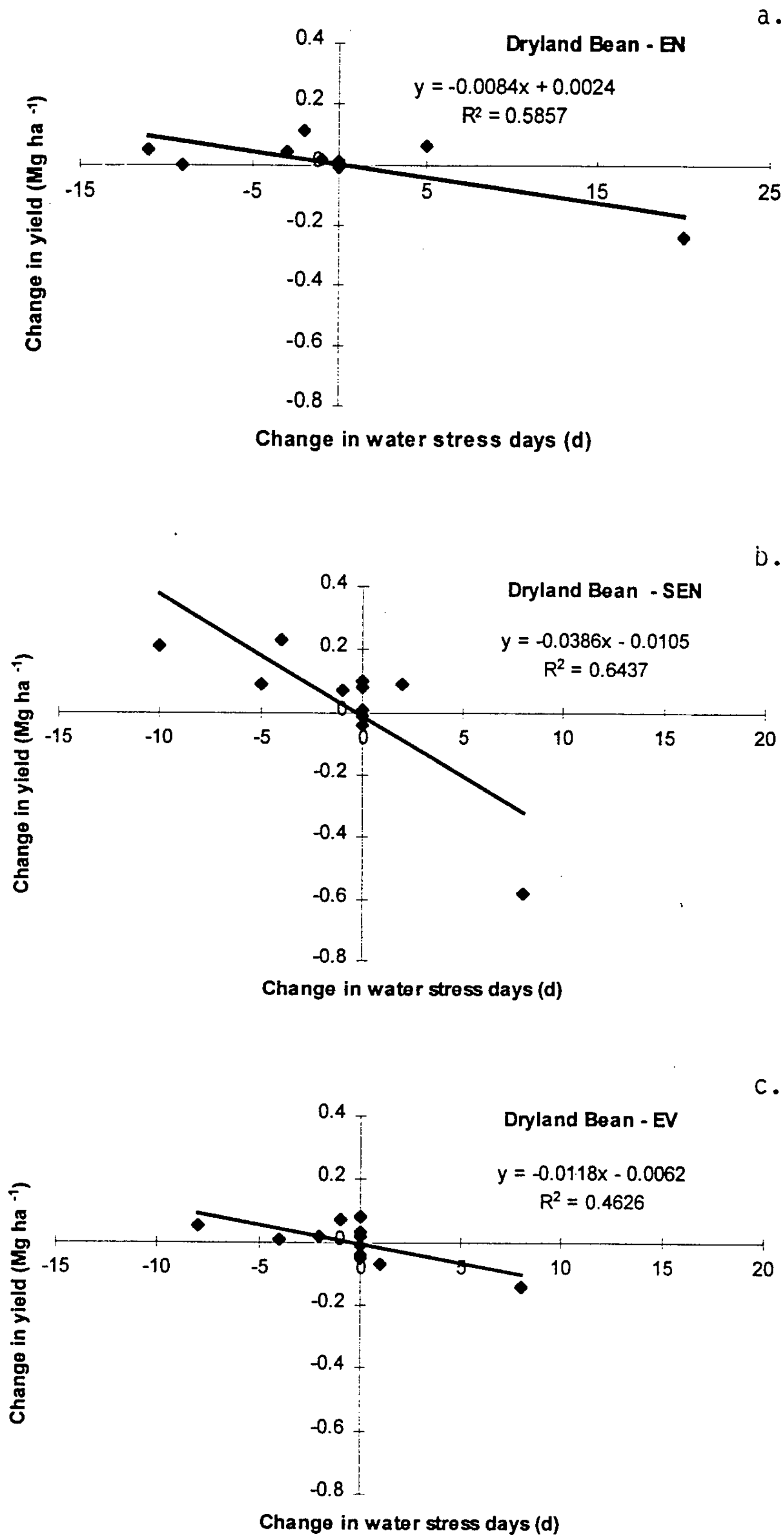


Fig.III.23. Mexican dryland bean yields as a function of change from Neutral water stress days under (a) El Niño, (b) Strong El Niño, and (c) El Viejo ENSO scenarios

D. ENSO Effects on Evapotranspiration, Runoff and Erosion

D. 1 Canada

Prairie Provinces

In the Prairie Provinces, annual potential evapotranspiration (PET) values calculated with the Penman-Monteith equation ranged from 736 (C4) to 1264 mm (C12) (Table III.10a). Deviations in PET under EN were positive and corresponded generally with positive deviations of average annual temperatures (Table III.1). Overall, the median increase in PET under EN was 24 mm. Under the SEN condition, PET increased with respect to the Neutral State in most farms, but decreased on a few others. Changes in PET ranged from -9 to +50 mm with a median change of 18 mm. Calculated PET decreased in all farms under the cooler conditions of EV. The median decrease in PET was -10 mm while PET deviations under EV ranged from -26 to -3 mm.

Actual ET under Neutral conditions in the barley-canola-wheat rotation ranged from 337 to 484 mm and had a median value of 401 mm. Under the EN scenario, ET deviations with respect to Neutral conditions ranged from -50 to 31 mm. A median ET deviation of -1 mm indicates that about half the farms had positive deviations in ET while the other half had negative deviations. Increases in ET were simulated on farms located in northern, more humid regions of the Prairie Provinces. Exceptions occurred on farms simulated with the Swift Current weather station (C18, C19, and C21) which show positive ET deviations. The increase is attributed to changes of winter through summer precipitation in EN years. While winter and spring precipitation decreased slightly, summer precipitation actually increased, thus resulting in an overall increase in ET (Tables III.2 and III.10 a). In contrast, winter precipitation at Lethbridge during EN years was about half that received during Neutral years. Spring precipitation during EN years continued to be lower (-18%) than that received during Neutral years thus contributing overall to a lower ET (Tables III.2 and III.10 a).

Changes in ET during SEN years varied widely from -119 to 78 mm with a median value of 11 mm. Changes in ET under SEN were weakly associated with those under EN, suggesting that the former scenario is not a stronger expression of the latter one (SEN = 0.9238EN - 2.6933; R^2 = 0.177). Furthermore, an examination of the changes in winter air temperatures simulated during EN and SEN years (Table III.1) appears to support the previous statement. Changes in ET during EV years were also negative and positive relative to Neutral years ranging from -16 to 66 mm with a median value of 15 mm.

Simulated annual runoff (Q) during Neutral years ranged from 0 to 38 mm with a median value of 1 mm (Table III.10 a). Although no direct comparisons can be made, the simulated values appear to be lower than those calculated using the SCS curve-number method. When grouped by textural classes the saturated hydraulic conductivity estimates were generally greater than those reported by Rawls et al. (1983, cited by Haan et al., [1994]) (data not shown). In the three alternative ENSO scenarios the calculated deviations in Q were both positive and negative. For example, Q deviations during EN years ranged from -24 to 26 mm and had a median value of 0 mm. Overall, the largest increases in Q were predicted to occur in the cooler northern regions of the prairies.

The variable eroded soil thickness (mm of soil depth) selected for analysis includes both types of erosion (*i.e.*, wind and water). Simulated 30-y total soil erosion ranged from 0 to 75 mm with a median value of 3 mm. Generally, water erosion rates simulated with the Moderate Rate Universal Soil Loss Equation (MUSS; Williams, 1995) were lower than those of wind erosion simulated with the Wind Erosion Continuous Simulation Equation (WECS; Williams, 1995). Experimental data on wind and water erosion are very scarce in the Prairie Provinces; thus, most regional estimates of erosion risks have been obtained through the use of simulation models and knowledge of soil properties and weather parameters. For example, Chanasyk and Woytowich (1987) reported annual rates of water erosion in the Peace River Region of Alberta to range from 0.2 to 1.2 Mg ha^{-1} for various treatment combinations of cereal and oilseed crops. Simulated annual water erosion for farm C3 in the same region averaged 0.9 Mg ha^{-1}.

The only measurements of wind erosion in the Prairie Provinces were reported recently by Larney et al. (1995) for a location near Lethbridge, Alberta. Dust collector measurements made from 6 December 1991 to 18 April 1992 under bare fallow totaled 135 Mg ha^{-1}. During this period there were a total of 11 erosion events with a maximum event registering 30 Mg ha^{-1} (3 April 1992). Simulated annual wind erosion for farm C8 under continuous cropping averaged 1 Mg ha^{-1}. The farms for which wind erosion was a major factor of soil degradation were located within regions of the prairie mapped as having moderate to high wind erosion risk (Wall et al., 1995).

Changes in soil erosion during EN years ranged from -1 to 5 mm with a median value of 0 mm. Soil erosion either did not change or decreased during EV years (range: -11 to +5 mm; median: 0). SEN conditions brought some notable increases in soil erosion on a few farms (range: 0 to +21 mm; median: 1 mm).

Atlantic Provinces

Potato is a major cash crop in the Atlantic Provinces. Simulated PET values calculated for the seven farms in the Atlantic Provinces ranged from 718 to 926 mm (Table III.10 b). Small changes in PET were predicted to occur during EN years (range: -7 to +4 mm). Significant increases in PET were predicted to occur during SEN years (range: +28 to +61 mm). Evapotranspiration was predicted to decrease slightly across the region following seasonal decreases in temperature and precipitation (Tables III.1 and III.2). Increases in ET due to SEN conditions were substantive and consistent across the region. El Viejo years reduced ET with respect to N years. Annual predicted Q during N years was generally low (range: 0 to 6 mm), but consistent with slope and textural characteristics of the representative farms used. Slope gradient varied from 2 to 4%. The soils ranged from sandy loam to loam in texture, resulting therefore in rather high saturated hydraulic conductivity values (range: 8.7 to h^{-1} - 12.1 mm h^{-1}). The SEN condition caused Q to increase significantly relative to the Neutral condition by as much as 13 mm. Predicted water erosion was low and rather insensitive to the various ENSO states.

British Columbia, Ontario, and Quebec

Corn was the major crop simulated in the provinces of British Columbia, Ontario, and Quebec. In British Columbia, PET during N years averaged 833 mm and changed little under any of the three ENSO scenarios (Table III.10 c). In Ontario and Quebec, annual PET ranged from 906 to 1088 mm during Neutral years but revealed significant increases under the three ENSO scenarios. Values of ET simulated under Neutral conditions averaged 478 mm in British Columbia and ranged from 519 to 631 mm in the provinces of central Canada. The only common result in these two regions was the decrease in ET under EN conditions. There were increases and decreases in ET for the other two conditions (Table III.10 c).

Estimated runoff was sizable especially on farm C2 where it reached 20 mm. Salient features of this farm include high annual precipitation (1840 mm, Table III.10 b) falling on silty clay soils lying on 2% slopes. The most significant change for any of the ENSO scenarios occurred on this farm during EV years when Q increased by 110% (Table III.10 c). This was accompanied by a similar increase in soil erosion. The other significant deviation occurred on farm C41 during SEN years where simulated soil erosion increased by 354%. This scenario had a significant increase in spring and summer precipitation falling on a silt loam soil with a 4.5% slope under a corn-soybean rotation.

Table III.10 a. Simulated ET, PET, runoff and soil erosion for Canadian canola, barley and wheat farms under Neutral conditions and deviations from Neutral due to EN, SEN and EV.

