Expl Agric. (1997), volume 33, pp. 291–299
Printed in Great Britain

MODELLING THE LONG-TERM YIELD EFFECTS OF COMPENSATION IN INTERCROPPING USING DATA FROM A FIELD EXPERIMENT

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(Accepted 16 January 1997)

SUMMARY

Employing data from an intercropping field experiment which measured the yields achieved by a surviving crop when the other crop failed at 0, 6 or 10 weeks after sowing, the use of a simple computer model to study the long-term yield effects of compensation in intercropping is described. Assuming different probabilities of crop failure for one or both of the crops, the model provided a comparison of long-term intercrop and sole crop yields from intercropping systems of oat–mustard, mustard–bean and oat–bean. It showed that if failure was restricted to only one of the crop species, intercropping suffered less yield decline with increasing probability of failure than did sole cropping only if there was a sufficiently high yield of the surviving crop. However, in the more realistic situation where each crop was subjected to the possibility of failure, this decline in yield was less in intercropping than sole cropping for all three combinations because poor yields when one species was the surviving crop were offset by good yields when the other species was the survivor. Mustard–oat and mustard–bean gave no yield advantage in the absence of failure (Land Equivalent Ratios less than 1) but they outyielded sole cropping for failure probabilities above about 5% and 15%, respectively. All combinations gave large intercropping advantages at high probabilities of failure. Oat–bean always had a strong yield advantage, even with no failure.

The model is very simplistic but it illustrates the potential for modelling long-term effects from field data. Limitations of the model are discussed and it is emphasized that these can be overcome if information to make the underlying assumptions more realistic is available.

INTRODUCTION

By examining relatively large bodies of data, several studies have provided evidence of intercropping systems producing greater yield stability than sole cropping (Francis and Sanders, 1978 for maize–beans; Baker, 1980 for cereals–groundnut; Rao and Willey, 1980 for sorghum–pigeonpea; Rao and Morgado, 1984 for maize–beans). The data were from different experiments or locations over a limited number of years, but the results are commonly taken as an indication of possible long-term stability over many years. Rao and Willey (1980) suggested a number of mechanisms that may bring about this improved stability from intercropping but the above studies were able to indicate only the combined effect of whichever of these might have been involved. However, one mechanism referred to in all the studies was that of compensation, which is usually

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described as the increased growth possible by the surviving crop if one crop fails. Indeed, it is generally believed that compensation is the mechanism most likely to contribute to improved stability in intercropping (Francis, 1989).

Using data from a field experiment, this paper describes a simple computer model that provides an assessment of the contribution that the compensation mechanism can make to long-term yield effects assuming different times and probabilities of failure. A measure of compensation was obtained in the field experiment (Nasir, 1992) by simulating failure of one component crop at different stages of growth and measuring the final yield of the surviving crop. It is this final yield of the surviving crop that determines whether intercropping is a better alternative than sole cropping in the event of a crop failure, and therefore whether it provides greater long-term stability. Strictly speaking, however, this final yield is the result both of any increased growth after failure (the true compensation effect) and of any competitive interaction with the other crop prior to failure. While some distinction can be made between these two effects in the results presented later, this distinction is not usually possible; for example, it is not possible with the yield data used in the studies referred to above. It seems sensible, therefore, to regard both effects, whether they can be distinguished or not, as being part of what can be broadly termed the compensation mechanism, and this is the approach adopted here.

MATERIALS AND METHODS

Field experiment

The field experiment, conducted at the University of East Anglia, Norwich, was reported in full by Nasir (1992). Experimental details are reported here as background information on the data used in the model. Crop treatments comprised all two-crop combinations of mustard (*Brassica nigra*), oats (*Avena sativa*), and field beans (*Vicia faba*) with sole crops of each. Early failure was simulated by not sowing one of the components, and medium or late failure was simulated by removing one component at six or ten weeks after sowing respectively. A ‘control’ intercrop treatment for each combination was not subjected to any simulated failure. Crops were sown on 23 April and harvested on 14–15 August (113 and 114 days after sowing). The site had received phosphorus and potassium at 40 kg P_2O_5 and 40 kg K_2O ha^{-1} in the previous autumn and nitrogen at 60 kg N ha^{-1} was applied at sowing. Crops were sown in rows (30 cm spacing), and the intercrops were 50:50 ‘replacement’ treatments in which alternate rows of each crop had the same within-row spacing as their sole crops. There were four randomized blocks with a plot size of 1.2 m × 8 m (12 rows). Yields were determined from the central eight rows of each plot.

