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Effects of Climate Change on Plants: Implications for Agriculture

Agro-meteorological metrics for communicating climate change impacts to land managers

M RIVINGTON[1], K B MATTHEWS[1], K BUCHAN[1], D MILLER[1] and G BELLOCCHI[2]

[1]*Macaulay Institute, Craigiebuckler, Aberdeen, AB15 8QH, UK*
[2]*Agrichiana Farming, Abbadia di Montepulciano, Via di Sciarti n. 33/A, 53040 Siena, Italy*

Summary

Agro-meteorological metrics indicate conditions that aid agricultural decision making. Metrics derived from estimated future climate data provide an opportunity to communicate the potential impacts of climate change on agriculture to land management stakeholders. Metrics indicate how changes in the biophysical environment can inform adaptations to farming systems to achieve financial viability, food security and environmental sustainability. The research consisted of four steps: evaluation of data from a Regional Climate Model (RCM); downscaling RCM data to specific locations; generation of agro-meteorological metrics using observed and downscaled RCM weather data; metrics evaluation by stakeholders in workshops and deliberation on the potential impacts and adaptations. Metrics indicate the growing season starts earlier but the end of field capacity does not change. The period when crop growth is water-limited, and the maximum soil water deficit are both estimated to increase. Stakeholders found the use of agro-metrics enhanced their ability to generate specific adaptation strategies.

Key words: Climate change, agro-meteorology, adaptation, mitigation, communication

Introduction

In order to develop a medium for communicating the potential impacts of climate change to land management stakeholders, it is important to consider the type of information that is useful to them and which is currently understood. Agro-meteorological metrics are estimates that are regularly used by farmers, advisors and academics to characterise states determined by the weather that effect land management decision making. This user familiarity with metrics, and the fact that they can be estimated from both observed and future projection weather data, makes them an ideal medium for communicating the potential impacts.

Policies developed to achieve appropriate adaptation and mitigation responses to climate change within the land use sector need to take into consideration the biophysical components that determine tactical decision making. Central to this is identifying the key factors, thresholds and tolerances determined by the weather that form the basis for land manager decision making. This situation provides a good opportunity to demonstrate how research can facilitate knowledge co-construction and sharing by using agro-meteorological metrics as a medium for deliberation. In the context of climate change mitigation and adaptation, such a model should result in a greater probability of desirable outcomes, as research achieves the three key factors of salience, legitimacy and credibility. Without these it is less likely that stakeholder groups and researchers will form workable relationships, by reducing the capacity for researchers to function as facilitators and potentially deepening divisions between the policy and practice groups.

However, there are several issues concerning the use of climate model estimates, one is scenario uncertainty, and the other the uncertainties associated with model quality and scales or representation. The second issue is important as RCM estimates are determined for spatial scales considerably larger (typically 50 × 50 km) than those at which agro-metrics are applied. This research does not consider scenario uncertainty (indeed only one model for one greenhouse gas emissions scenario was used). The Hadley Centre's HadRM3 had previously been evaluated against observed data (Rivington *et al.* ,2008a) and found to produce both good and poor estimates of the past climate (hindcast) at specific sites. It was concluded that the hindcast estimates contained biases of sufficient magnitude to render modelled future projection data unsuitable for use in daily time step models (i.e. cropping systems) or estimating secondarily derived values (i.e. evapotranspiration). The hindcast data were sufficiently close to the observed, to enable meaningful bias correction based on the errors being present in the hindcast and future projections (Rivington *et al.*, 2008b).

This paper presents the implementation of a flexible and customisable framework for deriving agro-meteorological indicators from the outputs of an RCM and the subsequent communication with stakeholders. The paper presents the implementation of a range of metrics, some that relate to single climatic variables such as temperature and rainfall, but others that seek to synthesise the interactions between these variables to derive agro-meteorologically significant indicators such as accessibility periods or maximum soil moisture deficits. We also argue that for the climate change assessments to be meaningful to stakeholders they need to be presented at the scale of management (farm, catchment or conurbation) and in a form that is meaningful to the stakeholders. Findings from both the generation of the metrics and the process of deliberation with stakeholders are presented.

Materials and Methods

Daily observed precipitation (mm), maximum (*Tmax*) and minimum (*Tmin*) air temperature (ºC) and total downward surface shortwave flux (direct and diffuse solar radiation, S_o, MJ m^2 day^{-1}) data from seven sites in Scotland, UK, for the period 1960–90 were provided by the British Atmospheric Data Centre (BADC: http://badc.nerc.ac.uk/home/index.html). Simulated data for the 2070–2100 ('future') time periods produced by the Hadley Centre's HadRM3 RCM A2c configuration (medium-high GHG emissions scenario) were also supplied by the BADC.