Farm	ET				PET				Runoff				Eroded topsoil depth			
		Deviation from N				Deviation from N				Deviation from N				Deviation from N		
	N	EN	SEN	EV	N	EN	SEN	EV	N	EN	SEN	EV	N	EN	SEN	EV
	mm				mm				mm				mm			
C3	357	31	-3	15	738	4	-9	-15	24	26	26	27	2	5	4	5
C4	410	1	-15	-3	736	11	4	-16	0	1	0	3	0	0	0	0
C5	436	6	23	9	989	16	21	-22	0	7	0	2	0	0	1	1
C6	458	-16	-82	-9	929	34	9	-13	2	-2	-2	3	1	0	0	1
C7	414	-50	-119	20	1218	33	32	-9	0	0	0	1	2	1	4	0
C8	416	-50	-119	21	1137	30	32	-10	0	0	0	1	1	0	1	0
C9	392	-12	-52	21	1070	19	50	-10	27	-14	-23	-14	1	0	0	0
C10	419	6	14	1	805	13	13	-17	0	2	3	0	0	0	0	0
C11	422	6	15	2	896	11	13	-16	1	8	13	8	0	0	0	0
C12	339	-23	-54	-3	1264	53	22	-18	0	0	0	0	9	1	3	-2
C13	338	-23	-53	-3	1112	45	20	-15	0	0	0	0	0	0	0	0
C14	400	22	8	24	821	15	8	-5	0	1	1	0	0	0	0	0
C15	337	-38	-34	0	1152	34	25	-9	0	0	0	0	1	0	0	0
C16	385	-16	35	12	845	37	34	-8	11	-5	-10	-8	0	0	1	0
C17	369	-2	14	17	911	22	4	-6	1	-1	2	0	0	0	0	0
C18	359	14	-63	61	1196	24	46	-26	1	0	-1	-1	8	1	6	-1
C19	359	16	-64	65	1194	25	48	-26	0	0	0	0	26	2	22	-11
C20	369	-2	14	17	909	21	2	-7	1	-1	-1	7	0	0	0	0
C21	360	17	-64	66	1196	25	46	-26	0	0	0	0	12	1	12	-3
C22	383	30	32	29	840	21	6	-5	0	0	0	0	0	0	1	0
C23	383	30	30	26	839	21	6	-4	0	0	0	1	0	0	0	0
C24	401	-23	59	21	1024	42	25	-4	1	-1	9	-1	1	0	1	0
C25	359	-4	44	29	1128	31	13	-18	5	0	14	-5	4	2	1	0
C24	372	17	59	20	834	18	1	-11	2	12	10	4	0	0	1	0
C27	379	19	78	31	886	20	10	-12	0	0	0	0	0	0	1	0
C28	402	-26	55	19	1106	48	28	-3	1	0	29	16	3	2	1	0
C29	397	-45	-26	20	1090	36	-3	-19	3	-3	-3	2	1	1	0	0
C30	409	-1	38	-5	798	17	5	-9	0	0	1	0	0	0	1	0
C31	436	22	22	23	929	15	-9	-16	1	-1	5	2	1	1	0	2

Table III.10 a (continued). Simulated ET, PET, runoff and soil erosion for Canadian canola, barley and wheat farms under Neutral conditions and deviations from Neutral due to EN, SEN and EV.

Farm	ET				PET				Runoff				Eroded topsoil depth			
		Deviation from N				Deviation from N				Deviation from N				Deviation from N		
	N	EN	SEN	EV	N	EN	SEN	EV	N	EN	SEN	EV	N	EN	SEN	EV
	mm				mm				mm				mm			
C32	439	-14	24	4	985	31	35	-6	0	0	0	1	2	0	1	0
C33	455	-9	-5	-16	943	26	12	-8	39	-24	-20	-30	1	0	0	0
C34	425	-8	27	4	913	29	33	-6	0	0	0	0	0	0	0	0
C35	476	-13	-10	-14	960	29	47	-6	25	-20	-20	13	1	0	0	0
C36	484	17	-23	5	988	23	37	-15	8	-5	-4	-7	3	-1	0	-2
C37	416	6	11	5	827	21	13	-6	2	-2	-1	-2	0	0	0	0
C38	471	5	14	6	994	23	18	-7	21	-6	16	11	2	-1	1	0
C39	428	14	-20	-9	985	32	38	-10	0	1	0	0	4	0	1	-1

Table III.10 b. Simulated ET, PET, runoff and soil erosion for Canadian potato farms under Neutral conditions and deviations from Neutral due to to EN, SEN and EV.

Farm	ET				PET				Runoff				Eroded topsoil depth			
		Deviation from N				Deviation from N				Deviation from N				Deviation from N		
	N	EN	SEN	EV	N	EN	SEN	EV	N	EN	SEN	EV	N	EN	SEN	EV
	mm				mm				mm				mm			
C43	465	-12	18	-16	775	1	28	-3	2	0	1	1	0	0	0	0
C44	458	-12	18	-16	775	1	28	-2	6	-2	-4	-2	0	0	0	0
C45	465	-6	23	-4	842	3	58	8	2	-1	10	1	0	0	0	0
C46	437	3	22	-1	836	3	57	7	0	0	8	0	0	0	0	0
C47	461	-12	19	-5	839	4	58	8	5	0	-2	1	0	0	0	0
C48	510	-9	33	-12	926	1	53	5	3	-1	3	-1	0	0	0	0
C49	508	-9	33	-11	925	0	53	5	2	-1	-1	-1	0	0	0	0
C50	431	0	36	-14	747	-7	53	-2	3	1	13	1	0	0	1	0
C51	445	-18	11	-31	718	-6	61	3	3	1	11	1	0	0	1	0

Table III.10 c. Simulated ET, PET, runoff and soil erosion for Canadian corn farms under Neutral conditions and deviations from Neutral due to EN, SEN and EV.

Farm	ET				PET				Runoff				Eroded topsoil depth			
		Deviation from N				Deviation from N				Deviation from N				Deviation from N		
	N	EN	SEN	EV	N	EN	SEN	EV	N	EN	SEN	EV	N	EN	SEN	EV
	mm				mm				mm				mm			
C1	458	-1	-16	4	821	0	4	1	4	-3	-2	-2	1	-1	0	0
C2	497	4	-49	12	844	-3	-7	-1	20	1	-4	22	3	1	0	4
C40	619	-15	1	-11	1088	37	34	19	2	-1	3	-1	0	0	0	0
C41	631	-14	-6	-11	1085	37	35	19	2	-1	6	-1	1	1	5	0
C42	519	-16	6	-2	906	19	50	-7	7	-3	-2	-4	0	0	0	0

D. 2 United States

Simulated ET was greater on corn farms (Table III.11 a.) than on wheat farms (Table III.11 b.). Wheat farms are located in the drier regions, which explains much of the difference. However, when corn and wheat growth is simulated at the same farm site, ET is greater for corn than for wheat. Many of the wheat farms are located in areas of water shortage where annual ET and precipitation values are nearly in balance. Simulated runoff at these sites was negligible under the four ENSO conditions, even in cases where precipitation is increased above Neutral. The highest PET for both corn and wheat was found on farms located in the Central and Southern Great Plains (U12, U41-44). PET was also high on farms located along the Southeastern Gulf coast and Florida. PET values generally decrease with increasing latitude signaling the importance of temperature in determining PET.

Under the EN climate, actual ET decreased for all of the wheat farms except for U20 and for 45 of the 54 corn farms. ET increased under EN on corn farms located on the South Atlantic Gulf (U47, 48, 49, 50, 56) and along the Canadian border (U24, 26, 27). In most cases, decreases in ET were related to decreases in precipitation. Actual ET increased under the SEN climate on 18 of the wheat farms and 39 of the corn farms. The ET increases for both wheat and corn occurred in the Southern Great Plains and also the Texas Gulf Coast (e.g. farms U44, 45, 46, 47, 48, and 49). In the Midwest and Corn Belt, ET also increased for both wheat and corn crops. Wheat farms (U1, 2, 3) in the Pacific Northwest experienced a drop in ET under the SEN climate. For the EV climate, corn farms in the Southeast generally experienced increased ET. Farms in the Cornbelt and Central and Northern Great Plains growing both corn and wheat had decreased evapotranspiration under EV.

ENSO climate impacts on runoff and soil erosion varied by region and by crop. Changes in the timing and intensity of precipitation events affect runoff, of course, but it is also affected by other climatic and environmental factors including soil texture, soil slope, crop water use and farm management practices. On the wheat farms located in regions of water scarcity, precipitation and evapotranspiration are in rough balance leaving little for runoff. ENSO related changes in precipitation in these regions had little impact on runoff or soil erosion. Only on the wheat farms in California and the southern and eastern Great Plains did runoff change among the climate scenarios.

Runoff for most of the wheat farms was either unchanged or decreased under EN conditions with only four wheat farms (U15, 21, 23, 31) showing increased runoff. Runoff varied on the corn farms under EN conditions with runoff decreasing on 26 farms and increasing on 19 farms. Many of the decreases were located in the Midwest and Great Plains and seven of the increases were located in the South Atlantic (U49, 50, 54, 55, 56, 65, 66). The greatest changes in runoff under EN climate included a 22 mm increase for corn farm U49 and a 10 mm decrease for wheat farm U6.

Corn farms in the southern Great Plains (U43, 44, 45, 46), the Gulf Coast (U47, 48, 49, 50) and Corn Belt (U34- 39) showed increased runoff under SEN conditions. Corn farms U49 and U50, located along the Gulf Coast, show the largest increases in runoff (134 and 112 mm, respectively) in response to increases in precipitation during winter, spring and fall. Wheat farms experienced their greatest increases in runoff under SEN conditions (53, 18 and 58 mm on farms U6, 35 and 44, respectively). Runoff decreases under SEN were small for both corn and wheat farms. The largest decrease on a corn farm was 8 mm (farm U53) and 4 mm on a wheat farm (U30).

EV conditions also increase runoff on a number of corn farms, but the increases are not as extreme as under SEN. Runoff increased on corn farms along the Atlantic coast (farms U56 - U66) but the greatest increase in runoff occurs on corn farm U44 in the southern Great Plains. EV decreased runoff on 12 wheat farms and increased runoff on 8 farms. The largest decrease was farm U6 in the Northern Great Plains (-11 mm) while the largest increase is on farm U44 (36 mm) in the Southern Great Plains.

Erosion was more severe on corn than on wheat farms. This holds true, as well, where both crops are grown on the same farms. Much of this difference can be attributed to the more frequent tillage and partially uncovered soil in corn cultivation. Regional patterns of soil erosion also emerge. Farms in the Central and Southern Great Plains (U10, 12, 14, 19, 41-44) showed high levels of erosion under both corn and wheat cultivation. In this region both wind and water erosion are prevalent. Farms U39 and U40 in the Ohio Valley also displayed high levels of erosion under corn cultivation. High levels of erosion along the Texas Gulf Coast (U47 – 51) are a consequence of heavy runoff at these sites.

Soil erosion varied as a function of crop growth and ENSO condition. Erosion decreased on 8 wheat farms and increased on 5 under the EN climate. Four of the increases occur in the Western and Central Great Plains (U7, 10, 12, 19). Erosion decreased on wheat farms by 1 to 6 mm. Depth of eroded topsoil increased on 21 corn farms under EN with the largest increase being 32 mm on farm U39. Only 9 corn farms show decreased soil erosion with most of the decreases less than 6 mm. Farms U40 and U51 are the exceptions reporting decreases of 39 and 74 mm, respectively, under EN.

More farms show increases than decreases in soil erosion under the SEN climate. For wheat, the most significant increases were on farms U6, 10, 16 and 44 with increases ranging from 10 to 51 mm. Soil erosion decreased on only eight wheat farms with six of the decreases (U19-20, 41-43) clustered in the Central and Southern Great Plains. Under SEN, erosion on corn farms increased throughout the Southern Great Plains and eastern half of the U.S.. The largest increases were recorded on farms U39, U44 and U50, where soil erosion increased by 81, 150 and 63 mm, respectively. Locations for the farms with decreasing erosion under SEN vary: three farms in the Midwest (U13, 20, 30), one farm in the Ohio Valley (U40) and two in the Mid-Atlantic (U60, 63). Of those 6, only farm U40 shows a substantial decrease in erosion (24 mm).

A total of 6 wheat farms experienced increased erosion and 7 experienced decreased erosion under the EV climate. Except for farm U44, where erosion increased by 83 mm, changes under EV ranged from a -5 mm to a +3 mm. Increases in soil erosion were frequent for corn farms under the EV condition with 25 increases and 10 decreases. Corn farms in all regions of the country report increased erosion with the largest on the Southern Great Plains farm U44 (112 mm) and the Gulf Coast farm U51 (32 mm). Erosion response to the EV climate was variable for a region extending from the Central Great Plains into the Northern Midwest. Corn farms U13, 15, 18, 20-21and 30 registered decreases in erosion under EV climate while farms U14, 17, 19, 22 and 24 show increased erosion.

Table III.11 a. Simulated ET, PET, runoff and soil erosion for United States dryland corn farms under Neutral conditions and deviations from Neutral due to EN, SEN and EV.