Computer model

The model was designed to provide a long-term evaluation of the effects of compensation in the event of crop failure. Mean biomass yields (g m^{-2}) measured over all replicates in the field experiment were used in the model, all intercropping yields being expressed as a proportion of full sole crop yields (Table 1).

The intention was to examine the performance of a given intercrop combination when either or both of the components could fail. The two main decisions made in the model were whether a component crop fails and, if the crop has failed, the time of failure.

The model assumed a range of failure probabilities: 0 (no failure), 25% (one run in four), 50% (one run in two), 75% (three runs out of four) and 100% (failure every run of the model). For a given component the model determined randomly for each run of the model whether failure occurred (yes or no), taking into account the probability of failure. If failure occurred, the model determined randomly the time of failure, which was limited to zero, six or ten weeks after sowing as in the field experiment. For any given analysis (for example, a given probability of failure for a specific crop), the model was run 500 times, generating 500 sets of biomass data. Each run of the model was treated independently and, as simulated in the field experiment, crop failure was assumed to be complete with no possibility of partial failure. For all situations the field experiment provided the appropriate biomass yields, either for the surviving crop when failure occurred, or for both crops if no failure occurred.

Two versions of the model were produced. In the first, only one of the two crops could fail. For example, in the mustard–oat combination the model was run 500 times initially with only the possibility of mustard failing and then it was run 500 times again with only oat able to fail. This version of the model was intended to show long-term effects of species differences in compensation. In the second version a more realistic situation was provided by allowing both crops to fail. Both were subjected to the same probability of failure but the failure of each was

Table 1. *Biomass yields for sole crops and intercrops of mustard, oats and beans, and the yield of the surviving crop in intercrops where one crop fails at zero (early), six (medium) or ten (late) weeks after sowing. Yields are means of four replicates from the field experiment reported by Nasir (1992). Figures in parentheses are the 95% confidence limits*

Intercrop	Sole crop yield ($g\ m^{-2}$)	Intercrop – no failure (% of sole crop yield)	Yield of surviving crop in intercrops where other crop fails (% of sole crop yield)		
			Early failure	Medium failure	Late failure
Mustard–oat					
Mustard	825.0	61 (10)	89 (6)	81 (4)	72 (6)
Oats	612.5	34 (10)	112 (11)	86 (6)	46 (4)
Mustard–bean					
Mustard	825.0	69 (12)	89 (6)	93 (10)	81 (11)
Beans	643.8	21 (2)	78 (4)	71 (10)	0 (0)
Oat–bean					
Oats	612.5	102 (2)	112 (11)	113 (10)	115 (4)
Beans	643.8	37 (22)	78 (4)	67 (7)	31 (4)

independent of the other. Therefore, it was possible in a single event for both crops to fail. The timing of the failure was also determined independently for each crop. In this version, because each crop was subjected to the given probability of failure, the total number of failures was higher than in the first version.

Expected yields from a 50:50 sole crop system, in which unit area is divided equally between the two sole crops and in which crops were subjected to the same probabilities of failure as the intercrops, were also calculated for comparison. This system indicates the yields that would be achieved by separate sole crops subject to the same failures as the intercrops but without the possibility of compensation.

RESULTS

The results of the model, as average long-term yields over the 500 runs, are shown in Fig. 1 and 2. At each failure probability, intercropping results are presented as yields for the individual crops (the histograms) and as total yield obtained by adding the yields of both crops (unbroken line). Similarly, a total yield for sole cropping is given by adding the individual crop yields for the 50:50 sole crop system (broken line).

For all three intercropping combinations, when only one of the crops is subjected to failure (Version 1 of the model, Fig. 1a–f) it can be seen, as expected, that the long-term yield of that crop declines as the probability of failure increases. Conversely, the long-term yield of the surviving crop increases as the probability of failure increases. This increase in yield of the surviving crop indicates that some compensation is occurring for each crop in all three combinations and that the effect of this on long-term yields increases if failure occurs more frequently.

The long-term total yields of intercropping when only one crop is subjected to failure (Fig. 1, unbroken lines) show that, as the probability of failure increases, the extent to which the increasing yield of the surviving crop is able to compensate for the declining yield of the failing one differs for particular crops and crop combinations. For the mustard–oat combination, there is virtually complete compensation if mustard fails so total intercropping yield is maintained at a more or less constant level whatever the degree of failure (Fig. 1b). If oat fails in this combination compensation is not quite complete so there is a slight decline in total intercropping yield with increasing probability of failure (Fig. 1a).

