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Optimum Crop Planning using Multi-Objective Differential Evolution Algorithm

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Abstract: This study presents a Multi-objective Differential Evolution Algorithm (MDEA) which is a family of Evolutionary Algorithms (EAs) that can be used to solve multi-objective constrained optimization problem. MDEA technique is adapted to crop planning in a farmland in the Vaalharts Irrigation Scheme (VIS) in South Africa. The objectives of the model are to maximize the total Net Profit (NF) in monetary terms (South African Rand, ZAR) generated on the farm by planting 4 different crops, maximize total planting area (m^2) and minimize the irrigation water use (m^3). Numerical results produce non-dominated solutions which converge to Pareto optimal fronts. From the results, the total net profit, irrigation water and planting area range from ZAR 272 390 to ZAR 1 001 900, 317 030 to 689 310 m^3 and 260 937 to 757 040 m^2, respectively. From the analysis of the results, it is suggested that the irrigation water supplied to the study area be increased to enable farmers to generate more profit. Also, the irrigation technology should be changed to water economic technology. It is found that the proposed MDEA can be used for solving crop planning problem and generate non-dominated solutions from where a farmer can select a solution that suits his particular situation.

Key words: Crop planning, multi-objective, differential evolution, Pareto fronts, constrained optimization

INTRODUCTION

Agriculture uses more than half of surface water in South Africa. Many studies have been undertaken to minimize the water use in agriculture especially irrigation water. This is has led to various irrigation techniques been proposed. Irrigation is important to agriculture in South Africa because most farmers depend solely on it. Rainfall is erratic and the country is dry with less than 500 mm rain on average annually over about two-third of her area. Farmers buy water from Department of Water Affairs and Forestry (DWAF) which manages water resources in South Africa. When water is available to a farmer, he should be able to use the scarce water judiciously. Every cubic meter of water should be accountable. As agriculture is the predominant user of most of the water resources, efficient use of water for irrigation can help in sustainable development of agriculture (Janga and Nagesh, 2008). Therefore, crops to be planted must be economical with minimal water loss during irrigation. If farmers concentrate on only economical crops, other crops may not be planted. This will make some crops to be very scarce and hence expensive. Crop planning in a water scarce environment is a serious challenge. A farmer can make more profit using less water for irrigation when crops are well planned than when they are not planned.

Under a multi-crop environment, various crops compete for the available water whenever the water available is less than the irrigation demands. In water-scarce conditions, the deficit allocation among the competing crops has significant influence on irrigation system performance (Janga and Nagesh, 2008). Irrigation planning objectives are conflicting in nature. There are many objectives that must simultaneously be satisfied not only maximization of a single objective. Therefore, crop planning is thus handled in multi-objective framework so that suitable and sustainable strategies can be developed for practical implementation (Raju *et al*., 2006). Vasan and Raju (2007) highlighted some possible improvement that can be implemented to make irrigation sustainable. They are: (1) optimum cropping pattern and reservoir operating policy that will yield optimum net benefit, (2) conjunctive use of surface and ground water to tackle spatial and temporal variation of resources and (3) integration of mathematical models and irrigation planning methodologies.

Applying optimization techniques in water resources management is not a new idea. Various techniques have been applied in an attempt to improve the efficiency of reservoir(s) operation. These techniques include Linear Programming (LP); Non-Linear Programming (NLP); Dynamic Programming (DP); Stochastic Dynamic Programming (SDP) and Heuristic Programming such as

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Genetic Algorithms (GA), Shuffled Complex Evolution, Fuzzy logic and Neural Networks etc. Some studies have reported the use of Evolutionary Algorithms (EAs) for multi-objective optimization (Croley and Rao, 1979; Kumar and Reddy, 2007; Madsen *et al*., 2006; Nagesh *et al*., 2006; Tospornsampan *et al*., 2005; Raju and Nagesh, 2004, 2006; Raju and Vasan, 2004). Some of these studies (Raju and Vasan, 2004; Nagesh *et al*., 2006; Raju and Nagesh, 2006) have reported the application of EA (Genetic Algorithm (GA), Simulated Annealing (SA), Evolutionary Strategies (ES), Particle Swarm and Ant Colony optimizations) to cropping pattern as well as irrigation planning. The studies find the algorithms effective. Comparisons of the results with other optimization techniques have also been done (Raju and Nagesh, 2004; Nagesh *et al*., 2006). It was concluded that the results obtained are similar. Differential Evolution (DE) and Linear Programming (LP) are applied to a case study of Bisalpur project in India (Raju and Vasan, 2004). The objective of the study was to determine cropping pattern which maximizes net profit. Mujumdar and Ramesh (1997) developed a short-term reservoir operation model for irrigation. The model consists of two components including an operating policy model and a crop water allocation model that were formulated using deterministic dynamic programming. Teixeira and Marino (2002) also developed a DP model to solve the problem of two reservoirs in parallel supplying water for irrigation districts. In the model, forecasted information including crop evapotranspiration, reservoir evaporation and inflows is updated, which allowed application of the model for real-time reservoir operation and generation of a more precise irrigation schedule. The DE has been used for multi-objective optimization especially in water resources with good results (Rakesh and Babu, 2005; Babu and Jehan, 2003; Reddy and Kumar, 2007; Santana-Quintero and Coello, 2005). Several studies (Deb *et al*., 2002; Xue *et al*., 2003; Rakesh and Babu, 2005; Babu *et al*., 2005; Madavan, 2002; Parsopoulos *et al*., 2004; Robic and Filipic, 2005) have proposed ways of extending DE to handle multi-objectives.

A new DE algorithm for Multi-Objective Optimization Problem (MOOP) is proposed in this study and called Multi-objective Differential Evolution Algorithm (MDEA). The DE algorithm proposed is based on the existing DE algorithm proposed by Price and Storn (1997). The difference is its implementation of multi-objectives. Though the proposed MDEA can be used on any strategy, the strategy used in this study is DE/rand/1/bin which is the most widely used of all the ten strategies of DE. DE/x/y/z indicates DE for differential evolution, x is a string which denotes the vector to be perturbed, y denotes the number of different vectors taken for perturbation of x and z is the crossover method (exp: exponential; bin: binomial).

Crop planning under water scarce condition is a mathematical optimization model. A farmer needs to know the combination of crops to plant on the available area of land using available irrigation water to maximize his profit. The model in this study is adapted to a farmland in the Vaalharts Irrigation Scheme (VIS) in South Africa.

The main objective of the study is to find the corresponding planting areas where each of the 4 crops namely, maize, groundnut, Lucerne and Pecan nuts should be planted to maximize both the total Net Profit (NF) in South African Rand (ZAR) and total planting area (m^2) when a farmer is minimizing irrigation water. The main objective of the study results in the formulation of three model objectives. The first objective is to maximize the total Net Profit (NF) in monetary terms (South African Rand, ZAR) generated by planting the 4 crops (on 771,000 m^2 of land). The second objective is to maximize the total planting area (m^2), while the third objective is to minimize the irrigation water use. The overhead costs per annum, household expenses per annum and fixed liabilities per annum on the average for the selected farm are taken from Grove (2006).

MATERIALS AND METHODS

Multi-objective Differential Evolution Algorithm (MDEA) combines the advantages of Multi-Objective Differential Evolution (MODE) proposed by Babu and Jehan (2003) and the algorithm proposed by Fan *et al*. (2006) while overcoming the shortcomings of the algorithms. In this way, MDEA runs faster with better and more Pareto optimal solutions. The description of the MDEA is as follows. The vectors are randomly generated to create initial solutions to the problem. The generated solutions are allowed to undergo mutation, crossover and selection for a number of generations. The solutions that evolve are checked for domination and the dominated solutions are removed. The selection procedure of Fan *et al*. (2006) is modified. The trial solution survives to the next generation if it is better or equal in all the objectives to the target solutions. The MDEA produces many non-dominated solutions on the Pareto front than the algorithm by Fan *et al*. (2006). Moreover, the algorithm by Fan *et al*. (2006) has not been modified to handle constraints except bound constraints. The MDEA can handle multiple constraints. If any of the constraints is violated, a high value (10^8) is added to the objective to make the solution infeasible (Deb, 2001). In this way, the solution will not be selected when compared with other solutions because of high value since the algorithm is minimizing the objectives. The unique feature of MDEA is that the domination check is performed only once on the population members in the last generation alone not in all the generations as in some other algorithms.