Farm	ET				PET				Runoff				Eroded topsoil depth			
		Deviation from N				Deviation from N				Deviation from N				Deviation from N		
	N	EN	SEN	EV	N	EN	SEN	EV	N	EN	SEN	EV	N	EN	SEN	EV
	---- mm ----				---- mm ----				---- mm ----				---- mm ----			
U12	452	-34	-15	-20	2064	3	-13	28	1	-1	0	2	176	6	11	7
U13	496	-5	63	-38	1789	-25	71	50	3	-1	-2	-1	1	0	-1	-1
U14	568	-62	-10	-61	1846	38	115	42	2	0	-1	-1	69	7	0	6
U15	719	-51	29	-46	1542	30	34	-6	6	1	5	-2	2	0	1	-1
U17	658	-101	23	-92	1487	65	9	-43	1	0	2	1	21	4	1	2
U18	632	-22	8	-20	1306	47	23	-31	15	-9	-4	-7	6	-2	0	-3
U19	768	-48	36	11	1954	-4	-44	-6	2	-1	1	2	119	15	6	13
U20	763	-1	39	1	1381	2	10	-13	16	-2	0	-1	6	0	-1	-1
U21	812	-39	31	-38	1454	13	28	20	14	10	-1	-5	6	3	0	-1
U22	735	-29	-39	-5	1435	-17	-19	-6	6	2	4	3	3	0	2	2
U23	794	-4	44	16	1389	18	-2	-8	7	2	10	2	2	0	1	0
U24	473	1	26	19	973	9	109	79	3	1	5	1	30	8	14	10
U25	614	-22	17	-7	1177	49	23	-18	3	2	0	0	2	0	1	-1
U26	612	2	0	-3	1136	-8	11	-1	1	-1	3	1	0	0	1	0
U27	152	8	13	1	946	23	31	0	1	0	1	1	0	0	0	0
U28	630	-34	11	-23	1237	-42	31	-35	3	-2	-2	-1	0	0	0	0
U29	578	-8	8	21	1150	62	74	62	2	-1	0	-1	0	0	0	0
U30	680	-38	14	-33	1288	28	69	-2	5	-4	-4	-4	1	-1	-1	-1
U31	750	-18	32	3	1334	-14	71	-26	11	0	0	-3	3	1	0	0
U32	685	-46	7	5	1292	-25	54	-6	1	0	2	0	0	0	0	0
U33	742	-83	-36	15	1432	-23	20	45	7	-3	0	-2	10	3	3	2
U34	772	-67	-13	-21	1414	-32	-3	-18	8	-1	7	-2	8	-1	3	2
U35	774	-26	-2	-9	1391	28	23	-8	6	-3	11	-1	1	0	1	0
U36	837	-64	-7	-15	1429	-28	36	-21	4	3	1	2	0	0	0	0
U37	766	-25	4	23	1266	5	13	6	15	-9	16	-5	4	-3	8	-2
U38	743	-24	15	31	1259	-6	3	28	11	-8	18	0	8	-6	12	-1
U39	798	-39	17	42	1241	27	52	45	8	1	9	3	88	32	81	49
U40	841	-49	18	38	1292	37	40	54	19	-11	-4	-4	70	-39	-24	-17
U41	546	-13	-7	-17	2228	2	47	1	2	0	-1	1	266	15	3	6
U42	599	-47	-113	-94	2249	-12	-37	-12	2	-1	-2	-1	213	7	-3	19
U43	675	-30	26	3	2007	-3	-5	13	15	-4	11	2	254	9	5	18

Table III.11 a (continued) Simulated ET, PET, runoff and soil erosion for United States dryland corn farms under Neutral conditions and deviations from Neutral due to EN, SEN and EV

Farm	ET				PET				Runoff				Eroded topsoil depth			
		Deviation from N				Deviation from N				Deviation from N				Deviation from N		
	N	EN	SEN	EV	N	EN	SEN	EV	N	EN	SEN	EV	N	EN	SEN	EV
	mm				mm				mm				mm			
U44	823	-2	75	27	1928	-6	-46	-4	85	-11	48	32	276	-3	150	112
U45	796	-22	69	38	1618	0	39	7	10	0	10	3	7	-1	7	1
U46	718	-49	103	37	1548	41	-26	34	10	0	30	11	11	2	16	6
U47	646	51	85	16	2047	-25	-25	-16	4	0	8	0	61	2	4	3
U48	819	0	122	16	1903	-45	-86	11	11	-1	12	3	44	4	2	5
U49	856	9	60	-7	1725	-41	-20	-26	153	22	134	-4	24	4	22	5
U50	925	7	6	-12	1596	-38	-24	1	124	10	112	17	70	13	63	14
U51	844	-52	17	19	1502	14	6	-2	23	-6	7	14	231	-74	32	32
U52	819	-27	30	40	1483	31	53	49	7	1	10	3	3	0	1	0
U53	759	-5	24	4	1468	-11	-18	14	28	-5	-8	-2	1	0	0	0
U54	784	-20	20	49	1642	13	51	48	5	1	3	7	1	0	0	1
U55	852	-14	2	-22	1576	-18	23	1	21	9	0	-1	4	2	1	1
U56	879	18	52	6	2005	14	33	63	5	2	0	4	0	0	0	0
U57	712	4	4	16	1239	11	14	31	2	4	2	0	0	2	1	0
U58	673	-3	-5	24	1285	21	17	-32	1	-1	0	0	1	0	0	0
U59	625	-4	5	12	1068	30	21	12	2	-1	1	0	1	0	0	0
U60	625	-29	-43	0	1229	0	-82	11	2	1	-1	0	1	0	-1	0
U61	646	-57	-45	11	1217	-22	-19	25	3	3	2	3	1	1	0	1
U62	744	-36	27	15	1264	18	46	13	4	-3	4	0	1	-1	0	0
U63	837	-51	2	-2	1430	7	28	14	6	-1	-3	3	9	1	-4	4
U64	811	-22	-26	33	1413	35	9	52	7	-1	-3	1	2	0	0	0
U65	790	-40	-6	38	1546	-15	-30	17	7	2	2	2	3	2	2	1
U66	845	-24	-4	13	1504	11	4	26	8	2	2	4	1	0	0	1

Table III.11 b. Simulated ET, PET, runoff and soil erosion for United States winter wheat farms under Neutral conditions and deviations from Neutral due to EN, SEN and EV.

Farm	ET				PET				Runoff				Eroded topsoil depth			
		Deviation from N				Deviation from N				Deviation from N				Deviation from N		
	N	EN	SEN	EV	N	EN	SEN	EV	N	EN	SEN	EV	N	EN	SEN	EV
	mm				mm				mm				mm			
U1	235	-59	-7	-16	1744	-99	-35	-25	0	0	0	0	0	0	0	0
U2	418	-93	-35	14	1426	41	-33	36	0	0	0	0	0	0	0	0
U3	384	-58	-70	26	1368	-29	78	26	0	0	0	0	0	0	0	0
U4	314	-77	36	-3	1529	-35	52	16	0	0	0	0	0	0	0	0
U5	337	-61	21	-8	1655	16	55	-4	1	0	2	0	0	0	0	0
U6	259	-40	63	-8	1452	10	63	-3	17	-10	53	-11	9	-5	23	-4
U7	309	-34	-38	28	1418	21	-2	27	1	0	0	0	13	2	4	-1
U8	404	-21	-30	11	1775	-43	23	-28	0	0	0	0	10	-6	-6	-5
U9	370	-48	-48	16	1405	38	0	29	0	0	0	0	5	0	2	1
U10	448	-28	-47	-29	1381	35	88	51	0	0	0	0	26	1	12	3
U11	295	-18	-1	-26	1782	-20	4	49	0	0	1	0	2	0	0	0
U12	451	-34	-15	-20	2066	5	-15	31	1	0	-1	2	50	2	5	0
U13	494	-17	67	-36	1788	-22	60	54	5	-1	-2	-2	0	0	0	0
U14	541	-46	11	-45	1851	34	102	35	4	-1	-3	-2	24	-2	5	-2
U15	633	-30	5	-33	1546	31	30	-5	7	3	8	-1	0	0	1	0
U16	513	32	78	-63	1730	-37	-46	35	1	-1	2	-1	24	-1	10	3
U17	613	-60	-42	-74	1486	70	11	-39	4	-2	0	-1	6	-1	-1	-1
U18	562	-57	-20	-32	1313	47	22	-31	13	-6	0	-4	0	0	0	0
U19	682	-34	27	4	1956	-7	-48	-9	4	0	-1	1	46	3	-3	1
U20	677	1	71	32	1389	1	12	-8	19	0	3	-3	2	0	-1	-1
U21	680	-55	16	-12	1458	16	21	24	18	11	1	-4	2	0	0	0
U22	629	-35	4	4	1441	-18	-25	-7	10	-1	2	-1	0	0	0	0
U23	668	-10	50	34	1391	17	-5	-2	8	4	14	5	1	0	0	0
U30	589	-46	7	-20	1296	27	65	-3	4	-2	-4	-3	0	0	0	0
U31	619	-30	28	6	1336	-13	65	-24	12	2	0	-1	1	0	1	0
U35	639	-30	10	-1	1396	29	17	-9	6	-2	18	0	0	0	0	0
U41	544	-12	-5	-20	2233	3	44	4	2	-1	-2	1	54	-1	-4	0
U42	597	-44	-113	-95	2251	-14	-42	-10	2	-1	-1	1	43	0	-4	2
U43	716	-13	35	-11	2009	-4	-10	15	14	-3	8	2	55	-2	-2	0
U44	811	-21	80	39	1936	-7	-45	1	87	0	58	36	138	1	51	83
U45	817	-5	56	48	1651	0	45	7	12	0	12	3	2	-1	0	-1

D.3 Mexico

Evapotranspiration

Actual (as opposed to potential) annual ET under dryland corn ranged from 341 mm on farm M7 in the Arid/Semiarid region to 1012 mm on farm M21 in the Humid Tropic (Table III.12 a.). The range for dryland bean was narrower, from a minimum of 348 mm (M8 in the Arid/Semiarid region) to a maximum of 819 mm (M21) (Table III.12 c.). ET on dryland winter wheat ranged from 335 mm (M8) to 673 mm y^{-1} (M14 in the Arid/Semiarid region) (Table III.12 e.).

Simulated ET on irrigated farms was, of course, greater than on dryland with corn and wheat requiring well over 1000 mm on certain farms in the Arid/Semiarid and Temperate regions. Irrigated beans required somewhat less water with a notable low of 257 mm on farm M3 in the Arid/Semiarid region. The distribution of changes in ET on the dryland farms (Table III.12.a) varies by ENSO state and by crop. EN, SEN, and EV reduce ET in 9 or 10 of 16 cases for dryland corn but the farms so affected differ somewhat. SEN and EV increase dryland bean ET (Table III.12 c.) in 7 or 8 of the 13 farms modeled. Dryland wheat ET (Table III.12 e.) is increased from Neutral in almost all cases by the three ENSO states.

Hydrology and Soil Erosion

Runoff and soil erosion are determined by rainfall amount and intensity, soil type, and topography, as well as by crop and management practices. Because of the steep topography on which rainfed crops are commonly grown in Mexico, dryland agricultural systems show significantly more soil erosion than do irrigated production systems (Tables III.12 a through III.12 f). Irrigated crops are grown on land with slopes no greater than 2%.

Under dryland corn culture both runoff and soil erosion were sensitive to ENSO state and ecological characteristics (Table III.12 a.). There was an increase in the median value of runoff deviations of ENSO states with respect to the Neutral state except in two cases. The first was in the Humid Tropic (M19, M21, and M22) where the median runoff deviation under SEN decreased by 12 mm with respect to the Neutral state. The second exception occurred in the Dry Tropic (M5, M11, M16, M23) where the median runoff deviation under EV decreased by 5 mm with respect to Neutral years. In general, soil erosion on dryland-corn land increased relative to Neutral years under each of the ENSO states. One notable exception is farm M19 where erosion decreased during EN or SEN years but increased during EV years.

Surface runoff on irrigated corn mostly increased with respect to Neutral under all ENSO years (Table III.12 b.). Simulated runoff was nearly doubled during SEN years on farm M10 in the Temperate region of Mexico. Soil erosion on irrigated corn was either unchanged or increased slightly during ENSO years. The largest and most consistent increases in soil erosion across all irrigated farms occurred during SEN years and ranged from 0 to 6 Mg ha^{-1}.

Under dryland bean management runoff and erosion were mostly increased under EN, SEN and EV (Table III.12 c.). For example, a significant increase of 298 mm with respect to the Neutral was simulated for farm M5 in the Dry Tropic during SEN years. There were, however, farms where runoff under EN, SEN and EV decreased relative to Neutral (e.g., farm M11 in the Dry Tropics). Erosion accompanied the direction but not the relative magnitude of runoff changes. On irrigated bean farms, runoff mostly increased under EN and SEN while it mostly decreased during EV years (Table III 12 d.).

Under dryland wheat management, runoff increased relative to Neutral during SEN and EV years. The response was mixed during EN years (Table III.12 e.). Erosion rates and changes were small under dryland wheat. Simulation results using the SEN weather pattern caused runoff to increase across all irrigated wheat farms (Table III.12 f.). Erosion rates on wheat land under irrigation were small in all cases.

Table III.12 a. Simulated ET, PET, runoff and soil erosion for Mexican dryland corn farms under Neutral conditions and deviations from Neutral due to EN, SEN and EV.