In the absence of any failure in this mustard–oat combination, the total intercropping yield is slightly lower than the total yield of the 50:50 sole crop system (Fig. 1a and b); in the field experiment the Land Equivalent Ratio (LER) for this system was in fact only 0.95. However, as the probability of failure increases, the yield of the 50:50 sole crop system declines in direct proportion to the degree of failure (because no compensation is possible in this system) and it becomes progressively lower than the total intercropping yield. Thus, even though this mustard–oat intercrop offers no advantage in the absence of failure, the effect of compensation enables it to outyield the sole crop system when the probability of

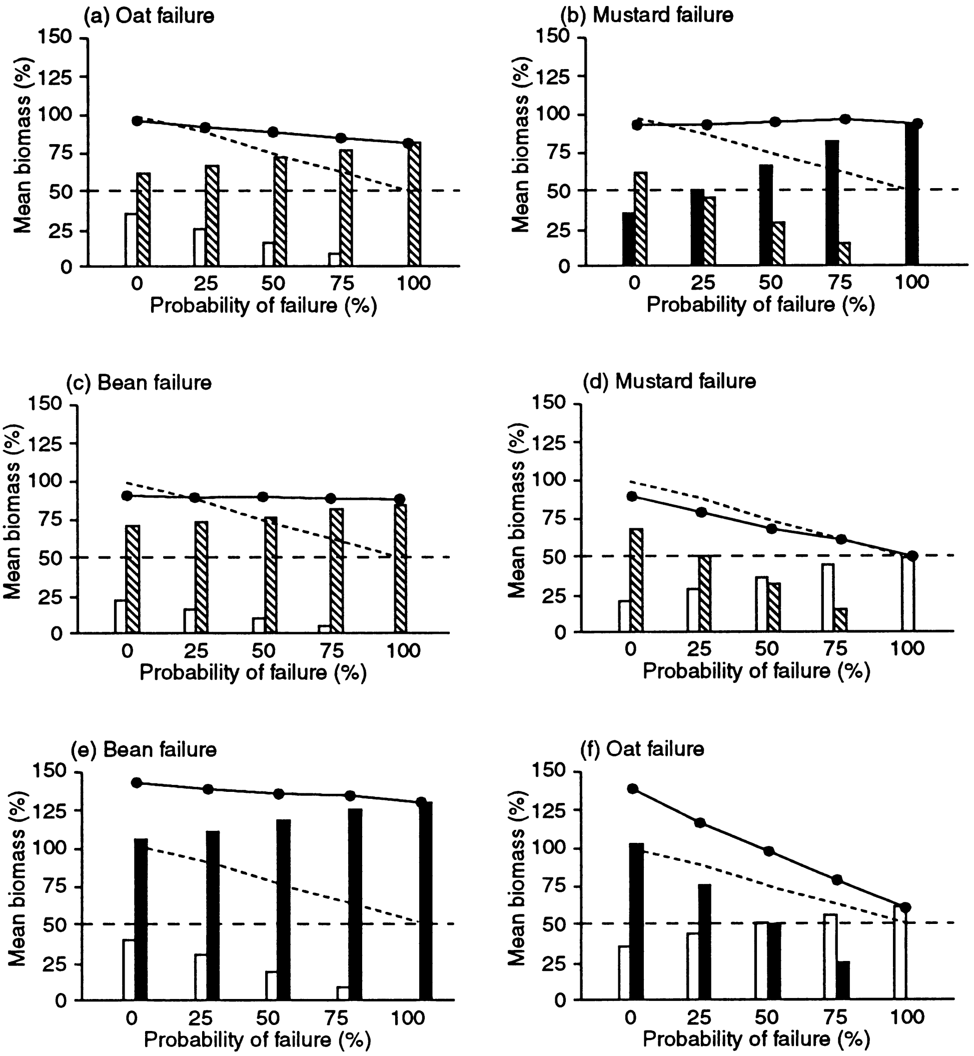


Fig. 1. Mean biomass yield for each crop: oat, ■, mustard, ▨, and bean, ☐, (as a percentage of the equivalent sole crop yield) generated by 500 runs of a model for each crop in intercrops of mustard–oat (a and b), mustard–bean (c and d) and oat–bean (e and f), with one of the crop species in each system subjected to different probabilities of failure. Total intercrop yield (-●-) and total sole crop yield (......) from a 50:50 sole crop system where the area is divided equally between the two sole crops are also shown.

failure rises above about 10–15% and it becomes increasingly advantageous as failure becomes more frequent.