The crop planning optimisation problem in this study was conducted from June 2007 to December 2008 at Vaalharts Irrigation Scheme (VIS) in South Africa. The crop planning problem is solved using the proposed MDEA. The pseudo code of MDEA is presented below. The proposed MDEA methodology is summarized in the following steps.

(1) Input the required DE parameters like population size (NP), crossover constant (CR), scaling factor (F), maximum generation, number of objectives, bound constraints etc
(2) Initialize all the vector populations randomly in the limit of bound constraints
(3) Set the generation counter, g = 0
(4) Perform mutation and crossover operations on all the population members

- For each parent, select 3 distinct vectors from the current population. The selected vectors must not be selected from the parent vector
- Calculate new mutation vector, $V_i(g)$ using the expression:

$$V_i(g) = X_{i3}(g) + F^*(X_{i1}(g) - X_{i2}(g))$$

where, $X_{i,j}(g)$ is the vector j in population i of generation g.

- Perform crossover using binary crossover method because of the strategy DE/rand/1/bin used in MDEA

(5) Evaluate each member of the population and check the offspring for domination. Replace the parents with offspring if the offspring is better or equal to the parent in the objective in the next generation otherwise, the parents proceed to the next generation.
(6) Increase the generation counter, g, by 1. i.e., g = g+1 and check if $g = g_{max}$. If $g<g_{max}$, then go to step 4 above and repeat mutation, crossover and selection. If g = gmax, then go to step 7
(7) Use naïve and slow method (Deb, 2001) of removing the dominated solutions in the last generation. In naïve and slow method, each solution is compared with every other solution in the population to check if it is dominated by any solution in the population. If the solution is found to be dominated by any solution, it means that there exists at least one solution in the population which is better than it in all the objectives. Hence, the solution cannot belong to the non-dominated set
(8) Output the non-dominated solutions

The Pseudo code for multi-objective differential evolution algorithm (MDEA)

```
*Initialize the values of D (number of parameters), NP (population size), Cr
(crossover constant), F (scaling factor), k (number of objectives) and
MAXGEN(maximum generation)
*input the boundary constraints of the problem
*Initialize all the vectors of the population randomly
    For i = 1 to NP
        For j = 1 to D
                X_{i, j} = Dlower_j + random number [0, 1] * [Dupper_j-
                Dlower_j] (X = vectors)
        Next j
    Next i
*Initialize gen = 1
for gen = 1 to MAXGEN
    for i = 1 to NP
        For m = 1 to k
                Evaluate the objective values
        Next m
        Check the constraints violation
        If violated objective value = objective value + 8*10^8 (Deb, 2001)
        For j = 1 to D
            (Mutation stage)
            Select 3 different vectors for perturbation different
            from i such that i≠r1≠r2≠r3
            V_{gen, i} = X_{gen, r3} + F(X_{gen, r1} − X_{gen, r2}) (V_{gen, i}
            is the mutation vector)
            (Crossover stage)
            u_{gen,i,j} = { v_{gen,i,j}  if (rand_j ≤Cr or j = n
                          { x_{gen,i,j}  otherwise
            and n ∈{1, …,D}(u_{j,i,gen} is the trial vector)
        next j
        (Selection stage)
        Start comparing vectors U_{gen,i} and X_{gen,i}
        For m = 1 to k
            evaluate kth objective, f_k(U_{gen,i})
            If f_k(U_{gen,i}) = f_k(X_{gen,i})
                Select vector U_{gen,i}, the trial vector
                (X_{gen+1,i})= (U_{gen,i})
                go to next step
            Else
                Next m
            endif
            select X_{gen,i} the current population member for the next
            generation
            (X_{gen+1,i})= (X_{gen,i})
        next m
    next i
next gen
*remove the dominated solutions from the last generation using naïve and
slow method proposed by (Deb, 2001)
print the results
```

THE STUDY AREA

Figure 1 shows the map of the study area. The study area is a farmland in the Vaalharts Irrigation Scheme (VIS). The size of the farm is 771,000 m^2. Vaalharts irrigation

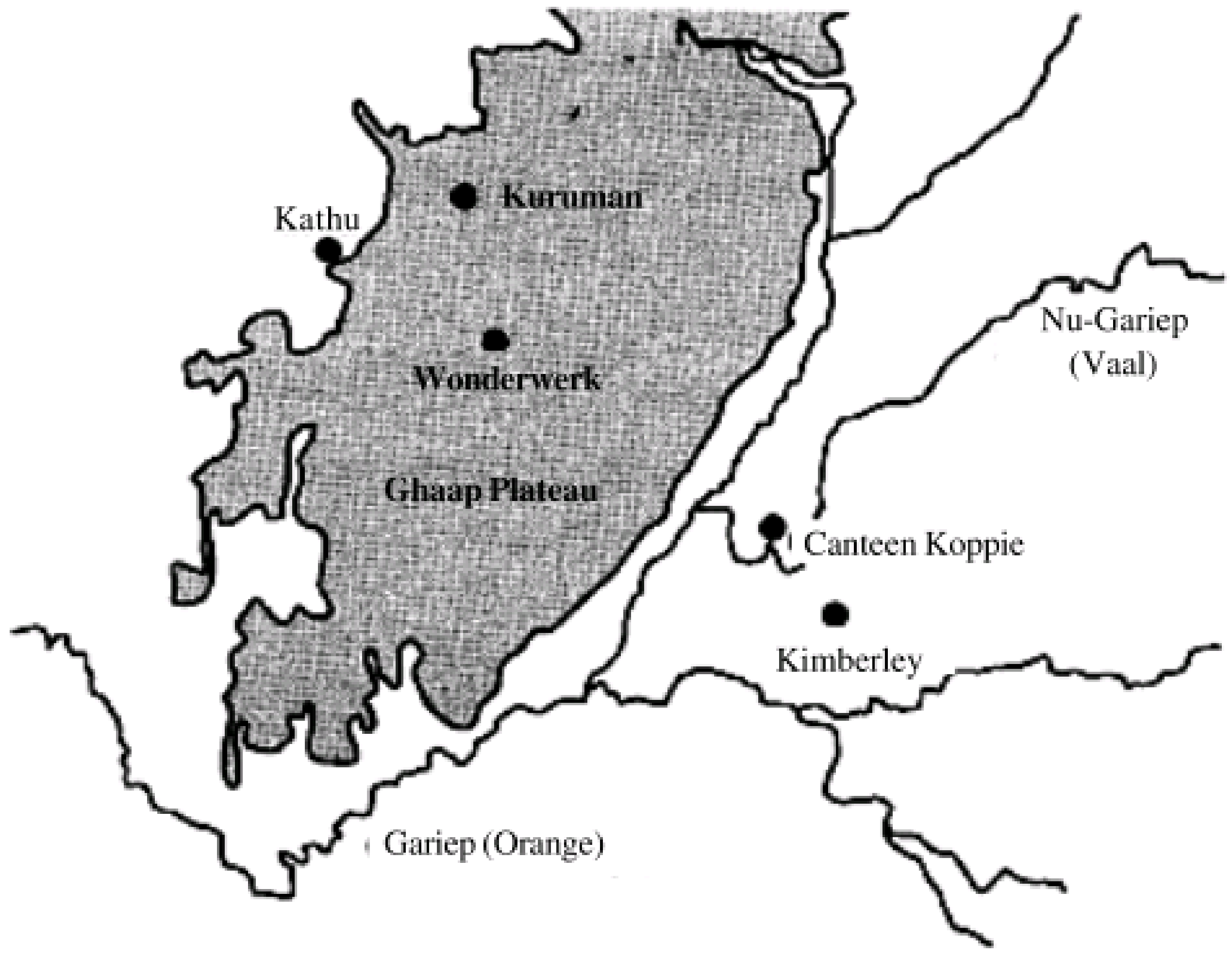

Fig. 1: The study area

scheme is in the East of Fhaap Plateau on the Northern Cape and North West province border in South Africa. VIS covers about 36 950 ha and is one of the largest areas in the world. Water is provided to some 680 farmers (Grove, 2006). The scheme is supplied with water abstracted from Vaal River at the Vaalharts weir about 8 km upstream of Warrenton. A canal is used to convey the water to the scheme.