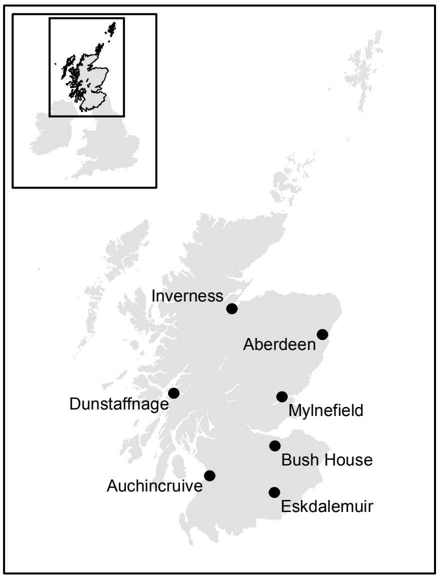

Fig. 1. Sites in Scotland where agro-metrics were estimated.

Meteorological summaries (mean monthly temperature and rainfall) and agro-meteorological metrics (agro-metrics) were produced using observed weather data and RCM data that had been evaluated and downscaled according to Rivington *et al.* (2008a,b). A description of the agro-metrics and methods to estimate them is available in Matthews *et al.* (2008). The agro-metrics implemented in the framework were grouped by type:

- Date: when the first or last incidence of a phenomenon occurs.
- Count: the number of days on which a criterion is met.
- The accumulation of a variable above or below a threshold value.
- Indices, where an index value is calculated and compared against a standard.

The soil moisture metrics are derived using a simple soil moisture balance model, (http://www.macaulay.ac.uk/LADSS/soil_water_budget.html). The agro-metrics were chosen to provide a sufficient range of indicator values determined by the weather that were important for land managers. They are not restricted in their application to particular locations and have an open-ended structure for re-definition, customisation and development.

The process of data provision, agro-metric generation and motivation of the research team was explained (as the transparency of the process builds credibility), and the agro-metrics themselves were presented to stakeholders for evaluation and as a medium to promote discussion during a series of workshops at each case study site (relevance improving salience). Agro-metrics were given to pairs of stakeholders as A3 paper charts, rather than overhead projections, as this encouraged greater participation and discussion. Presentation of the agro-metrics can be either as: single metric per site, multiple metrics per site; or single metric at multiple sites. However, for the workshops, single or combined metrics were presented for the particular site.

Results

A full set of results and the actual graphical format of representation of the agro-metrics for many of the sites where workshops were held are available at: http://www.macaulay.ac.uk/LADSS/agromet_cc_indicators.html and http://www.macaulay.ac.uk/LADSS/comm_cc_consequences.html. Presented here are summaries of some of the agro-metrics for 7 sites, comparing the value derived from observed weather data (1960–90) with that from the HadRM3 A2c scenario estimates for 2070–2100. Table 1 shows that the start of growing season is projected to occur earlier in the future, on average by 36 days, and end later, by 17 days. Similarly the last spring air frost occurs 39 days earlier and the first autumn air frost occurs 37 days later in the future. The number of days when air and grass frosts occur decreases by 35 and 73 days, respectively, in the future scenario. However, the date for the end of field capacity is not projected to change much, occurring only 7 days earlier than under the past climate. Conversely, the start of field capacity in the autumn occurs 25 days later. The maximum soil moisture deficit is estimated to increase (become drier) by on average 16.6 mm, with the date this is reached occurring 27 days later. The difference between a longer growing season but with potentially restricted access due to wet soil conditions results in a discrepancy between growing season length and the access period length, the later increasing by 24 days compared to the 58 days for the growing season.

Fig. 2. shows the difference between sites for a selection of the agro-metrics. Again here the relatively small change between sites for the end of field capacity is apparent. The start of growing season and Tsum200 (thermal time accumulation to 200°C) indicate that field operations could commence earlier. Eskdalemuir shows the largest potential change in growing season, starting 55 days earlier, but the west coast sites of Auchincruive and Dunstaffnage have a relatively small change, reflecting the relatively early start they already experience.