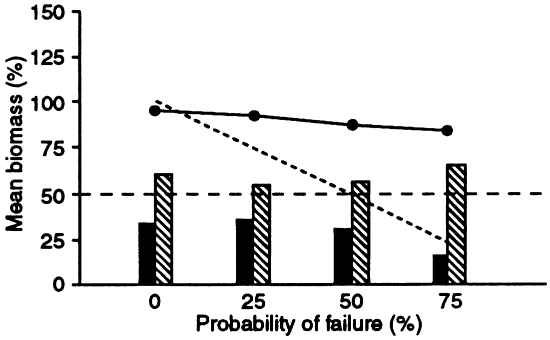
In the mustard–bean combination, for bean failure (Fig. 1c) the yield patterns are very similar to those of the mustard–oat above. Compensation by the mustard fully offsets the loss in yield of the beans and total intercropping yield is therefore maintained for any probability of failure. And although this combination is again lower yielding than the 50:50 sole crop system in the absence of failure (LER 0.91

in the field experiment), it begins to outyield sole cropping at about 20–25% bean failure and becomes increasingly advantageous with more frequent failures. If mustard fails in this combination the long-term effects are quite different (Fig. 1d). Although there is some compensation by the surviving beans, as seen by the increase in yield of this crop with increase in probability of failure, this does not compensate for the loss in mustard yield and total intercropping yield declines markedly as failure becomes more frequent. This decline in total intercropping yield is similar to the decline in total yield of the 50:50 sole crop system and so, if it is mustard that fails, intercropping never outyields sole cropping.

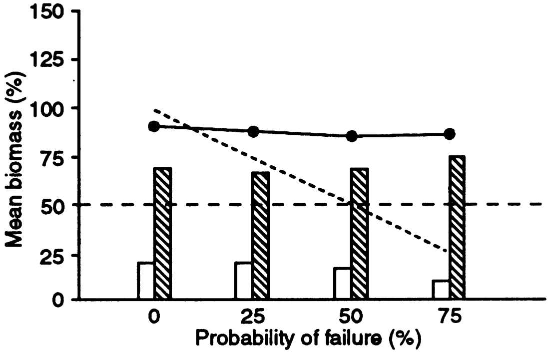
This absence of any intercropping advantage even at the highest levels of mustard failure is essentially because the long-term average yield of the surviving beans is low. This low bean yield cannot be attributed entirely to insufficient compensation in the strict sense (that is, insufficient increase in bean yield following mustard failure). A further factor was that beans were strongly suppressed by the more competitive mustard (in the intercrop with no failure bean yield was only 21% of a full sole crop) and so compensation for the six- and ten-week mustard failures had to occur from a suppressed growth of beans. In fact compensation was quite good following the six-week failure, final bean yield being 71% of a full sole crop. But for the ten-week failure no bean yield was recorded because this crop lodged badly following removal of the mustard (Table 1). Undoubtedly this nil yield of beans for the ten-week failure of mustard was a key factor contributing to the low long-term average yield of this crop when some probability of failure was assumed.

The oat–bean intercrop differed from the other two combinations in that it was much higher yielding than sole cropping even in the absence of failure (LER = 1.4). If beans failed there was almost full compensation from the oats so total intercropping yield declined only slightly with increased probability of failure (Fig. 1e). The oats were clearly able to make use of the increase in row spacing resulting from the loss of bean rows, even if the bean failure was late (Table 1). This resulted in the advantage for intercropping increasing progressively as the yield of the 50:50 sole crop system declined in proportion to the degree of failure. With oat failure, compensation by the beans did not offset loss in oat yield and total intercropping yield declined markedly with increasing probability of failure (Fig. 1f). As in the mustard–bean combination, a poor average yield for the surviving beans was again due partly to some suppression by the other crop prior to failure; and again there was a particularly low yield of beans (31%) when oats failed late. However, although this poor performance of the surviving beans resulted in total intercropping yield declining more rapidly than the 50:50 sole crop yield, some intercropping advantage was still maintained even at the highest level of failure.