Vaalharts Irrigation Scheme (VIS) is located in a summer rainfall area. This area battles with low, seasonal and irregular rainfall. The average rainfall is 442 mm year^{-1} (Jager, 1994). The average precipitation in summer months, October to February differs between 9.1 and 9.6 mm day^{-1} while in July precipitation is only 3.6 mm day^{-1}. The water quota for the North and West canal is 9 140 m^3/ha/annum. The total water use charge is 8.77 cents per cubic meter of water which consists of a charge of 8.24 cents for irrigation water use, a catchment management charge of 0.5 cents per cubic meter and a water research charge of 0.03 cents per cubic meter of water (Grove, 2006). The common crops grown in the area are wheat/barley, maize, groundnuts, cotton and other permanent crops like Lucerne, Pecan nuts, grapes, olives and some other fruits.

MODEL FORMULATION

The farm used as a case study has an area of 771,000 m^2 of land. It is supplied with 9 140 m^3/ha/annum of water. A farmer plants 4 different crops namely maize, groundnuts, Lucerne and Pecan nuts. Each crop is planted in at least 50,000 m^2 of land and at most in known maximum irrigated areas. These constitute the boundary constraints of the problem. The minimum planting areas ensure the availability of all the crops in the market while the maximum planting areas ensure that a farmer will not have storage or selling problem if the yields exceed the storage facilities available or if the demand is less than the supply which may make the selling price to fall. The monthly estimated gross irrigation water requirement (mm ha^{-1}) for the selected crops under flood irrigation in Vaalharts in Groove (2006) are used in this study.

The objectives are formulated as follows.

Objective 1: Maximization of total net profit:

$$\begin{aligned}\text{Max NF} &= \sum_{i=1}^{N}(TI_i \times A_i) - (A_i \times CWR_i \times C_w) - (C_{OV} + C_{HE} + C_{FL}) \\ &= \sum_{i=1}^{N} A_i\left[TI_i - (CWR_i \times C_w)\right] - (C_{OV} + C_{HE} + C_{FL})\end{aligned} \quad (1)$$

Where:

NF = Total net profit on the whole farm
N = No. of crops
TI = Total income of ith crop in ZAR/annum
A_i = Area where ith crop is grown in m^2
CWR_i = Crop water requirements for crop i
C_W = Cost for water per m^3 = 8.77cents (ZAR 0.0877)
C_{OV} = Overhead costs per annum
C_{HE} = Household expenses per annum
C_{FL} = Fixed liabilities per annum

To compute the total income (ZAR m^{-2}) from each crop, the selling price (ZAR t^{-1}) (Agriculture, 2008) of crop(i) is multiplied by yield (t ha^{-1}) (Agriculture, 2008) and divided by 10 000.

$$Ti_i\ (\text{ZAR m}^{-2}) = \text{Price}_i\ (\text{ZAR t}^{-1}) \times \text{Yield}_i\ (\text{t ha}^{-1})/10000 \quad (2)$$

Objective 2: Maximization of total planting area: Total planting area of the farm should be maximized to increase the employment in the farm.

$$\text{Max } A = \sum_{i=1}^{N} (A_i) \quad (3)$$

Objective 3: Minimization of irrigation water: The volume of water used for irrigation is minimized

$$\text{Min. Vol.} = \sum_{i=1}^{N} (CWR_i \times A_i) \quad (4)$$

The three objectives above are subjected to the following constraints:

Constraint 1: Total planting area: The sum of all the planting areas, A where the crops are grown is less than or equal to the area available for farming which should 771,000 m^2.

$$A = \sum_{i=1}^{N} (A_i) \le 771{,}000 \quad (5)$$

Constraint 2: Monthly release: The irrigation in any month cannot exceed the canal capacity. The canal capacity can be converted to volumetric units (m^3), so that it becomes compatible with releases to the canal. According to Grove (2006), water is supplied to the farm for 5½ days a week. The water available for 1 h is 150 m^3 because of the canal capacity constraint. Therefore, the maximum volume of water that may be available on the farm is:

150 m^3 h^{-1} ×24 h×5.5 days×4 weeks = 79 200 m^3 monthly

Therefore,

$$IRD_t = 79\ 200; \quad t = 1, ..., 12 \quad (6)$$

where, IRD_t is the irrigation demand in month t which is the total of crop water requirements for all the crops in month t.

Thus, the total amount of water available in a year using the canal capacity as constraints is 79 200×12 = 950,400 m^3. The model minimizes the total volume of irrigation water. The volume of water is required to be less than 950,400 m^3 per annum.

Constraint 3: Minimum and maximum planting areas: To make sure that all the crops are grown in at least 50 000 m^2 of land, each area, A_i must be equal or greater than 50,000 m^2 and less than or equal to the maximum areas for each crop.

$$50000 \le A_i \le A_{i\max}, (i = 1, 2, ..., 4) \quad (7)$$

where, A_{imax} is the maximum area where each crop should be grown. This constraint is necessary to ensure that the 4 crops are planted to prevent shortage of some of the crops in the market.

Using the pseudocode for MDEA, the algorithm was coded in MATLAB 7.0 (The MathWorks Inc., USA) executed on a 1.7 GHz, 2 GB RAM PC and used to solve the stated objectives and constraints to demonstrate MDEA's ability to solve constrained multi-objective optimization problems of crop planning. The DE parameters used are population size (NP) = 100, crossover constant (Cr) = 0.95, scaling factor (F) = 0.5 as suggested by Price and Storn (2008). The total net profit and total planting area are maximized while total irrigation water is minimized. The model is run for a maximum generation of 1000.

RESULTS AND DISCUSSION

The crop planning model is solved using MDEA. The map of the study area is shown in Fig. 1. We have 4 different types of optimisation problems solved in this model. The first optimisation is formulated with three objectives of maximising both total net profit and total planting area and minimising the irrigation water. Figure 2 shows the Pareto optimal set for the crop planning model when maximizing total net profit and total planting area and minimising irrigation water. Figure 3 shows the non-dominated solutions for maximising total net profit and total area while minimising irrigation water. The analysis of the different planting areas for maize and groundnut in the non-dominated solutions for maximising total net profit and total planting area while minimising irrigation water is shown in Fig. 4. Figure 5 shows the analysis of the different planting areas for lucerne and peacan nuts in the non-dominated solutions for maximising total net profit and total planting area while minimising irrigation water.

The results of the second optimisation problem are shown in Fig. 6 and 7. The second optimisation has two objectives of maximising total net profit and minimising irrigation water. Figure 6 shows the Pareto optimal set for the crop planning model when maximising total net profit and minimising irrigation water. Figure 7 shows the non-dominated solutions for maximising total net profit and minimising irrigation water.

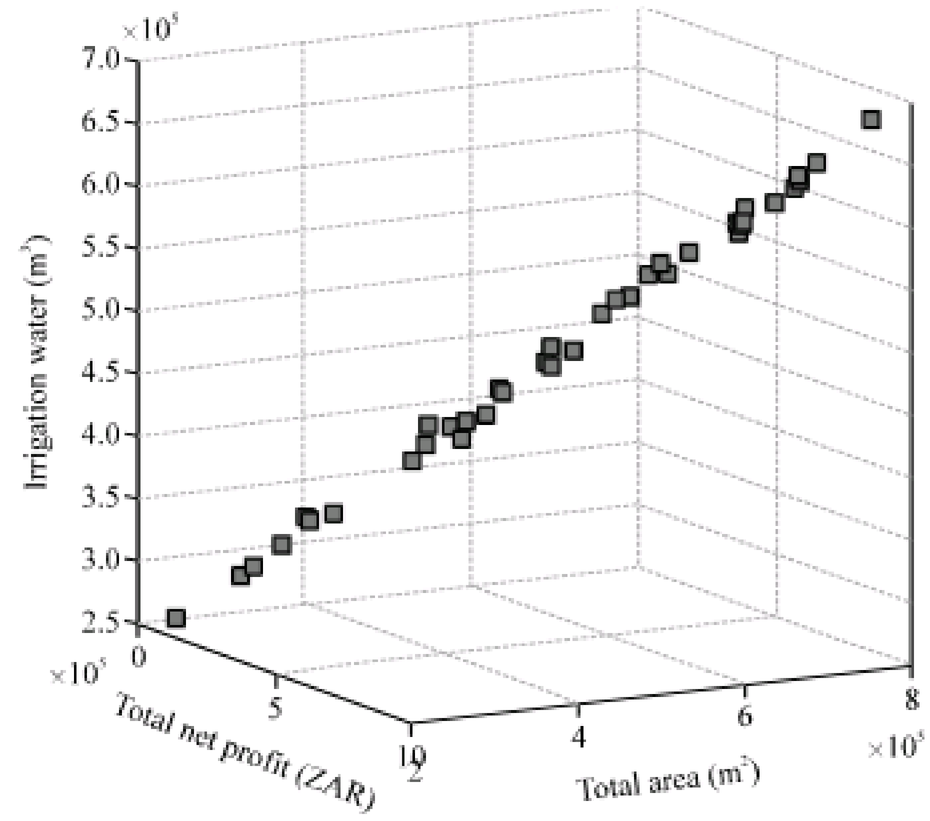

Fig. 2: Pareto optimal set for the crop planning model when maximizing total net profit and total planting area and minimizing irrigation water