Farm	ET				PET				Runoff				Average soil erosion			
		Deviation from N				Deviation from N				Deviation from N				Deviation from N		
	N	EN	SEN	EV	N	EN	SEN	EV	N	EN	SEN	EV	N	EN	SEN	EV
	mm				mm				mm				Mg ha^{-1}			
M4	547	-35	-25	-45	2828	8	-14	-33	58	100	48	14	1	3	1	0
M5	705	138	57	6	2797	-15	-127	50	332	168	271	-5	29	16	28	0
M7	341	56	-20	17	2736	-63	53	-16	20	25	66	24	1	2	4	1
M9	736	-7	-29	-25	2852	-106	6	-88	102	-4	-30	1	20	0	-7	-2
M10	703	-5	-6	-23	2501	69	29	117	32	9	180	-1	1	0	6	0
M11	767	-70	-117	-79	3086	31	229	112	120	-35	-30	-60	15	4	-5	-8
M12	575	42	2	5	2633	-169	14	-4	7	9	30	4	0	0	1	0
M14	772	-42	20	-65	2502	-189	-176	-84	41	-10	53	4	1	0	2	0
M15	704	20	-109	42	3103	76	281	-83	85	110	114	93	9	3	28	16
M16	535	175	72	54	2340	-53	-34	39	8	30	21	6	0	1	1	0
M17	610	-9	-24	-2	2596	-59	10	-36	2	3	1	4	0	0	0	0
M18	564	-105	74	70	2815	30	-52	1	4	-2	15	3	0	0	0	0
M19	735	-45	-102	-2	2397	9	62	2	252	-75	-61	22	38	-8	-7	21
M20	663	-18	-51	-40	2526	68	120	75	43	18	54	-12	1	1	1	0
M21	1012	-13	-36	-18	2325	-40	70	69	303	5	-12	7	8	0	0	0
M22	716	-21	21	-6	2316	-63	144	-97	22	6	21	-2	0	0	0	0
M23	708	74	126	-20	2944	-173	-146	-224	18	52	45	20	1	3	1	1

Table III.12 b. Simulated ET, PET, runoff and soil erosion for Mexican irrigated corn farms under Neutral conditions and deviations from Neutral due to EN, SEN and EV.

Farm	ET				PET				Runoff				Average soil erosion			
		Deviation from N				Deviation from N				Deviation from N				Deviation from N		
	N	EN	SEN	EV	N	EN	SEN	EV	N	EN	SEN	EV	N	EN	SEN	EV
	mm				mm				mm				Mg ha^{-1}			
M2	804	22	75	49	2589	51	-7	121	72	4	33	11	1	0	1	0
M3	1342	155	-33	133	3338	24	-155	22	79	22	17	7	0	0	0	0
M6	610	8	-18	20	2649	192	-78	35	39	13	79	1	0	0	3	0
M7	624	34	-45	-39	2712	-63	-129	-188	54	16	64	23	0	0	2	0
M10	1131	50	21	52	2489	69	29	115	106	16	194	8	1	0	5	0
M12	860	26	10	-19	2612	-169	14	-5	55	9	29	-2	0	0	1	0
M14	872	-14	-64	-66	2343	-169	-163	-77	193	-27	96	-3	3	0	6	0
M15	1295	-126	-100	68	3082	84	260	67	230	88	129	73	1	1	3	1
M16	925	-3	104	72	2330	-52	-35	40	75	25	34	15	0	1	1	0
M18	1030	-20	-27	30	2806	26	-54	2	73	3	13	1	0	0	1	0
M20	748	-6	-12	19	2383	61	108	70	93	23	75	-16	2	1	3	0

Table III.12 c. Simulated ET, PET, runoff and soil erosion for Mexican dryland bean farms under Neutral conditions and deviations from Neutral due to EN, SEN and EV.

Farm	ET				PET				Runoff				Average soil erosion			
		Deviation from N				Deviation from N				Deviation from N				Deviation from N		
	N	EN	SEN	EV	N	EN	SEN	EV	N	EN	SEN	EV	N	EN	SEN	EV
	mm				mm				mm				Mg ha^{-1}			
M5	643	121	23	24	2774	-15	-126	50	360	181	298	-7	33	17	31	-1
M6	461	17	25	16	2650	-4	-78	35	6	7	68	5	0	0	3	0
M7	374	71	9	13	2725	-64	52	-12	14	22	57	28	1	2	3	1
M8	348	104	15	29	2685	-162	-28	-167	2	3	11	4	0	0	0	0
M11	524	65	-68	5	3237	-38	107	56	126	-55	-80	-94	30	-17	-20	-25
M12	556	48	2	-2	2628	-168	15	-3	7	9	27	5	0	0	1	0
M16	470	68	44	20	2370	-51	-31	44	12	35	22	8	0	0	1	0
M17	581	-33	-39	-11	2624	-59	10	-37	4	5	1	4	0	0	0	0
M18	557	-99	59	65	2832	23	-56	2	6	-2	15	3	0	0	0	0
M19	648	-33	-86	14	2396	8	61	2	263	-84	-74	11	45	-9	-5	23
M20	592	-21	-68	-11	2550	69	121	76	59	20	64	-16	2	1	2	0
M21	819	-12	-51	-26	2324	-40	69	69	332	5	5	4	10	0	0	0
M22	651	-43	53	-8	2203	75	128	-89	97	10	49	-10	2	0	1	0

Table III.12 d. Simulated ET, PET, runoff and soil erosion for Mexican irrigated bean farms under Neutral conditions and deviations from Neutral due to EN, SEN and EV.

Farm	ET				PET				Runoff				Average soil erosion			
		Deviation from N				Deviation from N				Deviation from N				Deviation from N		
	N	EN	SEN	EV	N	EN	SEN	EV	N	EN	SEN	EV	N	EN	SEN	EV
	mm				mm				mm				Mg ha^{-1}			
M2	753	8	13	37	2755	59	-3	123	51	4	11	7	0	0	0	0
M3	257	219	374	-37	3105	34	-141	31	56	54	89	-5	1	0	0	1
M7	641	30	-28	-5	2712	-63	53	-14	38	19	65	26	0	0	1	0
M8	698	-8	-14	-69	2656	-161	-28	-167	43	-12	11	-8	0	0	0	0
M12	634	21	2	-14	2609	-166	17	-2	32	4	28	-3	0	0	1	0
M18	815	-12	-12	29	2816	24	-55	3	49	5	11	-1	0	0	1	0
M20	732	22	-29	5	2548	68	120	76	64	25	70	-12	1	1	2	0

Table III.12 e. Simulated ET, PET, runoff and soil erosion for Mexican dryland summer wheat farms under Neutral conditions and deviations from Neutral due to EN, SEN and EV.

Farm	ET				PET				Runoff				Average soil erosion			
		Deviation from N				Deviation from N				Deviation from N				Deviation from N		
	N	EN	SEN	EV	N	EN	SEN	EV	N	EN	SEN	EV	N	EN	SEN	EV
	mm				mm				mm				$Mg\ ha^{-1}$			
M7	357	50	-20	15	2549	118	53	-11	19	27	66	27	0	2	2	0
M8	335	86	1	23	2694	-163	-28	-171	2	3	12	4	0	0	0	0
M12	492	49	35	21	2637	-170	14	-7	10	11	26	5	0	0	0	0
M14	673	-4	43	-58	2473	-189	-176	-83	41	-6	44	5	1	0	1	0
M16	526	133	85	29	2350	-65	-30	47	8	28	16	7	0	0	0	0
M18	554	-100	67	68	2828	25	-54	2	9	-3	22	6	0	0	1	0

Table III.12 f. Simulated ET, PET, runoff and soil erosion for Mexican irrigated wheat farms under Neutral conditions and deviations from Neutral due to EN, SEN and EV.

Farm	ET				PET				Runoff				Average soil erosion			
		Deviation from N				Deviation from N				Deviation from N				Deviation from N		
	N	EN	SEN	EV	N	EN	SEN	EV	N	EN	SEN	EV	N	EN	SEN	EV
	mm				mm				mm				$Mg\ ha^{-1}$			
M1	600	-20	29	-56	3123	-61	-134	-26	61	9	25	-5	0	0	1	0
M2	692	3	14	-4	2583	54	-11	107	44	2	14	1	0	0	0	0
M3	860	44	115	-30	3348	18	-159	15	35	11	22	-1	0	0	0	0
M7	663	61	29	202	2542	-57	47	-14	41	24	73	41	0	0	0	0
M8	547	57	-4	18	2683	-162	-28	-169	28	0	15	4	0	0	0	0
M10	1118	10	-7	-7	2490	68	30	106	85	10	167	-1	0	0	0	0
M12	950	6	62	127	2609	-167	13	-22	62	3	30	17	0	0	0	0
M13	780	-45	-155	-37	3171	38	181	115	66	-13	31	-12	0	0	2	0
M14	1024	-9	42	13	2474	-189	-175	-83	66	-6	49	6	0	0	0	0
M16	727	72	22	12	2340	-51	-30	44	47	35	20	8	0	0	0	0

E Impact of Altered ENSO Frequencies on Crop Yield

E.1 Hypothesis

We return in this section to take one more look at ENSO effects on crop yield. In previous sections we presented and discussed results of the impact of ENSO events on crop yields and other variables for 142 representative farms across Canada, the U.S., and Mexico. Those results could be considered to represent "pure effects" of ENSO events in that the final impact of an ENSO condition was obtained by *stochastically* repeating the same scenario (e.g., El Niño) for 30 years. This modeling approach avoids dealing with the "interactive effects" of ENSO events as they would occur in a historic sequence. For example, and following the Japan Meteorological Administration methodology, of the 48 years elapsed from 1947 to 1994, 23 (48%) were classified as Neutral, 9 (19%) as El Niño, 3 (6%) as Strong El Niño, and 13 (27%) as El Viejo. Uncertainty exists, however, about the order in which these ENSO events distribute within a given historic series. For example, the return period of El Niño in the historic 1947-1994 series has varied between one and eleven years. It would be possible, then, that within a given time series the frequency of occurrence of these events might change substantially from another, even overlapping, time series. These uncertainties led us to hypothesize that a change in the kind and magnitude of an historic ENSO sequence may affect the total crop production capacity and the production variability of an agricultural region. The objective of the research reported in this section was, therefore, to examine the impact of altered ENSO frequencies on crop yield and yield variability.

E.2 Materials and Methods

For this study we used ENSO climatic datasets constructed from daily weather records with the Weather Parameter Generating Utility (WXPARM). This program reads daily extreme temperatures (maximum and minimum) and total precipitation data for a period and calculates monthly daily averages as well as the standard deviations for these variables. Four ENSO scenarios were constructed for each weather station according to criteria described in Section II: Neutral (N), El Niño (EN), Strong El Niño (SEN), and EL Viejo (EV). Seven representative farms from 53° to 16° N (two in Canada, three in the U.S., and two in Mexico) were selected to generate the synthetic scenarios of altered ENSO frequencies. A 48-daily weather series was created for each representative farm and each ENSO scenario (e.g., an EPIC file containing 48 years of daily N weather).

For each of the seven representative farms, a daily *synthetic* weather file was constructed from the daily weather files using the Weather Generator (WXGEN) to reproduce the historical series of ENSO years from 1947 to 1994 (Table III.13). Each ENSO year started on 1 October and ended on 30 September. Based on a total of 48 years we then increase the occurrence of each type of the ENSO event by 33 and 66%. Thus, in the case of the SEN 33% scenario we needed to increase the occurrence of a SEN event by one year (from 3 to 4). An N year following an SEN year (1957-1958) was selected as the first N year to replace; that was the only year replaced in the SEN 33% alternate scenario. Five other alternative ENSO scenarios were thus created: EV 33%, EV 66%, EN 33%, EN 66%, and SEN 66% (Table III.13).

Seven simulation runs were made for each of the seven representative farms, one for the historical sequence or "*baseline*" and the six alternative ENSO frequencies previously described. Yields of continuous spring wheat were simulated for the two Canadian farms and continuous corn for the five Mexican and U.S. farms. Yield results were summarized by calculating means and standard deviations of the four ENSO conditions (N, EN, SEN, and EV) for each of the seven 48-y runs (*baseline* plus six others with altered ENSO sequences).

E.3 Results and Discussion

In the baseline runs of the two Canadian farms yields were highest in EV years (Table III.14). In the C26 farm other yields in decreasing order were N, EN, and SEN. Greater yield variation (~0.4 Mg ha^{-1}) was simulated at the C8 farm among the other three ENSO conditions (N, EN and SEN). No the ENSO condition consistently produced the highest yields among the five corn farms in the U.S. and Mexico. EN years induced the lowest corn yields in three U.S. farms, but the results in the other two Mexican farms were not consistent. Corn often yielded least during EN (three times). The standard deviation of crop yields in baseline runs was highest during EN years in five out of seven cases.

The most pronounced effect of increasing the frequency of EN years was observed on farm M22 where yields increased by as much as 14% (EN 66%) from the EN baseline yield of 4.02 Mg ha^{-1}. Corn yields in the U19 farm decreased by 9%. This yield decrease, however, was accompanied by a 4% yield increase during N years. Increasing the frequency of occurrence of EN years by 33 and 66% did not affect average crop yields during SEN years.