Results from the soil water budget model indicate that the driest years will be substantially more severe than those that occurred in the period 1960–1990. Fig. 3. shows that the period when plants are water stressed is considerably longer, with soils becoming much drier. The frequency when

Table 1. *Changes in agro-meteorological metric values between 1960–90 and 2070–2100 periods for all sites*

Type	Metric / Indicator	Inve	Abd	Myln	Sites Bush	Esk	Auch	Duns	Mean
Date	Growing Season Start	-10	-48	-48	-51	-55	-20	-18	-36
	TSum200	-16	-20	-20	-22	-27	-16	-15	-19
	End of Field Capacity	-10	-12	-5	-3	-10	-6	-5	-7
	Last Air Frost (Spring)	-32	-38	-44	-41	-45	-33	-39	-39
	Last Grass Frost (Spring)	-17	-35	-31	-30	-21	-25	-18	-25
	Date of Maximum SMD	40	21	27	39	28	24	13	27
	First Grass Frost (Autumn)	31	62	55	72	79	54	55	58
	First Air Frost (Autumn)	24	41	29	38	64	38	25	37
	Return to Field Capacity	38	27	27	33	14	22	14	25
	Growing Season End	13	18	12	18	31	10	14	17
Day Counts	Air Frost	-29	-46	-34	-41	-58	-24	-17	-35
	Grass Frost	-73	-68	-74	-77	-72	-74	-73	-73
	Growing Season Range	31	74	49	62	82	37	36	53
	Growing Season Length	57	66	60	61	66	50	48	58
	Access Period Range	47	22	24	33	13	37	16	27
	Access Period Length	48	13	18	33	15	37	6	24
	Dry	233	25	29	22	21	19	7	22
	Wet	-37	-25	-29	-22	-20	-18	-7	-23
	Plant Heat Stress	15	5	14	11	11	11	14	12
Degree Days	Accumulated Frost	67	99	81	106	185	63	28	90
	Growing Day Degrees	874	765	804	810	755	835	930	825
	Heating Day Degrees	-823	-872	-840	-910	-950	-754	-820	-853
	Excess Winter Rainfall	-41	51	-7	25	-29	45	318	51.75
	Wettest week amount	20	20	5	-1	7	3	40	13.49
	Maximum Soil Moisture Deficit	28	2	11	27	22	16	11	16.57
Waves	Heatwave	3	1	2	3	0	1	2	1.71
	Cold Spell	-1	-1	0	0	-1	1	2	0.00
	Dry spell	2	1	2	4	0	3	-3	1.21
	Wet spell	-3	-1	0	-3	-4	-9	-4	-3.43
Indices	Precipitation Intensity	1.50	1.30	1.00	0.90	0.40	0.60	1.10	0.97
	Rainfall Seasonality	0/23	-0.20	0.31	0.33	0.22	0.26	0.19	0.25
	Rainfall Hetrogeneity	-79	109	62	126	121	66	408	116.08

such conditions occur also increases, varying between sites. At Mylnefield, soil moisture levels suggest crops became water stressed in 2 out of 10 years, but this increases to 8 out of 10 years in the future. The lateness and rapidity of recharge to field capacity in Fig. 3 was also observed for other dry years at other sites.

During the workshops the agro-metrics stimulated stakeholders to deliberate on what perceived climate changes they had already experienced, what the potential future impacts might be and what adaptation steps they could take to cope with them. The workshops enabled the best form and combination of metrics to be identified, importantly achieving the aims of support provision to the stakeholders and empowering them with the opportunity to contribute to the agro-metric