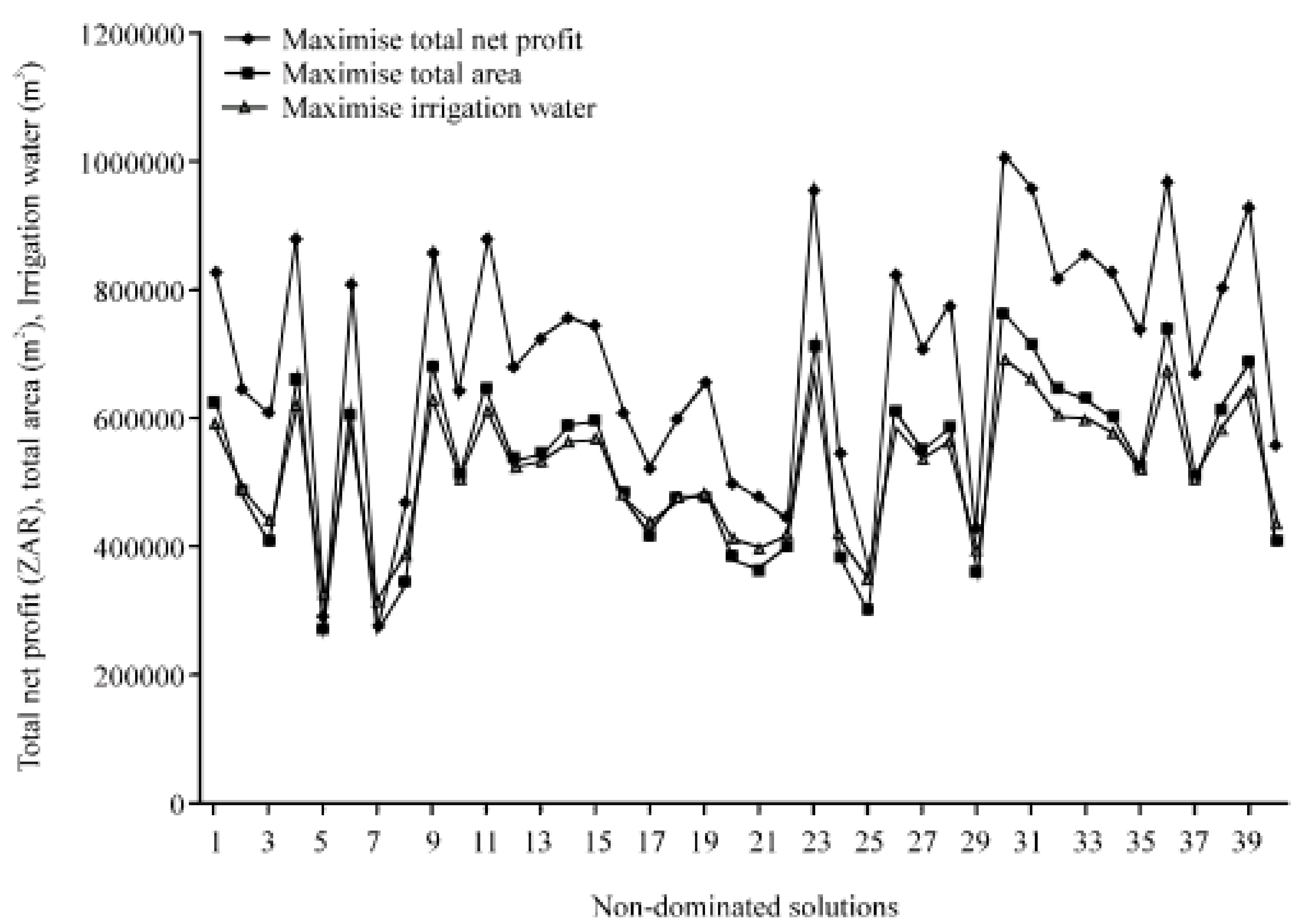

Fig. 3: The non-dominated solutions for maximising total net profit and total area while minimising irrigation water

Figure 8 and 9 show results of third optimisation problem for 2 objectives of maximising total net profit and minimising total planting area. Figure 8 shows the Pareto optimal set for the crop planning model when maximising total net profit and minimising total planting area. Figure 9 shows the non-dominated solutions for maximising total net profit and minimising total planting area.

The last optimisation also has two objectives of maximising total planting area while minimising irrigation water. Figure 10 shows the Pareto optimal set for the crop planning model when maximising total planting area and minimising irrigation water. Figure 11 shows the different total planting areas for the non-dominated solutions when maximising total area and minimising irrigation water.

It can be found from the Fig. 2 that the solutions converge to Pareto front. The solutions are also diverse on the Pareto front. The solutions provide the tradeoff between the conflicting objectives. All the solutions on the Pareto front are equally good. In the model, all the three objectives cannot be satisfied at the same time.