Yields decreased in the SEN 33 and 66% scenarios. Yields decreased on farms C8, M16, and M22 by as much as 22% (SEN 66%). Increasing the occurrence of SEN years from 33 to 66% did not change the relative yield change.

Increasing the frequency of occurrence of EV years by 33 and 66% generally caused small yield decreases, but the 66% scenario did not necessarily enhance the effect observed in the 33% scenario. The largest yield increase simulated for EV years was 8% when the frequency had been increased by either 33 or 66% (M16 farm). Modest yield increases of 4% occurred in the C8 farm when the frequency of EV years increased by 66%. Increasing the frequency of EV years had little effect on the average yields of EN and SEN years.

Table III.15 summarizes the aggregated yields under the different scenarios (baseline plus the three ENSO states). The differences are small but allow for a comparison between the baseline and ENSO events. The total production difference over a 48-year span can be calculated by finding the yield difference and multiplying it by 48. Increasing the frequency of EN can either increase of decrease overall production across the seven test farms. In these simulations, an increase of EV frequency appears to induce yield increases consistently across the seven farms.

In addition, we conducted a frequency analysis by calculating the number of years in which yields were either greater than or lower than a given threshold level. We counted as one a year in which the crop yield for an alternate ENSO scenario was at least 5% greater than or at most 95% lower than the corresponding yield of the baseline run. Table III.16 presents the results for the seven farms and Fig. III.24 graphically depicts the results for three of them. For example, replacing three N years by three EN years (EN 33%) had different impacts on the seven farms analyzed. In three of the farms (C8, U19, and M16) adding three EN years affected yields in more than three years. In the rest, the number of years in which yields were affected was three or less. The occurrence of more EN years had both positive and negative effects. While on most farms the impact was negative, the exception was the M16 farm where the inclusion of three EN years induced five years with a positive yield impact and only one with a negative yield impact. The U55 farm in the U.S. was the farm least responsive to changes in the frequency of ENSO events.

We conclude that changes in temporal patterns of ENSO events would affect crop yield and yield variability. The change in response from farm to farm to these temporal patterns suggests the presence of spatial patterns that need to be elucidated. Studies that combine both dimensions would augment the value of ENSO forecasts.

Table III.13. Historical sequence of ENSO[†] years (1947 - 1994) and years in which a Neutral condition is replaced by an ENSO event resulting in frequency increases of 33 and 66%.

Year	Event	Historical ENSO years				EN		SEN		EV	
		N	EN	SEN	EV	+33%	+66%	+33%	+66%	+33%	+66%
1947	EV				1947						
1948	EV				1948						
1949	EV				1949						
1950	N	1950									1950
1951	EN		1951								
1952	N	1952				1952	1952			1952	1952
1953	N	1953									
1954	EV				1954						
1955	EV				1955						
1956	EV				1956						
1957	SEN			1957							
1958	N	1958				1958	1958	1958	1958	1958	1958
1959	N	1959									
1960	N	1960									
1961	N	1961									
1962	N	1962									
1963	EN		1963								
1964	EV				1964						
1965	EN		1965								
1966	N	1966					1966			1966	1966
1967	EV				1967						
1968	N	1968									1968
1969	EN		1969								
1970	EV				1970						
1971	EV				1971						
1972	SEN			1972							
1973	EV				1973						
1974	N	1974									
1975	EV				1975						
1976	EN		1976								
1977	N	1977									1977
1978	N	1978									
1979	N	1979									
1980	N	1980									
1981	N	1981									
1982	SEN			1982							
1983	N	1983				1983	1983		1983	1983	1983
1984	N	1984									
1985	N	1985									
1986	EN		1986								
1987	EN		1987								
1988	EV				1988						
1989	N	1989									1989
1990	N	1990									
1991	EN		1991								
1992	N	1992					1992				1992
1993	N	1993									
1994	EN		1994								

[†]ENSO years: N: Neutral; EV: El Viejo; EN: El Niño; and SEN: Strong El Niño.

Table III.14. Mean (Avg., Mg ha^{-1}) and standard deviation (σ, Mg ha^{-1}) of dryland spring wheat (*Triticum aestivum* L.) yields in Canada and dryland corn (*Zea mays* L.) yields in the U.S. and Mexico simulated with EPIC using synthetic weather reproducing the historical *baseline* from 1948 to 1994 (23 y of Neutral , 9 y of El Niño, 3 y of Strong El Niño, and 12 y of El Viejo) and increasing the frequency of ENSO events by 33 and 66%.

Variable	ENSO	Spring Wheat				Dryland Corn									
		C26		C8		U30		U19		U55		M16		M22	
	State	Avg.	σ	Avg.	σ	Avg.	σ	Avg.	σ	Avg.	σ	Avg.	σ	Avg.	σ
Base	N	2.67	0.25	2.11	0.71	7.48	0.34	5.97	1.54	5.98	0.42	2.66	1.18	5.73	1.88
	EN	2.66	0.31	1.87	0.95	6.78	0.77	4.55	2.42	5.58	0.58	3.95	0.38	4.02	2.08
	SEN	2.84	0.26	1.72	0.70	6.97	0.33	5.66	0.43	6.23	0.22	2.97	1.24	2.90	2.25
	EV	2.93	0.26	2.17	0.81	7.36	0.39	5.73	1.87	6.12	0.39	2.48	1.28	5.71	1.49
EV 33	N	2.61	0.23	2.17	0.68	7.44	0.28	6.17	0.93	5.96	0.45	2.54	1.25	5.70	1.93
	EN	2.66	0.30	1.85	0.93	6.78	0.77	4.58	2.43	5.59	0.58	3.94	0.38	4.02	2.08
	SEN	2.84	0.27	1.71	0.69	6.97	0.33	5.65	0.44	6.23	0.22	2.97	1.24	2.90	2.26
	EV	2.95	0.22	2.18	0.82	7.31	0.48	5.65	2.17	6.13	0.35	2.68	1.31	5.93	1.50
EV 66	N	2.67	0.19	2.21	0.69	7.53	0.24	6.25	0.84	6.04	0.42	2.63	1.18	5.96	1.62
	EN	2.63	0.28	1.80	0.90	6.78	0.77	4.58	2.44	5.58	0.58	3.94	0.37	4.07	2.12
	SEN	2.83	0.25	1.71	0.69	6.97	0.33	5.65	0.43	6.22	0.22	2.97	1.25	2.90	2.26
	EV	2.90	0.23	2.24	0.79	7.27	0.46	5.86	1.99	6.05	0.39	2.68	1.30	5.85	1.67
EN 33	N	2.65	0.26	2.19	0.70	7.44	0.28	6.19	0.91	5.96	0.43	2.61	1.27	5.81	1.94
	EN	2.70	0.28	1.89	0.95	6.87	0.70	4.13	2.69	5.52	0.61	3.99	0.39	4.29	1.90
	SEN	2.84	0.26	1.72	0.70	6.97	0.33	5.65	0.43	6.23	0.22	2.97	1.25	2.90	2.26
	EV	2.93	0.26	2.15	0.81	7.36	0.39	5.65	1.89	6.12	0.39	2.50	1.29	5.71	1.48
EN 66	N	2.64	0.23	2.14	0.72	7.44	0.29	6.13	0.93	5.95	0.45	2.63	1.27	5.76	1.98
	EN	2.72	0.26	1.93	0.91	6.96	0.68	4.43	2.56	5.59	0.61	4.03	0.37	4.58	1.95
	SEN	2.84	0.26	1.72	0.70	6.97	0.33	5.65	0.44	6.23	0.22	2.97	1.25	2.90	2.26
	EV	2.95	0.23	2.14	0.83	7.36	0.39	5.71	1.87	6.12	0.39	2.53	1.31	5.71	1.48
SEN 33	N	2.67	0.25	2.16	0.72	7.47	0.34	5.93	1.57	5.99	0.43	2.74	1.20	5.84	1.85
	EN	2.66	0.31	1.88	0.98	6.78	0.77	4.57	2.43	5.59	0.58	3.95	0.38	4.03	2.08
	SEN	2.92	0.27	1.40	0.86	6.90	0.30	5.41	0.61	6.14	0.25	2.48	1.43	2.47	2.03
	EV	2.92	0.26	2.17	0.81	7.36	0.39	5.72	1.87	6.12	0.39	2.49	1.29	5.71	1.49
SEN 66	N	2.67	0.26	2.19	0.72	7.43	0.27	5.89	1.60	5.97	0.43	2.73	1.24	5.81	1.89
	EN	2.67	0.29	1.88	0.97	6.78	0.77	4.59	2.42	5.59	0.58	3.95	0.38	4.03	2.08
	SEN	2.89	0.24	1.49	0.77	6.85	0.29	5.81	1.05	6.16	0.22	2.32	1.29	2.48	1.76
	EV	2.92	0.26	2.17	0.81	7.36	0.39	5.73	1.87	6.12	0.39	2.48	1.28	5.71	1.49

Table III.15. Forty-seven year average wheat (*Triticum aestivum* L.) and corn (*Zea mays* L.) yields simulated with EPIC using synthetic weather reproducing the historical baseline from 1948 to 1994 (23 y of Neutral, 9 y of El Niño, 3 y of Strong El Niño, and 12 y of El Viejo) and increasing the frequency of ENSO events by 33 and 66%.

		Lat.	Long.			EN		SEN		EV	
Country	Farm	N	W	Crop	Baseline	33%	66%	33%	66%	33%	66%
					Mg ha^{-1}						
Canada	C8	50.0	112.8	Wheat	2.05	2.07	2.05	2.05	2.05	2.08	2.11
	C26	53.1	104.6	Wheat	2.75	2.75	2.76	2.75	2.76	2.75	2.77
USA	U30	42.7	91.9	Corn	7.29	7.24	7.25	7.26	7.23	7.24	7.24
	U19	37.6	97.4	Corn	5.62	5.49	5.49	5.57	5.59	5.66	5.72
	U55	29.6	83.1	Corn	5.93	5.91	5.91	5.97	5.96	5.97	5.96
Mexico	M16	25.6	98.1	Corn	2.88	2.96	3.04	2.88	2.85	2.88	2.93
	M22	16.4	93.4	Corn	5.22	5.21	5.21	5.17	5.09	5.28	5.35

Table III.16. Number of years of the 47-y simulation runs in which crop yields were either lower or greater than the baseline yield by a threshold level of at least 5% (represented in the column headings as *95% or <* and *5% or >*).

		Canada				United States						Mexico			
		C8		C26		U30		U55		U19		M22		M16	
Event	Year†	95% or <	5% or >	95% or <	5% or >	95% or <	5% or >	95% or <	5% or >	95% or <	5% or >	95% or <	5% or >	95% or <	5% or >
EN33	3	4	2	0	0	3	0	1	0	5	1	1	2	1	5
EN66	6	6	2	0	2	3	0	2	0	4	1	1	3	1	7
SEN33	1	1	0	0	1	1	0	0	0	2	0	1	1	1	2
SEN66	2	1	1	0	2	2	0	0	0	2	1	2	1	2	2
EV33	4	4	4	1	3	2	0	0	0	1	3	1	3	4	3
EV66	9	7	8	1	4	3	1	0	1	3	9	3	8	5	6

† *Year* refers to the number of N years of the 47-y historical frequency replaced by the corresponding ENSO year. (e.g. EN33 = 3 means that 3 N years of the 47-y series were replaced by EN years [see Table III.1 for further details]).