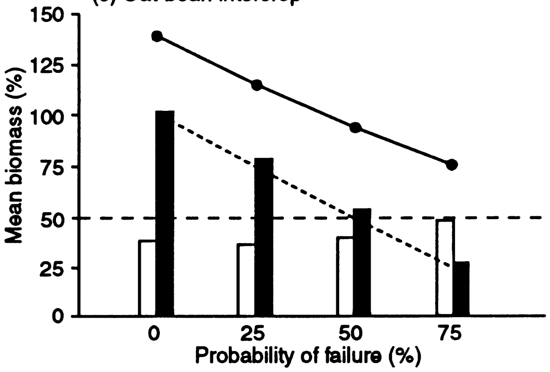
Fig. 2 presents what is likely to be a more realistic situation in practice, where both crops can fail. For the mustard–oat combination, total intercropping yield begins to exceed sole cropping at a very low probability of failure (about 5%) and intercropping becomes increasingly advantageous as the frequency of failure



(a) Mustard-oat intercrop



(b) Mustard-bean intercrop



(c) Oat-bean intercrop

Fig. 2. Mean biomass yield for each crop: oat, ■, mustard, ▨, and bean, □, (as a percentage of equivalent sole crop yield) generated by 500 runs of a model for each crop in intercrops of mustard–oat (a), mustard–bean (b) and oat–bean (c), with both of the crop species in each system subjected to different probabilities of failure. Total intercrop yield (-●-) and total sole crop yield (......) from a 50:50 sole crop system where the area is divided equally between the two sole crops are also shown.

increases (Fig. 2a). This is to be expected, given that this was the pattern of effects seen above for the failure of either of the individual crops. A similar pattern is shown by the mustard–bean combination (Fig. 2b), despite the differences observed between the individual crops. In this combination the large advantage that was seen to develop for intercropping with increasing probability of mustard failure (Fig. 1c) outweighs the lack of any advantage if beans fail (Fig. 1d), this effect being accentuated by the fact that the mustard intercropping yields are consistently higher than those of the beans. For the oat–bean combination (Fig. 2c), total intercropping yield declines quite markedly with increasing probability of failure, an effect largely attributable to the poor performance of beans when oat fails (Fig. 1f). However, this decline is no greater than that in sole cropping yield so this intercrop combination maintains its large advantage at all levels of failure.

DISCUSSION

A limitation of the modelling was that it was based only on one year's data, obtained from a typical, small-plot field experiment. Nevertheless, the model showed clearly that in certain circumstances the compensation mechanism can make a very important contribution to the stability of intercropping systems, enabling long-term intercropping yields to be maintained at higher levels than sole cropping. The mechanism was particularly well illustrated by the mustard–oat combination where, in the event of one crop failing, each crop is able to provide good compensation and a high yield if it is the surviving crop. Though this combination is slightly lower yielding than sole cropping if there is no failure, the compensation mechanism ensures that long-term intercropping yields are higher than those of sole cropping even with a very low probability of failure (whether for only one or both the crops), and this advantage becomes very substantial at high failure levels.

Conversely, the model showed that compensation in the event of crop failure does not ensure greater long-term stability of intercropping if yields of the surviving crop are too low. This was illustrated by the beans in both the mustard–bean and oat–bean combinations. If failure is restricted to the mustard and oats in these combinations, the low yields of the surviving beans results in intercropping never outyielding sole cropping in the mustard–bean combination, and in the intercropping advantage being diminished in the oat–bean combination. However, in both these combinations, if both crops are subjected to the possibility of failure the low yield of surviving beans is offset over the long-term by good yields when the other crop is the survivor. This results in intercropping being able to maintain increasingly higher yields than sole cropping as failure becomes a more frequent occurrence. It can be concluded therefore that if in practice both crops have some occurrence of failure, which is likely to be the case, intercropping can have greater long-term stability than sole cropping, even if only one of the crops provides good compensation as the surviving crop, provided of course that this is sufficient to offset the low yields when the other crop is the survivor.

The model, as presented here, is very simplistic. It assumes complete, instantaneous failure because this was the situation simulated in the field experiment and for which data were available. In practice, failure could well be partial and gradual. Similarly, it assumed failure could only occur at zero, six or ten weeks from sowing, again because these were the field treatments for which yields were available. It would have been possible to estimate the yields for any intervening time of failure by interpolation from the field data, but this would have had little or no effect on the long-term average yields predicted by the model, so it was decided to use only actual yields.

Other, more critical limitations of the model as presented are, first, that it assumed that failure of one crop was independent of the other. In practice, failure of the two crops might well be related, for example because some environmental stress affects both of them. Second, it was assumed that there was equal likelihood of failure occurring early, medium or late, and realistically failure is likely to be associated with particular times in the growing season. Third, in Version 2 of the model the probability of failure was taken as the same for each crop, which again is unlikely in practice. However, a major reason for presenting this present model is to illustrate the potential value of the approach. For any situation in which more detailed information is available, the model could be improved easily by making the underlying assumptions more realistic.

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