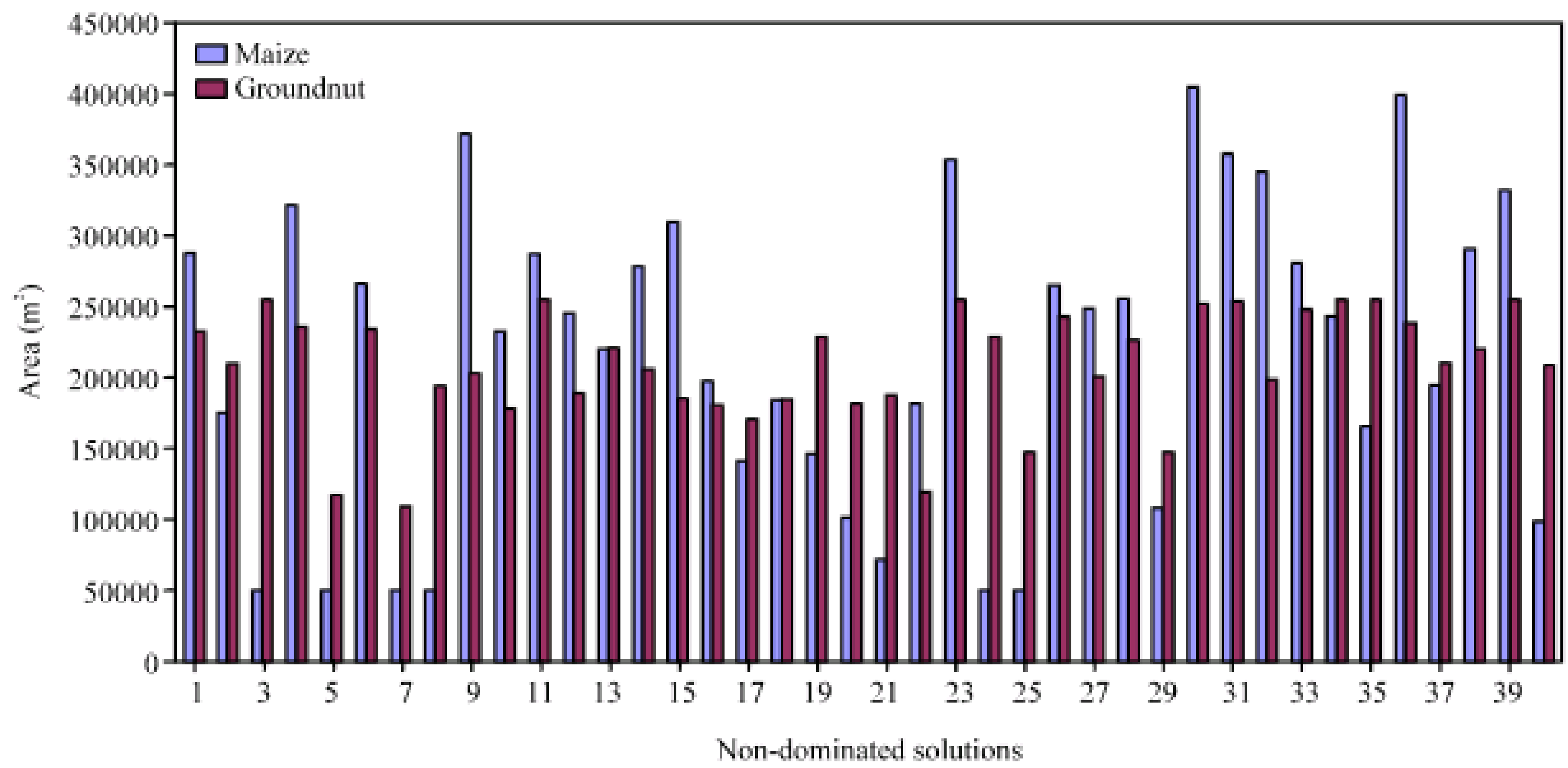

Fig. 4: Different planting areas for maize and groundnut in the non-dominated solutions for maximising total net profit and total area while minimising irrigation water

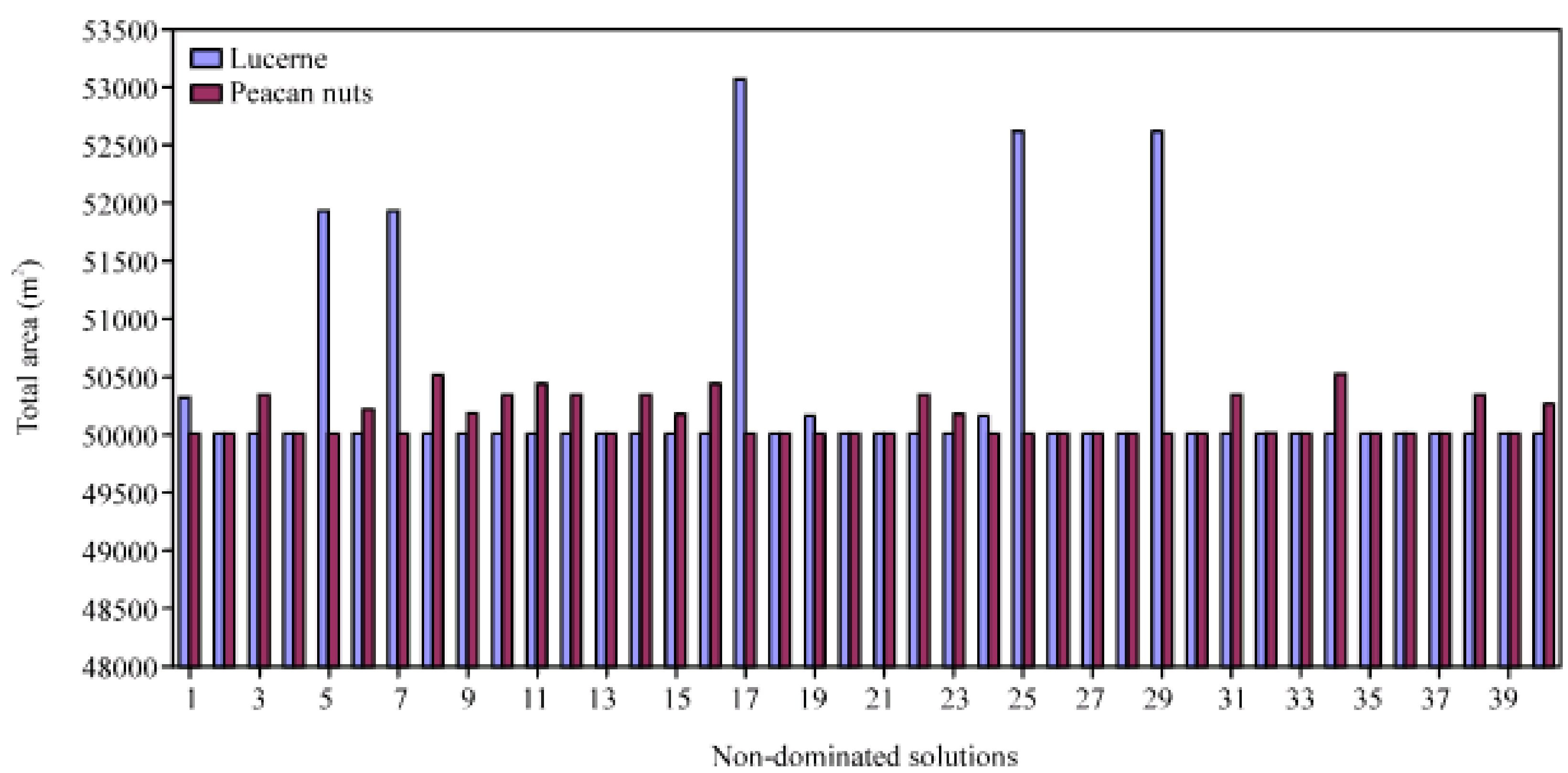

Fig. 5: Different planting areas for lucerne and pecan nuts in the non-dominated solutions for maximising total net profit and total area while minimising irrigation water

There can not be an improvement in one objective without worsening the others. In the Pareto optimal solution set, a solution is not better than the others in all the objectives. In practice, the decision-maker ultimately has to select one solution from this set for system implementation. In a multi-objective optimization, there cannot be a solution that will satisfy all the objectives but instead, there are sets of solutions in one simulation run which correspond to non-dominated solutions (Deb, 2001). It depends on a farmer to choose the best solution that suits him from the set of non-dominated solutions. The solutions are optimal in the sense that no other solution in the search space is superior to them when all the objectives are considered. The goal of multi-objective problems is to find as many Pareto-optimal solutions as possible to reveal trade-off information among different objectives (Deb, 2001). Once such solutions are obtained, higher level decision maker will be able to choose a final solution with further consideration like water availability, number of workers, equipment availability, presence or absence of groundwater to supplement irrigation water, the capital available, canal capacity, land area, market situation and available storage facilities as in the case of this study.

From the 40 non-dominated solutions in the Pareto set in Fig. 3, it can be found that the total planting area is directly proportional to irrigation water. In real situation, increase in planting area will result in increase in irrigation

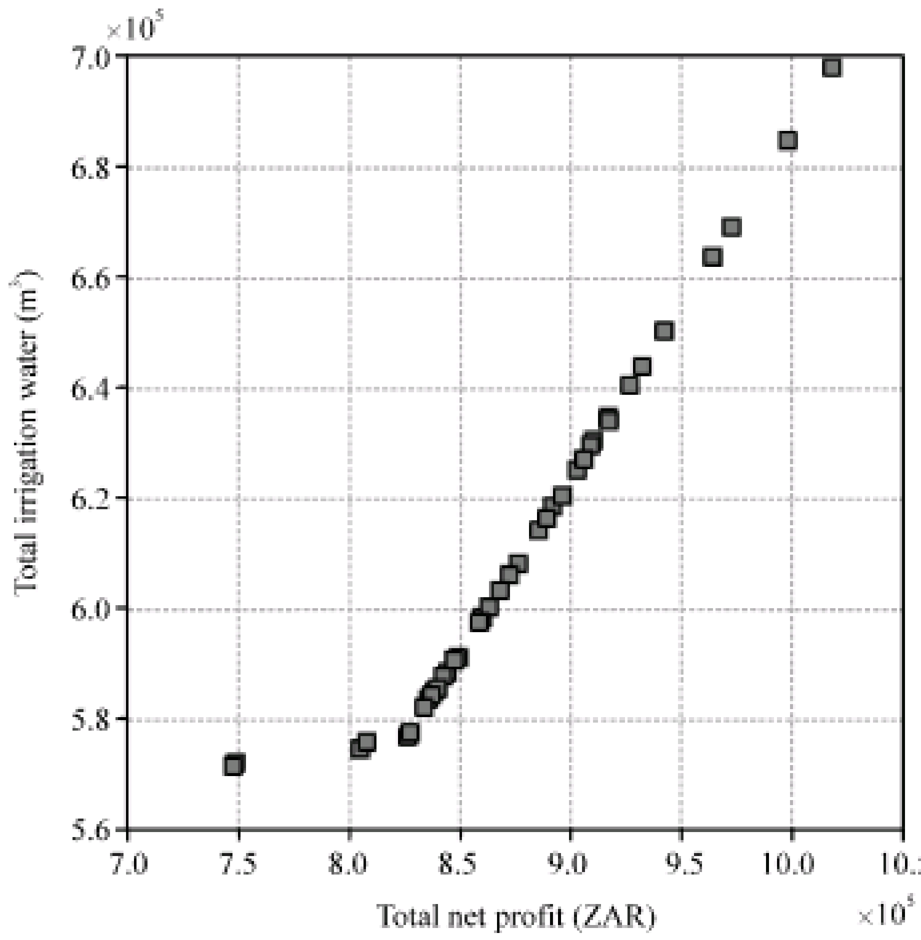

Fig. 6: Pareto optimal set for the crop planning model when maximizing total net profit and minimizing irrigation water