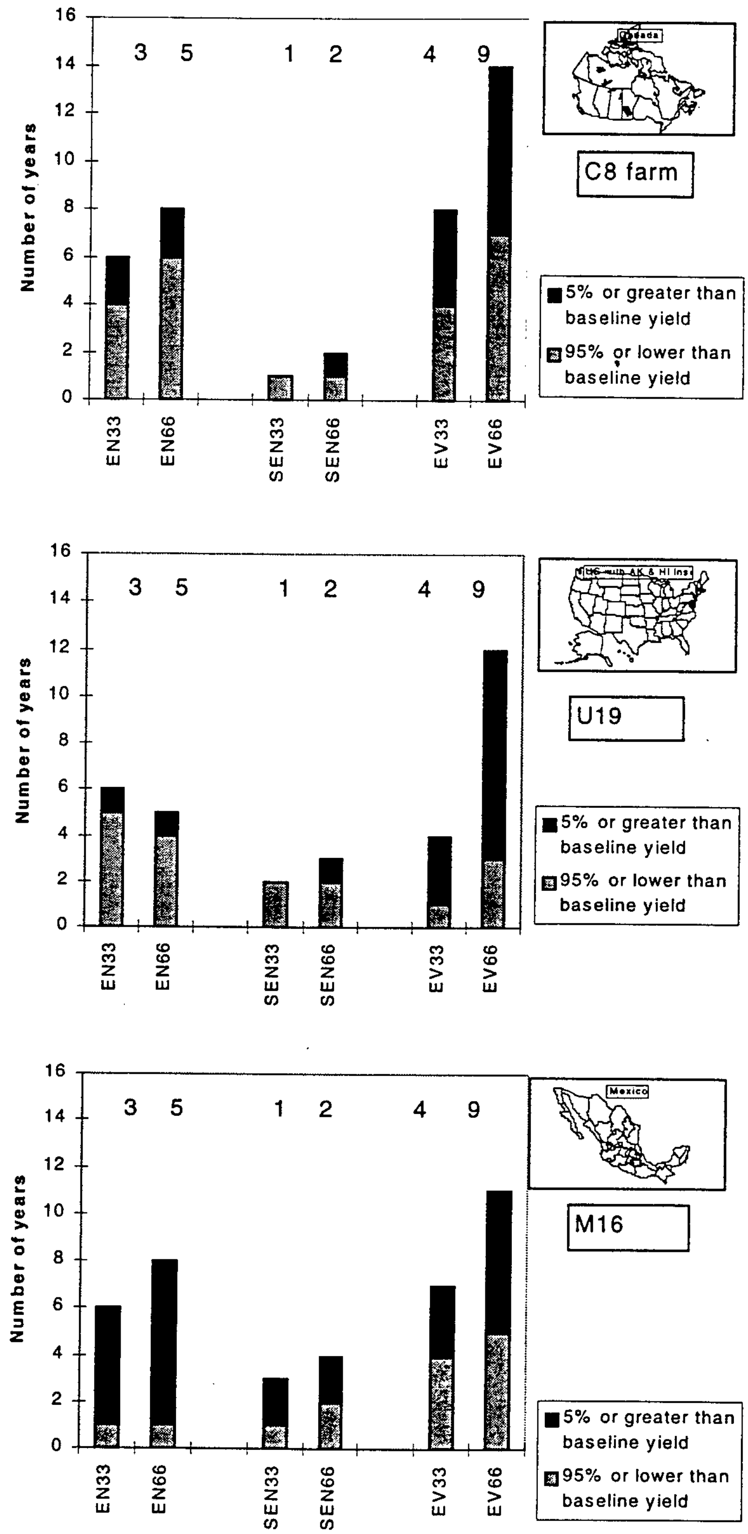


Fig. III.24. Number of years in which the yield difference between the frequency-altered scenario and the historical baseline reached the threshold levels of 5% (see text for definition of baseline yield). Numbers on top of each column represent the total number of years altered for each of the 33 and 66% ENSO scenarios.

F. Economic Analysis

MiniCAM 2.0 is a collection of simple models intended to estimate both the costs and benefits of measures designed to reduce greenhouse gas emissions. The economic component of MiniCAM contains production sectors for both energy and agriculture. Using results from EPIC simulations under a changed climate, MiniCAM has been used to link climate change to agricultural production and trade of agricultural products between regions. In this study, we use the same mechanism to link ENSO events to agricultural production and trade.

F.1 Agricultural Model in MiniCAM 2.0

MiniCAM contains an agriculture and land use (AgLU) component that solves for world prices of three composite goods: crops, animal products, and forest products. These three products represent competing uses of land in each MiniCAM region. Land is allocated among these uses according to payments to owners of land. The activity with the greatest return per hectare is allocated the largest share of land. In the case of crops, returns per hectare are calculated as revenue per hectare (price times yield per hectare) less a fixed cost per hectare. Land is used both directly and indirectly to produce animal products. Some land is used directly as pasture while other land is used indirectly to grow feed. For forest products, returns to land are calculated on a levelized basis over the time period from planting to harvest. A levelized return to land is the equivalent annual payment to landowners taking into account the cost of planting, number of years from planting to harvest, revenue at harvest, and the interest rate.

Each MiniCAM region has a production function for crops that is simply the amount of land allocated to crops times an average yield per hectare times a productivity parameter that can vary with climate. The productivity parameter has a default value of one, meaning that an unchanged climate implies no change in yield.

The composite productivity parameter and average yield per hectare in MiniCAM are averages across *all* crops that are major users of land. If the simulated crop yields generated by this ENSO study are to be used in MiniCAM, then yields must first be averaged across locations (EPIC farms) and after that, averaged across major field crops.

F.2 Aggregation of Yields across EPIC Farms

Simulated EPIC farms are scattered throughout the United States, Mexico, and Canada, providing broad geographical coverage. Each EPIC farm represents agricultural production for a specific geographical area.

Yields are aggregated across EPIC farms to obtain an average yield for each crop within each country. Results of this aggregation are shown in Table III.17. Yields from EPIC farms are weighted by harvested area for that particular crop. For example, when aggregating corn yields in the United States, EPIC farms in the corn belt are given greater weight than EPIC farms in other parts of the United States. Average yields are calculated for the following crops.

United States: Corn, Winter Wheat
Mexico: Corn, Beans, Wheat
Canada: Barley, Canola, Spring Wheat

In the United States, simulated yield results are available for 66 representative EPIC farms; 54 of these farms grow wheat and 31 of the farms grow corn. Some of the representative farms grow one crop and some grow both. It is assumed that each farm represents a geographic area within one of the GCAM regions. If there is only one EPIC farm in a particular GCAM region, then that farm represents crop growth for the entire region. If there are two or more farms in a GCAM region, yields from these farms are averaged to obtain a representative yield for that region. For averaging yields across GCAM regions, each GCAM region is given a crop-specific weight that is equal to the number of hectares harvested in 1990.

Each representative farm in Canada is assigned to a CRAM (Canadian Regional Agricultural Model) region in either Alberta, Saskatchewan, or Manitoba. Simulated crop yields are available for 37 farms in the Prairie Provinces. For each crop, an average yield is calculated for each CRAM region. Yields are averaged across CRAM regions using weights based on harvested area.

In Mexico, simulated yields are available for one representative farm within each state. This representative farm is used to represent crop growth for all harvested hectares in that state. Yields are aggregated across EPIC farms using historical data on area harvested by crop.

Table III.17. Average yields across EPIC representative farms (Mg ha^{-1})

		Average Yield	Deviation from Average		
Country	Crop	N	EN	SEN	EV
U.S.	Corn	7.05	-0.61	-0.54	-0.12
U.S.	Winter Wheat	1.76	-0.13	0.11	-0.02
Canada	Barley	3.91	-0.15	-0.16	0.10
Canada	Canola	2.68	-0.02	-0.01	-0.01
Canada	Spring Wheat	2.53	-0.07	-0.02	0.16
Mexico	Corn	5.10	-0.33	0.05	0.02
Mexico	Beans	1.16	0.00	-0.08	0.09
Mexico	Wheat	1.75	0.39	0.17	0.30
Mexico	Irrigated Corn	7.18	-0.20	0.08	0.13
Mexico	Irrigated Beans	2.55	0.03	0.03	-0.03
Mexico	Irrigated Wheat	4.53	0.05	-0.18	0.08

F.3 Aggregation across Crops

The MiniCAM model does not attempt to model individual crops, but instead simulates the production and consumption of a *composite crop*, where production and consumption are measured in units of Mg (metric tons). This assumes that some substitution is possible in the consumption of these crops.

To create a measure of yield for each country comparable to that used in MiniCAM, yields from Table III.17 are aggregated using historical production levels, in metric tons, as weights. Results of this aggregation are shown in Table III.18.

The method of aggregation used here, simply adding up metric tons, has the advantage of being easy to calculate and understand. An alternative would have been to give a greater weight to crops with a greater price per metric ton.

Table III.18. Average yields across crops (Mg ha^{-1})

Country	Average Yield N	Deviation from Average EN	SEN	EV
U.S.	5.63	-0.48	-0.36	-0.09
Canada	2.92	-0.09	-0.06	0.13
Mexico	5.36	-0.26	0.04	0.06

For all three countries, average yields from the El Nino simulations are approximately 3% to 9% below yields in the Neutral years.

F.4 Sensitivity Analysis using MiniCAM

Changes in yield due to ENSO events, when averaged across EPIC farms within a region, tend to be small relative to average yields. Before putting these yield changes into the MiniCAM model directly, four scenarios were created to characterize a range of potential yield patterns. Simple rules-of-thumb can be derived from these scenarios.

In this study, changes in yield due to ENSO events were simulated for the United States, Canada, and Mexico. The MiniCAM model contains separate regions for the United States and Canada, but Mexico is part of the Latin American region.

Scenario A assumes that average crop yields increase by 10% in the U.S., Canada, and Latin America only; crop yields are unchanged in all of the other MiniCAM regions. The Rest of World (R.O.W.) includes OECD Europe, Japan, Australia and New Zealand, Eastern Europe and Former Soviet Union, China, Middle East, Africa, and Southeast Asia. Scenario B assumes that all world regions experience a 10% increase in crop yields. The economic results from MiniCAM are quite different between scenarios A and B. Scenarios C and D are opposite in sign to scenarios A and B, and cover the cases of decreases in crop yield. Of the four cases, scenario C most closely represents the EN and SEN simulated yield patterns in Table III.18.

Thus, the scenarios for sensitivity analysis are:

A. Increase in crop yields of 10% for U.S., Canada, and Latin America only.
B. Increase in crop yields of 10% for all world regions.
C. Decrease in crop yields of 10% for U.S., Canada, and Latin America only.
D. Decrease in crop yields of 10% for all world regions.

Table III.19. Impact on price and production of crops in MiniCAM (percent change)

Scenario	World Price	World Production	Regional Crop Production U.S.	Canada	Latin A.	R.O.W.
A	-5.9 %	1.2 %	12.9 %	12.1 %	13.9 %	-2.7 %
B	-19.6 %	4.3 %	4.1 %	5.2 %	2.2 %	4.5 %
C	6.2 %	-1.1 %	-12.9 %	-12.1 %	-13.8 %	2.7 %
D	29.1 %	-4.8 %	-4.8 %	-5.8 %	-2.8 %	-5.0 %

Table III.19 reports MiniCAM results on the changes in world price of crops, world crop production, and crop production for selected regions. Scenarios A and B both represent increases in crop yields; world prices fall and world production increases. Prices fall the furthest, and production increases the most, when all world regions are assumed to have increases in crop yield. Note that the percentage increase in world production is less than the assumed 10% increase in yield. However, the world average increase in crop production of 1.2% in scenario A is not representative of any of the individual world regions.

Scenarios C and D are parallel to A and B, but with decreases instead of increases in crop yields. A definite symmetry is apparent in the results of Table III.19. The economic results of scenario C are roughly equal and opposite in sign to those of scenario A. Likewise, the results of scenario D are approximately symmetric to the results of scenario B.

In the MiniCAM model reference case, the U.S., Canada, and Latin America are all net exporters of crops. Table III.20 summarizes the change in crop exports for the four sensitivity cases. If the U.S., Canada, and Latin America are the only regions with changes in crop yields, then exports move in the same direction as crop yields. If all regions experience a change in crop yields, then the change in exports is much smaller, and exports could either increase or decrease.

Table III.20. Change in regional crop exports

Scenario	Change in Exports of Crops		
	U.S.	Can.	Latin A.
A	34.6 %	24.2 %	45.5 %
B	4.2 %	5.6 %	-1.4 %
C	-34.9 %	-24.6 %	-45.3 %
D	-5.1 %	-6.4 %	0.6 %

The following generalizations can be made from the MiniCAM results in Tables III.19 and III.20. Many of these generalizations are best thought of in terms of elasticity, which relate the percent change in some measure of interest to a percent change in yield.

1. If a change in crop yield due to an ENSO event is specific only to the U.S., Canada, or Latin America, then the elasticity of crop output with respect to crop yield in those regions can be greater than one. If these regions become more productive at growing crops relative to the rest of the world, land will be diverted from other uses into growing crops in those regions. This allows the quantity of crops produced, in metric tons, to increase by a greater percentage than the actual increase in crop yield.

2. If the change in crop yield is uniform throughout all world regions, then the elasticity of crop output with respect to crop yield is positive but less than one. In other words, if crop yields increase (fall) everywhere by the same percentage, then production will increase (fall) everywhere, but by a smaller percentage than yields.

3. Similar results are available for exports of crops from the U.S., Canada, and Latin America. If the change in yield is specific to only a few regions, than the elasticity of exports with respect to crop yield is greater than one. If the change in yield is the same worldwide, elasticities are much smaller.

F.5 MiniCAM Simulations with Yields from this Study

In this section, we use the yield changes from Table III.18 to modify agricultural productivity in the MiniCAM model.

As noted previously, this study provides information on potential changes in yield for the U.S., Canada, and Mexico only. As our sensitivity analysis shows, economic results from MiniCAM are very sensitive to assumptions about changes in yield for other world regions. In this section, we assume that crop yields in other world regions are unchanged due to ENSO events.