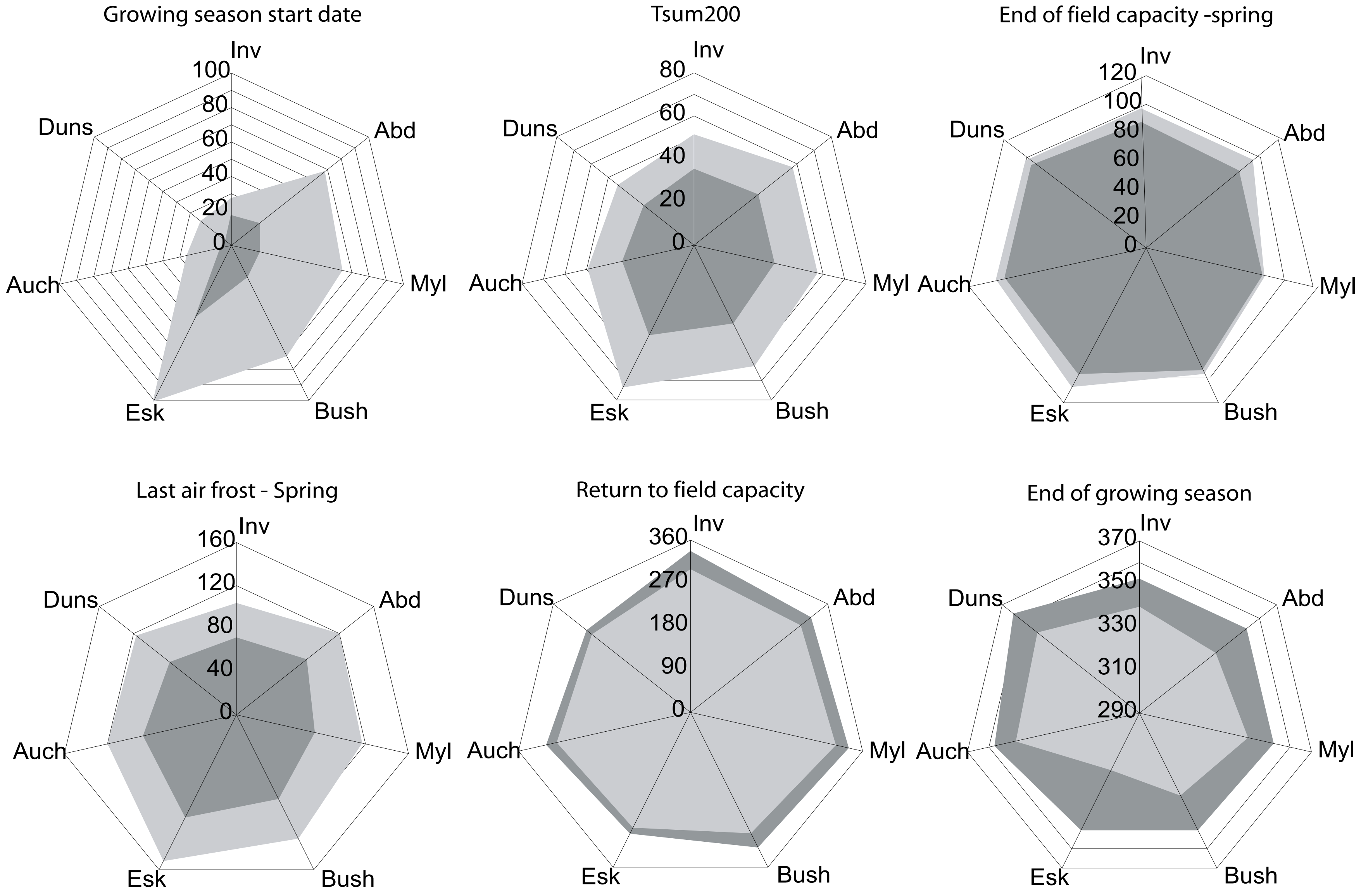

Fig. 2. Single agro-meteorological metrics (day of year) polar plots for 1960-1990 (light grey) and 2070–2100 (dark grey) periods. Site abbreviations correspond to first letters of site name - see Fig. 1.

refinement and giving a sense of ownership of the climate change issue (achieving legitimacy). Whilst stakeholders could discern possible effects of climate change directly from meteorological summaries (i.e. mean monthly temperature), the use of agro-metrics enhanced their ability to generate specific adaptation strategies. Metrics of greatest interest were the distribution of growing season and access days, potential for increased soil moisture deficits, reductions in the period of frost and the potential for plant heat stress.