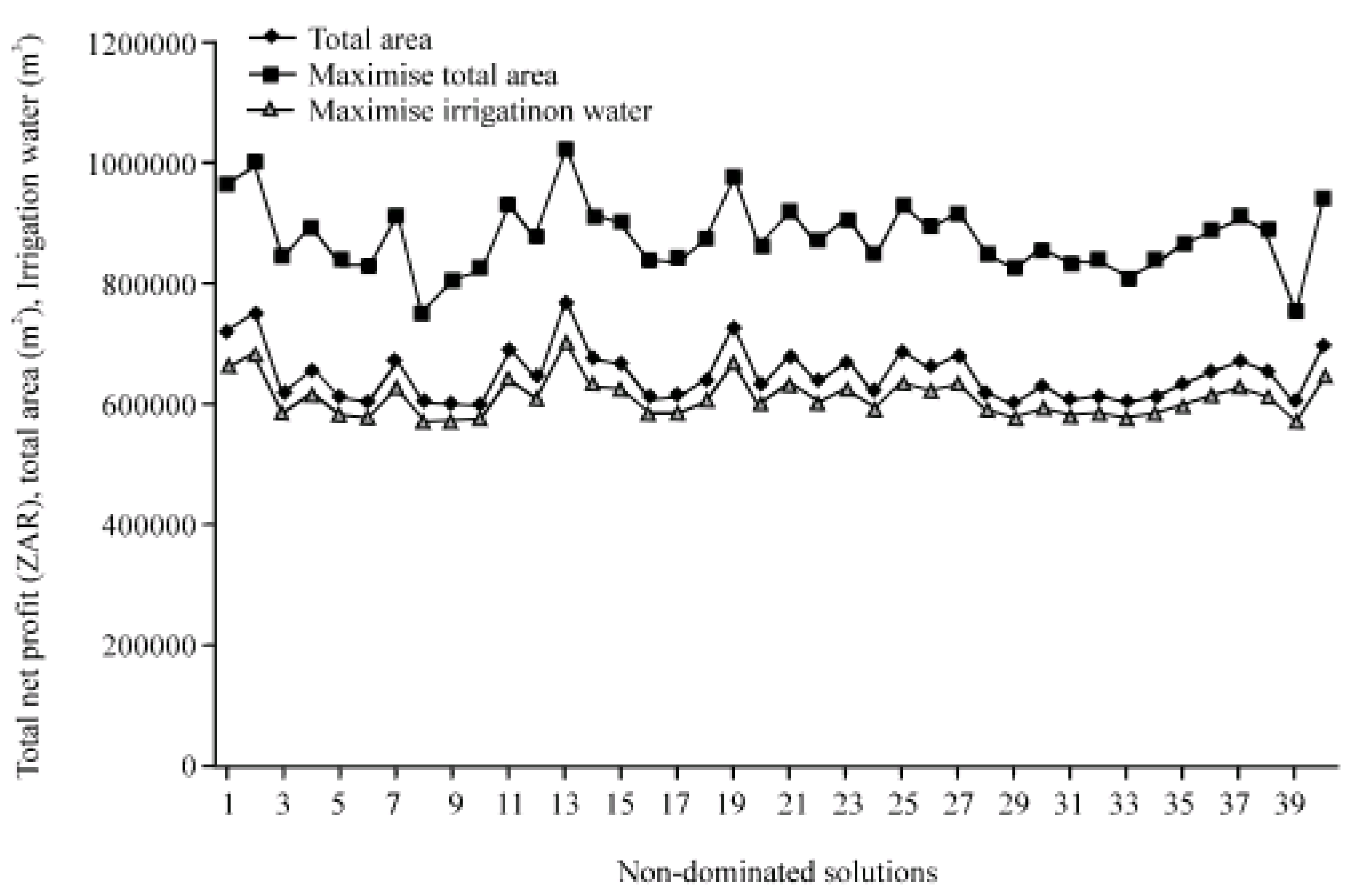

Fig. 7: The non-dominated solutions for maximising total net profit and minimising irrigation water

water that will be used. Figure 3 reveals that solution 30 is the best solution in terms of tradeoff of the 3 objectives. In the other solutions, all the points of irrigation water and total planting area nearly overlap. But, there is a high margin between the two in solution 30. Also, solution 30 produces highest total net profit of ZAR 1 001 900 of all the solutions. Therefore, solution 30 is recommended if all the other factors are the same.

It is found in Fig. 4 that maize is planted in higher planting areas than groundnut in 22 of the non-dominated solutions and groundnut has higher planting area in 16 of the solutions while both crops are equal in 2 solutions (solutions 13 and 18). It is found from the results that planting areas for maize are far higher than those of groundnut in solutions that have higher planting areas for maize. In solution 30 that is preferred, maize is planted in 405,020 m^2 which is far more than groundnut (planted in 252,020 m^2). It can be concluded that maize is more lucrative in the study area than groundnut.

In Fig. 5, Lucerne and pecan nuts are both planted in equal areas of land in 26 solutions while Lucerne is planted in 8 areas more than pecan nuts. The remaining

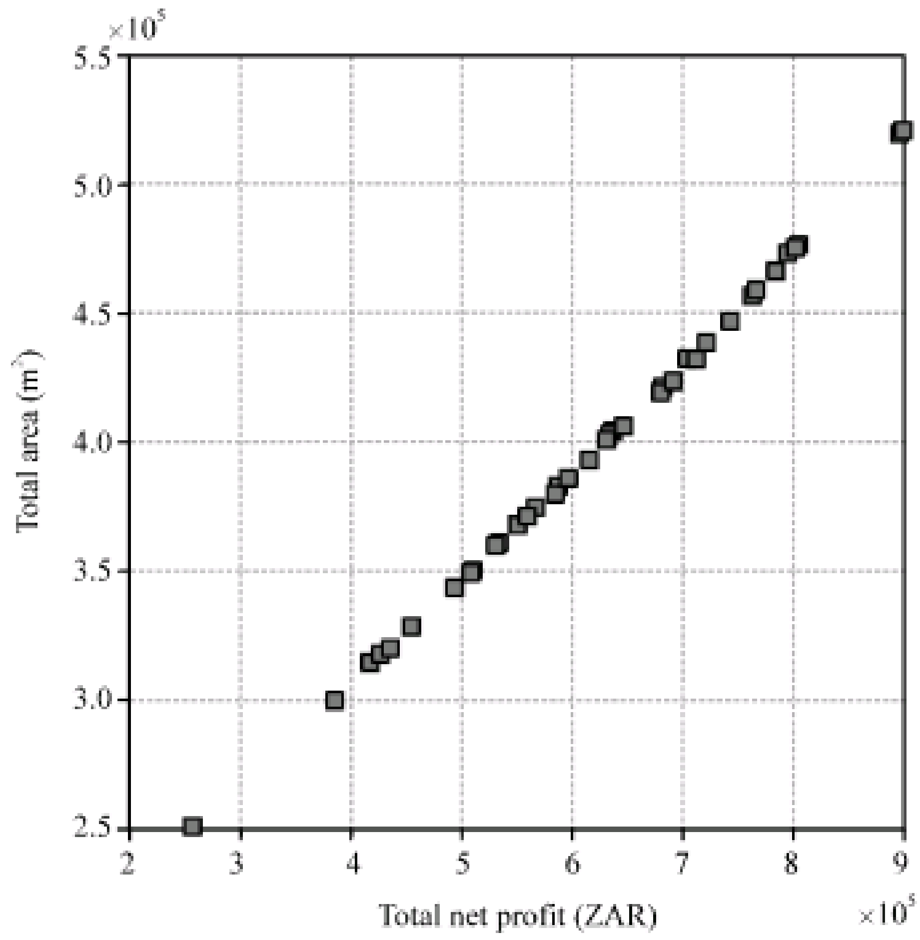

Fig. 8: Pareto optimal set for the crop planning model when maximizing total net profit and minimizing total planting area