For the EN, SEN, and EV cases, yield changes from Table III.18 were converted to indexes, where an index of 1.0 means no change. These indexes were then used in MiniCAM to modify crop productivity in the U.S., Canada, and Latin America regions. Percent changes in production and world price are shown in Table III.21.

Table III.21. Impact on price and production of crops in MiniCAM (percent change).

Scenario	World Price	World Production	Regional Crop Production			
			U.S.	Canada	Latin A.	R.O.W.
EN	4.1 %	-0.7 %	-11.5 %	-2.9 %	-6.0 %	1.8 %
SEN	1.9 %	-0.3 %	-9.1 %	-2.0 %	2.8 %	0.9 %
EV	0.0 %	0.0 %	-2.5 %	6.6 %	1.9 %	0.0 %

The EN results from Table III.21 are similar to sensitivity scenario C in Table III.19. This is the case where yields fall in the U.S., Canada, and Latin America, but are unchanged elsewhere. The SEN case impacts the U.S. and Canada in much the same way as EN, but with an effect of different sign in Mexico and less of an impact on other world regions. In the EV case, a small decline in U.S. crop production is offset by increases in Canada and Latin America, leaving the rest of the world unaffected.

F.6 Summary

The economic analysis described here makes use of a methodology originally developed to estimate the impact of global warming on the economies of eleven world regions. This methodology was adapted to simulate the impact of ENSO events on crop yields, regional production, and patterns of international trade. In the case of global warming, crop yields would change very little from year to year, but large changes could occur over long periods of time. In the case of ENSO events, most of the variation in crop yields would be between years, and not over long periods of time. Economic modeling is useful to show whether localized ENSO impacts will cancel each other out or reinforce each other when aggregated over geographic areas, crops, and time.

A global economic model, such as that in MiniCAM, provides an overall view of interactions between world regions, but little detail on processes within regions. One of the challenges of this study was to combine results from a detailed process model, such as EPIC, with the aggregate economic component of MiniCAM. Some simplifying assumptions were required to use the EPIC simulations, with limited coverage of crops and regions outside of North America, in a global economic model.

This analysis could be strengthened with future research in several areas. First, some measure of statistical significance of the simulated changes in yield should be developed. This would indicate which of the reported results are more likely to hold during future ENSO events. This really depends on the statistical significance of the changes in temperature and precipitation that were reported for our small sample of years covering ENSO events. Second, the land allocation mechanism in MiniCAM should be compared with other models that simulate the farmer's decision making process in greater detail. Third, this analysis could be extended to cover irrigated agriculture. ENSO events are likely to change the amount of water available each year for irrigation. Fourth, a more complete coverage of EPIC results across crops would be very useful. For example, wheat and corn were the only U.S. crops covered in this study. However, large areas of land are devoted to soybeans and hay. Some information on these other crops would allow a more complete comparison of the impacts of ENSO events across crops.

IV. General Discussion

Section description

In this section we summarize and discuss the major methodological and modeling results stemming from this project. We concentrate among other issues on: a) the rationale for the use of a modeling approach to elucidate ENSO effects on North American agriculture, b) our chosen approach for simulating temporal trends of ENSO states, c) our chosen approach for simulating spatial trends of ENSO states, d) the indicated effects of altered-ENSO frequencies on crop yield, e) the influence of ENSO states on continental agricultural productivity and global trade.

Why model?

What evidence exists of ENSO effects on agricultural production relies, largely, on statistical associations (e.g. Phillips and Rosenzweig, 1996; Cane et al., 1994) and anecdotal reports from the field (e.g. Magalhaes, 1996). A fundamental assumption of our work has been that it is possible to study the influence of ENSO-driven climate anomalies on agriculture with the help of mechanistic crop-growth simulation techniques. We have tested this assumption on North American agriculture using the EPIC model driven by standard, location-specific inputs of weather, landscape, soils, and management assembled by a consortium of natural resource modelers working within the framework of the NA3E program. This approach provides an opportunity to isolate the effects of climate from those of the many confounding factors (e.g., management level, incidence of pests and disease, economic determinants) that also influence regional yields. Phillips and Rosenzweig (1996) were able to correlate ENSO anomalies with records of aggregate state-wide corn yields in the US Corn Belt. Their empirical approach effectively explains some portion of experienced yield variability. Simulation builds on empiricism to increase mechanistic understanding of the relation between ENSO-driven climate variability and crop response.

Our results support the use of mathematical algorithms and geographically distributed input data to differentiate the effects of the various ENSO states on a regional basis. In addition, this project has provided an opportunity for the participating North American scientists to begin developing the continentally-coherent environmental databases and modelling capabilities required to achieve the objectives of the NA3E (North American Energy, Environment and Economy) program and to explore the logical use of model results within an integrated framework to predict the possible outcomes of global economic and trade indicators.

Additionally, our methodology can provide policy makers and researchers with a tool to test and analyse "what if" scenarios and explore possible responses to advanced forecasts of ENSO events. It also provides researchers with an integrated assessment tool for the study of ENSO anomalies on a widely diverse set of agricultural systems such as exist in Mexico, the U.S. and Canada. And, further, the methodology allows for analysis of the effects of ENSO-driven climatic variability on such environmental variables as runoff, water use and soil erosion.

Can the model reproduce the impacts of ENSO states on crop yields?

The EPIC model was able to reproduce well the year-to year variability of crop yields in six of nine randomly selected representative farms across Canada, the U.S. and Mexico. Further analysis of ENSO signals (measured as deviation of ENSO states with respect to Neutral years) revealed that EPIC was able to predict the direction and relative magnitude of the ENSO signal in 18 out of the 27 ENSO-farm combinations (9 farms x 3 ENSO states). However, the possibility that EPIC is not sensitive enough to fully capture the climatic differences found in the ENSO scenarios in the yield results cannot be ruled out. Additional effort is required to establish the causes for disagreement (and agreement for that matter) between historic regional and simulated crop yields.

Regional trends of recorded ENSO signals and simulated crop yields

El Niño: Warmer[5] winter temperatures in the Canadian Prairies during the EN state are clearly related to decreases in wheat yield. In Illinois, reductions in corn yield are spatially associated with moderate increases in summer temperatures and decreases in winter and summer precipitation. Moderate warming in spring and summer in Minnesota and Iowa together with reductions of precipitation during summer months, account for reductions in corn yield of up to 1 Mg ha^{-1}. Winter cooling and reduction in summer precipitation in Georgia and Florida also lead to decreases in crop yield. The pattern of corn yield deviations under EN conditions in Mexico is complex. Yield changes of up to ±1 Mg ha^{-1} are interspersed. The most visually-significant regional climatic trends that accompany these changes are cooler winter temperatures and moderate increases in precipitation.

Strong El Niño: Our spatial analysis and simulation results show that the SEN state is not just a stronger version of the EN state. In the Canadian Prairies the stronger increases in winter temperatures shift to the South and extend into the Northern Great Plains (North and South Dakota). Wheat yields in these regions are generally lowered but are interspersed with some moderate yield increases. The increases in winter temperature also extend throughout the Ohio valley. More moderate temperature increases occur there in summer. Corn yield decreases accompany these climatic changes. In the southeastern U.S., winter precipitation increases for the entire region. However, corn yields do not respond dramatically because of higher winter and summer temperatures and also small decreases or no change in summer precipitation. A distinctive pattern of cooling emerges during winter across the southwestern U.S. and northern Mexico but a lack of representative farms in these regions does not allow us to compare the spatial patterns of climate anomalies and crop yields there. Although in Mexico EN and SEN temperature and precipitation patterns are distinctively different, simulated yields do not appear to reflect these differences (e.g., compare corn yield deviations in central Mexico under EN and SEN).

El Viejo: The EV state creates a well-defined temperature signature throughout North America during winter. Lower winter temperatures in the Canadian Prairies induce increases in crop yields. From Arkansas to Ohio temperatures are higher in winter but somewhat lower in summer; precipitation is slightly greater in winter. Decreases in corn yields appear to be due, primarily, to decreases in precipitation either in spring or summer.

Yields decrease despite some increases in precipitation in winter. Yield decreases on most of the farms are clearly related to sharp increases in numbers of water stress days –often from 50 to 100% more.

Yield variability increases consistently with decreasing yield in all crops modeled. Canola yields and their variability are sensitive to changes in ENSO state. This is true, too, of corn yield variability in the U.S. Winter wheat in the U.S. and spring wheat in Canada both reveal the same degree of yield variability (i.e., a relative lack of response to ENSO states). Change in number of water stress days induced by the various ENSO states is a relatively good predictor of changes in crop yield.

ENSO-frequency analysis

Changes in frequency of occurrence of a given ENSO state appear to influence overall yield. However, the effects are small when averaged over the total duration of the simulation (about 50 years in our case). Both positive and negative yield responses can be expected to occur in any time series with altered frequency of occurrence of ENSO states. An increase in the frequency of occurrence of a given ENSO state induces yield changes for a more extended period of time than that strictly dictated by the frequency.

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[5] All comparatives herein are relative to the Neutral state

ENSO effects on evapotranspiration, runoff and erosion

Responses of environmental variables such as runoff to ENSO states are, at best, complex. For example, PET consistently increased across the representative farms in the Canadian Prairies during EN years. This was accompanied by a decrease in ET but not necessarily by a decrease in runoff. Changes in the distribution of precipitation during the year appear to have exerted a strong control on runoff processes. Changes in soil erosion under a given ENSO state do not necessarily accompany changes in runoff since the former process includes, on most farms, both types of erosion (i.e., wind and water).

In the U.S. soil erosion was more severe on corn than on wheat farms, partially reflecting differences in tillage intensity and plant canopy cover. Regional patterns of erosion emerged in the Central and Southern Great Plains and in the Ohio Valley. The response of erosion to ENSO state, however, was crop specific. While erosion decreased on wheat farms under EN it increased instead on corn farms. These results suggest the need for further studies at a higher temporal and spatial scale of resolution.

Runoff and erosion were sensitive to ENSO states in Mexico but again the response was crop specific. All ENSO states induced mostly increases in erosion under dryland bean management. Erosion often accompanied the direction but not the magnitude of runoff changes.

ENSO economic analysis

For the first time, an economic model has been used to extend the modeled influences of ENSO states on crop production to global agricultural production and trade. For the three North American countries, EN reduces national average all-crop yields relative to those that occur under Neutral conditions by from 3 to 9%. The MiniCAM analysis indicates very consequential effects on national production and exports and on world prices, depending on what happens in that year in the rest of the world. Our coupling of the crop simulation modeling results with a global economic model represents a first and relatively simple attempt at "integrated assessment" of climatic change/variability impacts. This approach can be applied, probably with more dramatic results, to study of the economic impacts of global warming on the agricultural economy.

Conclusions

- The temporal and spatial impacts of ENSO states on North American crop yields are predicted using a set of geo-referenced environmental databases and computer simulation modeling.
- Classification of historic weather records of air temperature and precipitation according to the Japan Meteorological Administration ENSO Index allowed for the creation of a series of map products depicting the regional and seasonal patterns of ENSO anomalies across North America.
- The agro-ecosystem simulator EPIC reproduced temporal trends of crop yield acceptably on a subset of representative farms used in this study. Further verification work needs to be conducted on the model's ability to reproduce ENSO signals. This work needs to include both temporal as well as spatial scales using continental historic crop yield databases.
- Computer simulations using constant ENSO-weather patterns allowed for the identification of broad regions within Canada, the U.S. and Mexico where crop yields appear to respond to ENSO-related climatic anomalies.
- Responses to ENSO anomalies appear to be crop specific.
- Identification of ENSO-sensitive regions is promising as a basis for further computer simulation studies at a higher level of resolution and/or actual monitoring of ENSO effects by means of remote sensing techniques.
- The environmental variables runoff and erosion modeled with EPIC were sensitive to ENSO anomalies but the patterns of response are complex.
- The distinction made between El Niño and Strong El Niño was appropriate and proved the latter not merely an amplification of the former. EN and SEN climate anomalies differed both in geographic and seasonal distribution and, often, in sign.
- Our simulation results suggest that a change in the frequency of occurrence of ENSO states would alter crop yields both positively and negatively for a period of years after those in which the frequency is altered.
- Change in number of water stress days experienced by the crop is a good predictor of yield response to the various ENSO states. This indicates that surveillance of ongoing ENSO effects is possible using microwave or other means for remotely sensing soil moisture conditions.
- An integrated assessment model (PNNL's MiniCAM), using the EPIC biophysical model results as input, was applied to predict changes in national and continental food production associated with each of the ENSO states. Results indicate that these impacts can significantly affect grain prices and world trade.