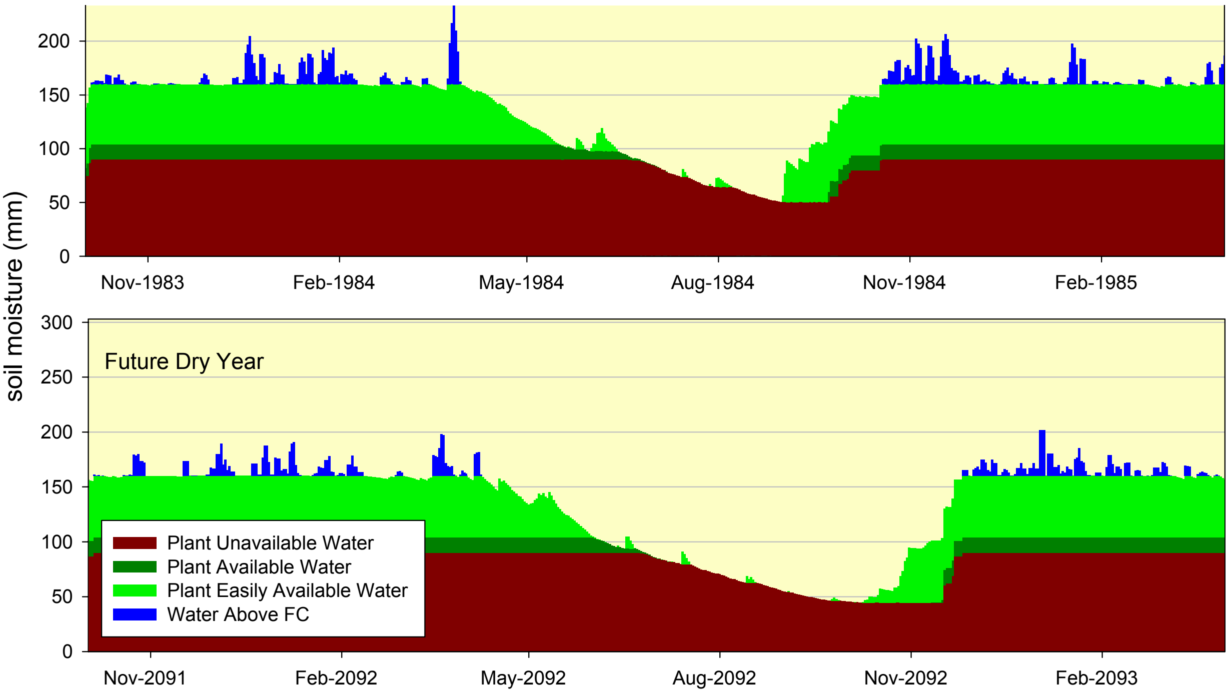

Fig. 3. Soil moisture estimates for Mylnefield from soil water balance model: driest year from 1960–90 (top) and 2070–2100 (bottom).

Discussion

The agro-metrics were particularly effective in encouraging stakeholders to consider both impacts and adaptation. They were willing and able to engage with the more complex agro-metrics where they could see their potential benefits as decision making indicators. By presenting time series of the soil water balance metrics for example, it was possible to identify particular iconic events in the historical dataset and to make comparisons with the future scenarios both in quantitative and qualitative terms. The outputs from these more complex analyses that integrate several weather variables also stimulated the stakeholders to question further the nature of the changes in patterns of weather and thus close the circle from impacts and adaptations to the climate drivers and their causes.

Future climate and soil water balances show that decision makers will have to adapt to new conditions that appear on the surface to be favourable to agriculture in Scotland, but which will also have greater levels of risks associated with water restricted plant growth. The magnitude and direction of changes indicated that a substantial readjustment will be required in land management. Changes in land capability for agriculture and forestry, as indicated here and elsewhere (i.e. Brown *et al.*, 2008) suggest a significant change in land use in the future. The growing season may start earlier and end later in the year, but the date of the end of field capacity in spring remains the same. Access to land at the start of the growing season will thus be restricted. Soil moisture deficits increase, with longer periods when soil moisture is at levels that restrict crop growth. Milder winters and earlier frost are likely to have a positive impact on pests and pathogen survival and dispersal, increasing the risks to crops and livestock.

Such conditions may necessitate changes to key aspects of land management, such as types of crops grown, livestock systems used and timing of management operations. Overall, a changing climate presents opportunities for agriculture in temperate locations such as Scotland, but also numerous threats. In order to take advantage of the opportunities and negate the threats, greater clarity is needed of the probability of future conditions. There are however consequences not just for agriculture and forestry, but also for water management, soil process (e.g. carbon storage) and biodiversity.

Acknowledgements

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References

Brown I, Towers W, Rivington M, Black H. 2008. The influence of climate change on agricultural land-use potential: adapting and updating a land capability system. *Climate Research* **37**:43–57.

Matthews K B, Rivington M, Buchan K, Miller D, Bellocchi G. 2008. Characterising and communicating the agro-meteorological implications of climate change scenarios to land management stakeholders. *Climate Research* **37**:59–75.

Rivington M, Miller D, Matthews K B, Russell G, Buchan K. 2008a. Evaluating Regional Climate Model estimates against site-specific observed data in the UK. *Climatic Change* **88**(2):157–185.

Rivington M, Miller D, Matthews K, Russell G, Bellocchi G, Buchan K. 2008b. Downscaling regional climate model estimates of daily precipitation, temperature and solar radiation. *Climate Research* **35**:181–202.