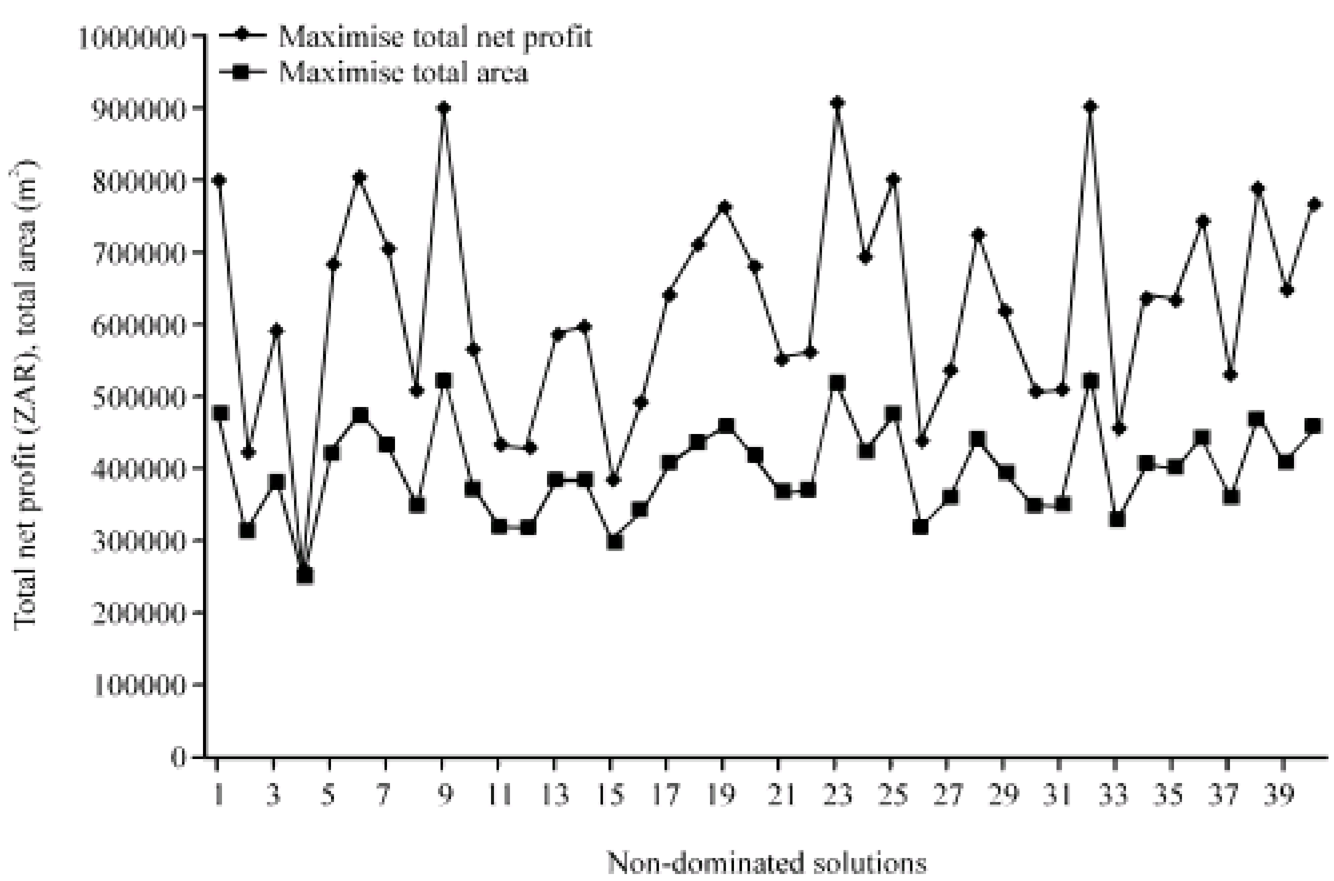

Fig. 9: The non-dominated solutions for maximising total net profit and minimising total area

16 solutions have pecan nuts higher than Lucerne. It is found that planting areas for Lucerne are far more than those of pecan nuts in solutions where Lucerne has more planting areas especially solution 17. In the recommended solution 30, both crops are planted in equal areas. In solution 17, Lucerne is planted in an area of 53,049 m^2 while pecan nuts is 50,000 m^2. Lucerne has the highest area in this solution while pecan nuts has the highest area of 50,506 m^2 in solution 8 and the planting area of Lucerne in solution 8 is 50 000 m^2.

Figure 6 only shows the two objectives of maximising total net profit and minimizing irrigation water without maximizing the total planting area. It is found that the solutions are well distributed along the Pareto front. More solutions are found in the region of total net profit of ZAR 825,000 and ZAR 925,000 and irrigation water of 575,000 and 635,000 m^3.

In Fig. 7, analysis of the non-dominated solutions shows that solution 13 has the highest profit of ZAR 1 018,800 with irrigation water of 698,170 m^3 and total planting area of 768,850 m^2. This solution is preferred if other factors are the same because the ultimate aim of a farmer is to generate the highest profit if the irrigation water can be supplied.

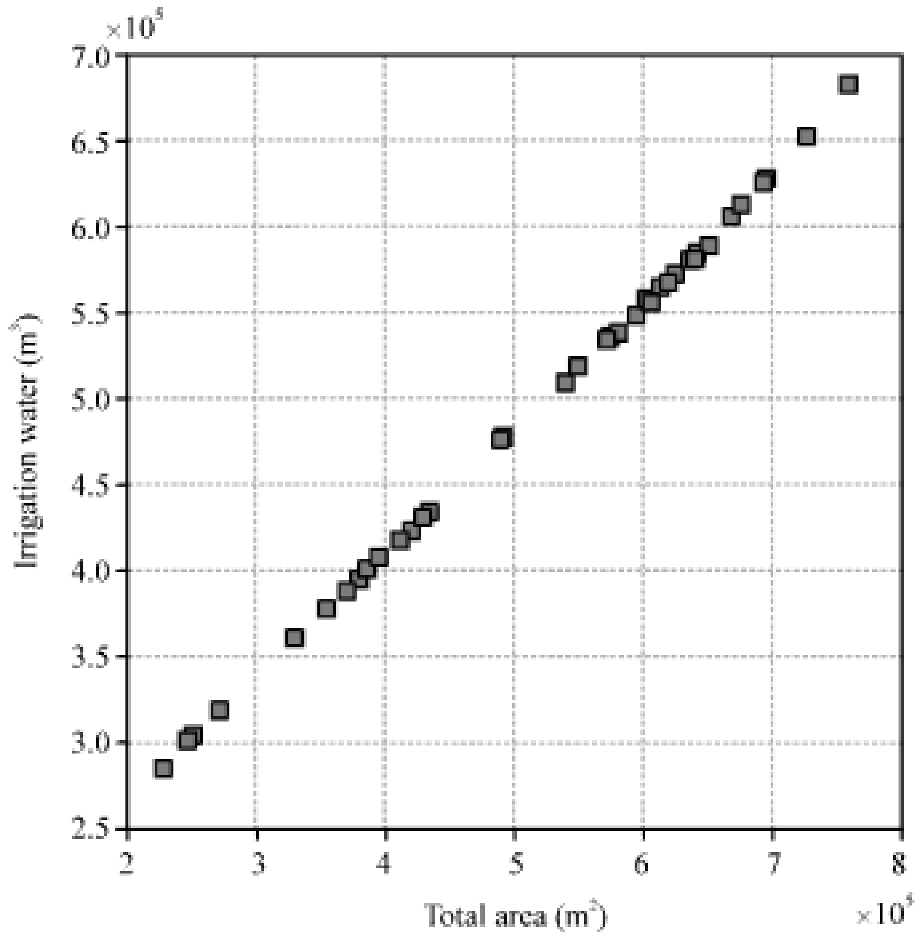

Fig. 10: Pareto optimal set for the crop planning model when maximizing total planting area and minimizing irrigation water