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APPENDICES

Appendix 1a: Description of selected Canadian representative farms

Province: Alberta
Climate Station: Edmonton International (53.66 N, 112.17 W)
Elevation: 690 m
Major Soil Type: Angus Ridge (Boroll)
Slope Length: 60 m
Slope Gradient: 2%
Crop rotation: Barley - Canola - Wheat
Growing degree days: Barley: 1500; Canola: 1200; Wheat: 1600

Year	Month	Day	Agricultural Operation
1	4	22	Field cultivator
1	5	5	Spike harrow
1	5	10	Planting and fertilization (Barley)
1	8	20	Harvest
1	8	10	Tandem disk
1	10	15	Field cultivator
2	4	22	Field cultivator
2	5	5	Spike harrow
2	5	14	Planting and fertilization (Canola)
2	9	7	Harvest
2	10	10	Tandem disk
2	10	15	Field cultivator
3	4	27	Field cultivator
3	4	29	Spike harrow
3	5	5	Planting and fertilization (Spring wheat)
3	8	30	Harvest
3	10	10	Field cultivator

Inputs	Description	Amount
Seed (Barley)	Planting	100 pl m^{-2}
Nitrogen	Fertilization	67 kg ha^{-1}
Phosphorus	Fertilization	10 kg ha^{-1}

Province: New Brunswick
Climate Station: Moncton (45.50 N, 67.00 W)
Elevation: 130 m
Major Soil Type: Parry (Umbrept)
Slope Length: 100 m
Slope Gradient: 2%
Crop rotation: Potato - Barley - Barley
Growing degree days: Potato: 1300; Barley: 1570

Year	Month	Day	Agricultural Operation
1	4	30	Moldboard plow
1	5	15	Tandem disk
1	5	15	Row planting
1	6	20	Row builder
1	6	30	Row cultivator
1	9	15	Harvest

Inputs	Description	Amount
Seed (potato)	Planting	
Nitrogen	Fertilization	100 kg ha^{-1}
Phosphorus	Fertilization	40 kg ha^{-1}

Appendix 1B: Description of selected United States representative farms

State: Iowa
Climate Station: Oelwein, Iowa (42.7 N, 91.9 W)
Major Soil Type: Kenyon (Udoll, loam)
Slope Length: 75 m
Slope: 4%
Rotation: Continuous Corn
Growing Degree Days: 1800

Year	Month	Day	Agricultural Operation
1	4	10	Tandem disk
1	5	1	Field cultivator
1	5	9	Herbicide application (sprayer)
1	5	14	Row planting with fertilization
1	5	18	Row cultivator
1	6	15	Row cultivator
1	10	29	Harvest

Inputs	Description	Amount
Seed (corn)	Planting	5 pl m^{-2}
Nitrogen	Fertilization	110 kg ha^{-1}
Phosphorus	Fertilization	30 kg ha^{-1}
Aatrex	Pesticide	1 kg ha^{-1}
Furadan	Pesticide	1 kg ha^{-1}

State: Kansas
Climate Station: Hill City, KS (39.4, 99.8)
Major Soil Type: Harney (Ustoll, silt loam)
Slope Length: 96 m
Slope: 3%
Rotation: Continuous Winter Wheat
Growing Degree Days: 1850

Year	Month	Day	Agricultural Operation
2	3	15	Herbicide application (sprayer)
2	7	1	Harvest
1	7	30	Tandem disk
1	8	15	Tandem disk
1	9	15	Anhydrous ammonia application
1	9	20	Fertilizer application (spreader)
1	9	29	Field cultivator
1	10	4	Planting

Inputs	Description	Amount
Seed (corn)	Planting	100 pl m^{-2}
Nitrogen	Fertilization	66 kg ha^{-1}
Phosphorus	Fertilization	5 kg ha^{-1}
Glean	Pesticide	1 kg ha^{-1}

Appendix 1C: Description of selected Mexican representative farms

State: Jalisco
Climate Station: Teuchitlan (20.5 N, 102.6 W)
Major Soil Type: Regosol (loam)
Slope Length: 100 m
Slope: 6%
Rotation: Continuous dryland corn
Growing Degree Days: 1724

Year	Month	Day	Agricultural Operation
1	4	19	Moldboard plow
1	6	9	Tandem disk
1	6	18	Row planting with fertilizer
1	7	6	Pesticide application (sprayer)
1	7	10	Fertilizer application
1	7	10	Row cultivator
1	7	20	Pesticide application (sprayer)
1	11	10	Harvest

Inputs	Description	Amount
Seed (corn)	Planting	4.4 pl m^{-2}
Nitrogen	Fertilization	120 kg ha^{-1}
Phosphorus	Fertilization	50 kg ha^{-1}
2-4-D	Pesticide (Herbicide)	1 kg ha^{-1}
Glean	Pesticide (Insecticide)	1 kg ha^{-1}

State: Sinaloa
Climate Station: El Fuerte (26.2 N, 108.5 W)
Major Soil Type: Vertisol (clay)
Slope Length: 100 m
Slope: 1%
Rotation: Continuous irrigated winter pinto beans
Growing Degree Days: 1466

Year	Month	Day	Agricultural Operation
1	1	5	Pesticide application (sprayer)
1	1	5	Pesticide application (sprayer)
1	2	21	Harvest
1	9	5	Tandem disk
1	9	15	Tandem disk
1	9	25	Row cultivator
1	10	10	Planting with fertilization
1	10	25	Pesticide application (sprayer)
1	11	5	Row cultivator
1	11	25	Row cultivator
1	12	15	Pesticide application (sprayer)
1	11	10	Harvest

Inputs	Description	Amount
Seed (corn)	Planting	13 pl m^{-2}
Nitrogen	Fertilization	80 kg ha^{-1}
Benlate	Pesticide (Fungicide)	1 kg ha^{-1}
Vitax	Pesticide (Fungicide)	1 kg ha^{-1}
Furadan	Pesticide (Fungicide)	1 kg ha^{-1}
Sevin	Pesticide (Insecticide)	1 kg ha^{-1}

State: Sinaloa
Climate Station: El Fuerte (26.2 N, 108.5 W)
Major Soil Type: Vertisol (clay)
Slope Length: 100 m
Slope: 1%
Rotation: Continuous irrigated winter pinto beans
Growing Degree Days: 1466

Year	Month	Day	Agricultural Operation
1	1	5	Pesticide application (sprayer)
1	1	5	Pesticide application (sprayer)
1	2	21	Harvest
1	9	5	Tandem disk
1	9	15	Tandem disk
1	9	25	Row cultivator
1	10	10	Planting with fertilization
1	10	25	Pesticide application (sprayer)
1	11	5	Row cultivator
1	11	25	Row cultivator
1	12	15	Pesticide application (sprayer)
1	11	10	Harvest

Inputs	Description	Amount
Seed (bean)	Planting	13 pl m^{-2}
Nitrogen	Fertilization	80 kg ha^{-1}
Benlate	Pesticide (Fungicide)	1 kg ha^{-1}
Vitax	Pesticide (Fungicide)	1 kg ha^{-1}
Furadan	Pesticide (Fungicide)	1 kg ha^{-1}
Sevin	Pesticide (Insecticide)	1 kg ha^{-1}

Appendix 2: Statistical tests to differentiate *El Niño* from *Strong El Niño*

Of the 30 years of record only two met the criteria for classification as Strong El Niño. What evidence, in terms of quantitative or geographic differences in climatic anomalies, supports this classification? Statistical tests using classical and geostatistical methods have been applied to this question with the following results:

Deviations from Neutral of daily winter (December – February) temperatures at 139 representative sites in Canada, the U.S., and Mexico averaged 0.92° (±1.28°[1]) under EN while they averaged 1.53° (±1.26°) under SEN. A two-sample t-test assuming equal variances for variables EN and SEN was significant at $p<0.0001$ and led us to reject the null hypothesis (H_0:$\mu_{EN} = \mu_{SEN}$) and accept its alternative (H_A:$\mu_{EN} \neq \mu_{SEN}$). Under the same set of hypotheses, a t-test assuming unequal variances (Hartley's F-max test[2] significant at $p<0.05$) of winter-precipitation deviations from Neutral for the same 139 sites revealed the EN condition (-8.4 mm [±28.4 mm]) to be different from the SEN condition (-0.6 mm [±38.3 mm]) at $p<0.056$ level of probability.

While classical t-tests analyses are useful techniques to detect differences between random variables, they make no use of spatial characteristics possibly present in data sets. We used semivariogram analysis (Isaaks and Srivastava, 1989; Englund and Sparks, 1991), a geostatistical technique, to discern patterns of spatial continuity between these meteorological variables. Semivariograms were estimated for the two variables under study (temperature and precipitation) and the two conditions (EN and SEN). Plots of the semivariance ($\gamma(h)$) at different lags (h) or distances (Fig. App.2 1 (a) and (b)) suggest not only a strong spatial dependence of both variables -a somehow result expected- but also clear differences between EN and SEN as indicated by the different variogram models (solid or broken lines drawn through data points) needed to describe the data sets.

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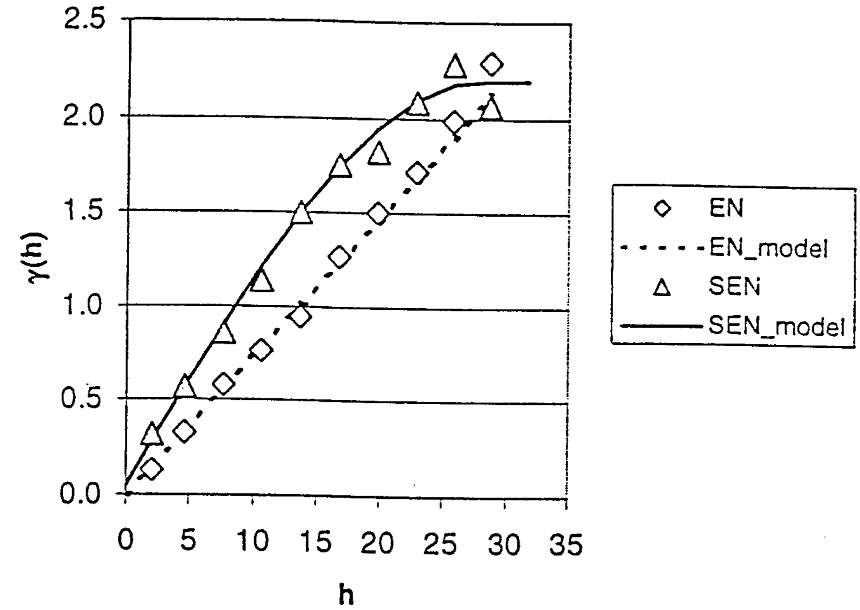
[1] ± 1 Standard Deviation

[2] An F ratio with the larger of the two variances in the numerator is calculated and compared against those of an F-ratio table with n_1-1 and n_2-1 *df.*

(a) Temperature



(b) Precipitation

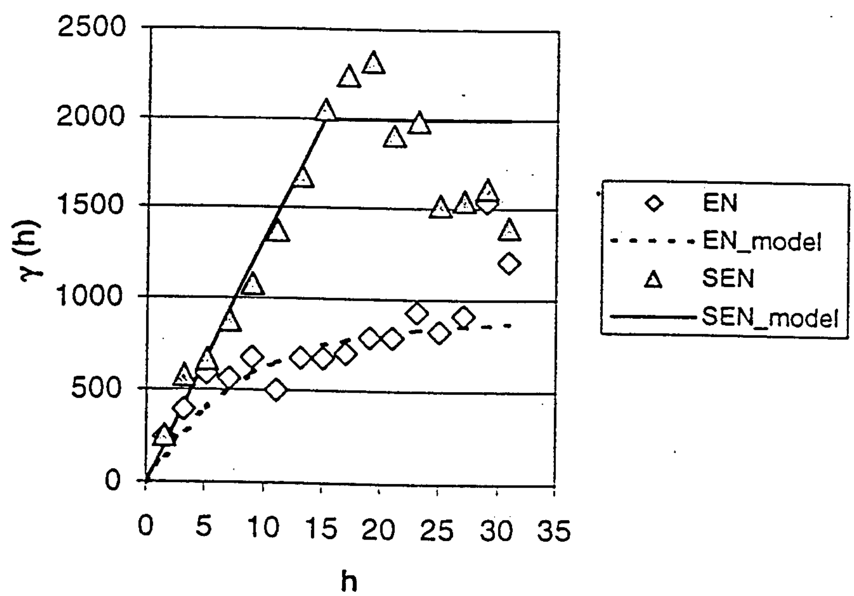


Fig. App.2 1. Omnidirectional semivariograms for winter (a) temperature and (b) precipitation deviations from Neutral for the EN and SEN conditions.

Report Number (14) PNNL--11699

Publ. Date (11) 199709

Sponsor Code (18) NASA; NOAA, XF

UC Category (19) UC-000; UC-000, DOE/ER