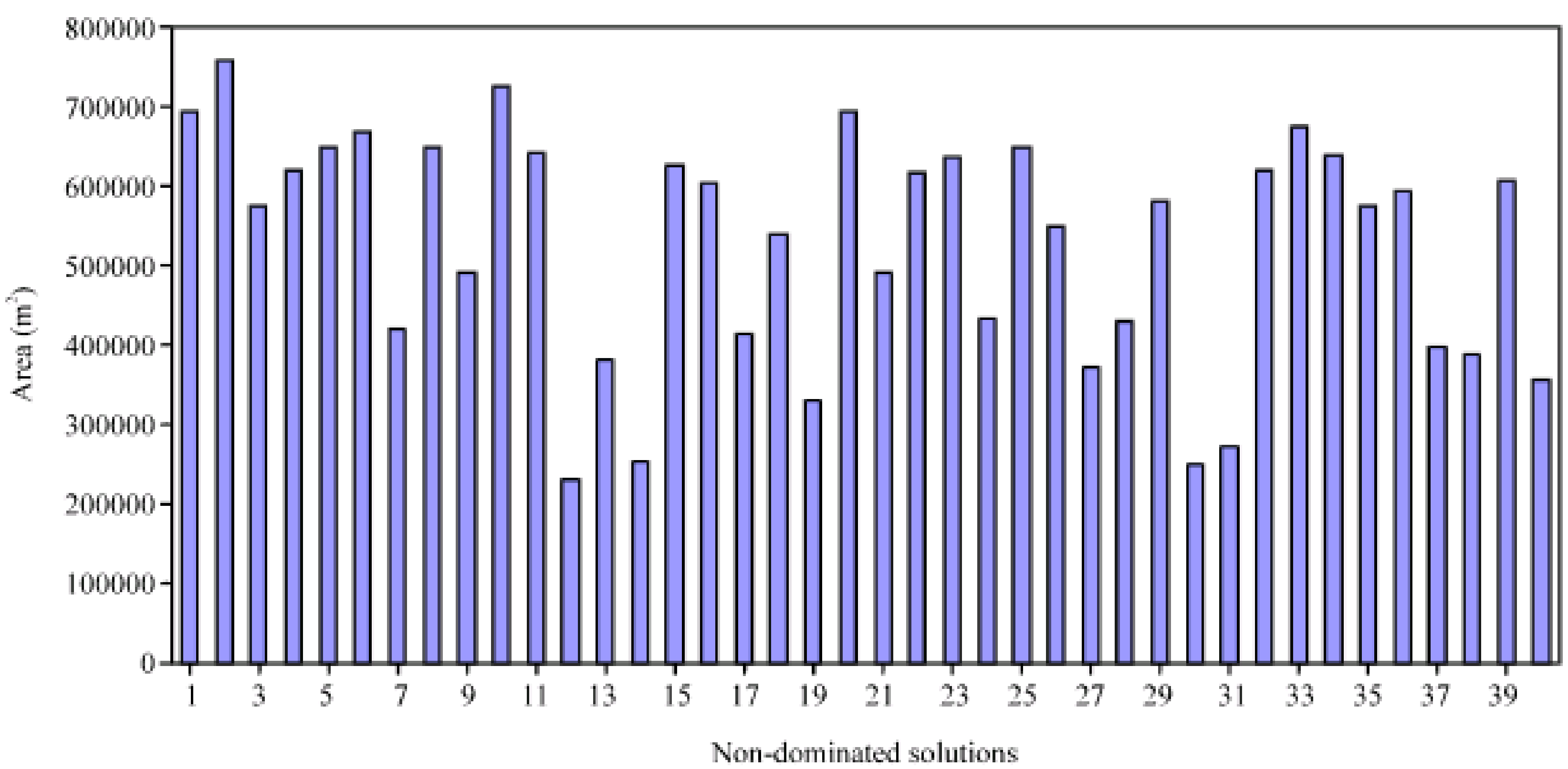

Fig. 11: Different total planting areas for the non-dominated solutions when maximising total area and minimising irrigation water

In Fig. 8, the two objectives of maximizing total net profit and minimizing total planting area are conflicting in that the total planting area for crops can not be minimized without reducing the total net profit. It is found in the figure that total net profit and total planting area are directly proportional. All the solutions fall on the Pareto front.

In Fig. 9, it is found that solutions 23 and 32 generate the highest profit of ZAR 899,230 and 898,700, respectively using very low total planting areas. Therefore, these solutions are preferred for this bi-objective crop planning optimisation. Though, solution 19 does not give the highest profit, it is also preferred because of very low total planting area and corresponding very high profit of ZAR 762,130.

In Fig. 10, it is found that all the non-dominated solutions presented are on the Pareto front. The two objectives of maximizing total planting area and minimizing irrigation water are directly proportional. The solutions can be divided into 3 clusters based on their convergence. The first cluster is from total planting area of 220,000 to 270,000 m^2 and irrigation water from 280,000 to 320,000 m^3. The second cluster is from 320,000 to 450,000 m^2 total planting area and 360,000 to 440,000 m^3 of irrigation water.

The third cluster is from 550,000 to 700,000 m^2 total planting area and 505 000 to 630 000 m^3 of irrigation water. Some solutions are scattered above and below these clusters.

It is found in Fig. 11 that the areas of land for all the solutions range from the minimum of 228,514 m^2 in solution 12 to a maximum of 760,281 m^2 in solution 2.

From the analysis of all the 40 non-dominated solutions, it is found that planting areas for pecan nuts are very low compared to its high demand in the market. This confirms the study of Grove (2006) which reports that if it is feasible to include Pecan nuts, the expected net present value will be higher. However, the impact of water shortages will be more severe. To increase the total net profit and also maximize the total planting area on the farm and the study area in general, the water allocation needs to be increased.

Double cropping, which can increase a farmer's profit, is possible with combination of some of the crops being planted in the area but this is limited by lack of enough irrigation water. In this way, land is being wasted thereby reducing a farmer's profit. The interim solution to the problem is for farmers to plant crops that are water efficient. A farmer may also seek alternative water supply like groundwater to supplement irrigation water allocated. The irrigation technology can be improved to reduce water loss. Flood irrigation technique can be water consuming. Farmers in the area can make use of other irrigation techniques to make more water available for other crops to cultivate more land.

This study has provided the recommended planting areas for the 4 different crops modelled in the study area with the objectives of maximising total net profit and total planting area while minimising irrigation water which is the main objective of this study. It is suggested that agricultural production in the Vaalhart irrigation scheme can be improved if water allocation to the area can be increased or other sources of water like groundwater can be used to supplement irrigation. The recommended planting areas differ from those suggested by Grove (2006) because of multiobjective nature of this model. Grove (2006) considers only single objective of optimising agricultural water use while incorporating risks. More crops can be experimented using double cropping by farmers in further studies when enough irrigation water is available to increase profit. Moreover, other strategies of MDEA can be developed and tested to determine the best strategy for crop planning model.

SENSITIVITY ANALYSIS

This analysis was performed to determine the best combination of NP, CR and F that will be the best for the crop planning optimization problem. The NP was varied from 10 to 100 at the step of 5, CR was varied from 0.1 to 1.0 at the step of 0.05 while F was varied from 0.1 to 0.9 at a step of 0.05. It was found that the best combination for this problem is NP = 40, CR = 0.95 and F = 0.5. This combination gives the highest number of non-dominated solutions in the lowest number of function evaluations. This model is particularly sensitive to changes in F than CR and NP.

CONCLUSION

The application of MDEA to crop planning model is demonstrated in this study. The model results demonstrate the ability of MDEA as applied to multiobjective constrained problem of crop planning. We have shown that MDEA can be successfully employed to search the feasible solution space for a complex cropping pattern that involves multiple objectives and constraints. The values show the convergence of the solutions to Pareto optimal front. Different solutions on the Pareto optimal fronts will generate trade-offs for the problem. The MDEA is suitable for crop planning in a multi-crop environment with limited water for irrigation as demonstrated. From the analysis of the solutions, the model is a good alternative for farmers to obtain the optimal crop planning in a water scarce environment like South Africa. The objectives of this study are achieved. The model in this study can be adapted to any irrigation scheme with minor modifications.

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