Need For Rain Water Harvesting in the Context of Urbanization.

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SYNOPSIS

Sustainable management of natural resources has attained the attention of decision makers in the early 20th century consequent to the crisis faced by the society due to unplanned developmental activities. The anthropogenic activities have affected the quality and quantity of natural resources, which is evident from the disappearance of waterbodies, degraded catchments and increased organic pollutants in waterbodies, which necessitated optimal resource planning. Spatial and temporal tools such as Geographic Information System (GIS) are helpful in analyzing the spatial data. To meet the growing demand for water due to burgeoning population, planners attention is diverted towards alternatives such as rainwater harvesting, treatment of waste water, recycling, etc. Rainwater harvesting and artificial recharge of ground water augments the ground water storage and improves the condition of the other water resources in the vicinity. Rainwater harvesting forms one of the most cost-effective methods for improving the water resources for domestic water requirements.

This paper analyses the feasibility of a harvesting structure at Indian Institute of Science (IISc) campus using GIS. IISc covers an area of 180 ha and forms a part of Sankey lake catchment (located to south east of the Institute). The location and size of harvesting structure was identified with a detailed investigation of the land use pattern, hydrological analyses, catchment delineation, and identification of potential water demand areas. Ecological, economical, social and technical aspects were also considered. Harvesting structure with an area of 1.5 ha and a depth of about 3m can hold about 48,000 m^3 of water. This was found sufficient to meet the requirement of swimming pool, gardening and toilet usage in the campus. Topographical analyses with the help of Digital Elevation Model (DEM) created using Geomedia Professional 5.1 and Geomedia Grid, suggested suitable location of the harvesting structure at eastern side of the campus. About 1.5 ha land is available in this region to construct harvesting structure. Hydrological analyses were carried out taking into account various land uses (sub-catchment delineation) to assess the water yield in the eastern part of the campus. The cumulative annual yield of the catchment ranged from 0.4 million m^3 to 0.8 million m^3.

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1.0 INTRODUCTION

Urbanisation is a form of metropolitan growth that is a response to often bewildering sets of economic, social, and political forces and to the physical geography of an area. It is the increase in the population of cities in proportion to the region's rural population. The 20th century is witnessing "the rapid urbanisation of the world's population", as the global proportion of urban population rose dramatically from 13% (220 million) in 1900, to 29% (732 million) in 1950, to 49% (3.2 billion) in 2005 and is projected to rise to 60% (4.9 billion) by 2030 (World Urbanization Prospects, 2005). Urban ecosystems are the consequence of the intrinsic nature of humans as social beings to live together (Sudhira *et al*., 2003; Ramachandra and Uttam Kumar, 2008, Ramachandra and Uttam Kumar, 2009; Ramachandra and Shwetmala, 2009). The process of urbanisation contributed by infrastructure initiatives, consequent population growth and migration results in the growth of villages into towns, towns into cities and cities into metros. Urbanisation and urban sprawl have posed serious challenges to the decision makers in the city planning and management process involving plethora of issues like infrastructure development, traffic congestion, and basic amenities (electricity, water, and sanitation), etc. (Kulkarni and Ramachandra, 2006). Apart from this, major implications of urbanisation are:

- **Heat island:** Surface and atmospheric temperatures are increased by anthropogenic heat discharge due to energy consumption, increased land surface coverage by artificial materials having high heat capacities and conductivities, and the associated decreases in vegetation and water pervious surfaces, which reduce surface temperature through evapotranspiration.

- **Loss of aquatic ecosystems:** Urbanisation has telling influences on the natural resources such as decline in number of water bodies and / or depleting groundwater table.

There has been a 632% increase in built up area from 1973 to 2009 leading to a sharp decline of 79% area in water bodies in Greater Bangalore mostly attributing to intense urbanisation process (Ramachandra and Uttam Kumar 2009). The rapid development of urban sprawl has many potentially detrimental effects including the loss of valuable agricultural and eco-sensitive (e.g. wetlands, forests) lands, enhanced energy consumption and greenhouse gas emissions from increasing private vehicle use (Ramachandra and Shwetmala, 2009). Vegetation has decreased by 32% from 1973 to 1992, by 38% from 1992 to 2002 and by 63% from 2002 to 2009. Disappearance of water bodies or sharp decline in the number of waterbodies in Bangalore is mainly due to intense urbanisation and urban sprawl. Many lakes (54%) were unauthorised encroached for illegal buildings. Field survey (during July-August 2007) shows that nearly 66% of lakes are sewage fed, 14% surrounded by slums and 72% showed loss of catchment area. Also, lake catchments were used as dumping yards for either municipal solid waste or building debris. The surrounding of these lakes have illegal constructions of buildings and most of the times, slum dwellers occupy the adjoining areas. At many sites, water is used for washing and household activities and even fishing was observed at one of these sites. Multi-storied buildings have come up on some lake beds that have totally intervene the natural catchment flow leading to sharp decline and deteriorating quality of waterbodies. This is correlated with the increase in built up area from the concentrated growth model focusing on Bangalore, adopted by the state machinery, affecting severely open spaces and in particular waterbodies. Some of the lakes have been restored by the city corporation and the concerned authorities in recent times.

Unplanned urbanisation has drastically altered the drainage characteristics of natural catchments, or drainage areas, by increasing the volume and rate of surface runoff. Drainage systems are unable to cope with the increased volume of water and are often encountered with the blockage due to indiscriminate disposal of solid wastes. Encroachment of wetlands, floodplains, etc. obstructs floodways causing loss of natural flood storage. Damages from urban flooding could be categorized as: direct damage – typically material damage caused by water or flowing water, and indirect damage – e.g. traffic disruptions, administrative and labour costs, production losses, spreading of diseases, etc.

Over exploitation of surface water sources like wells for drinking water and industrial use has also resulted in depleted water levels and drying up of bore wells or sea water intrusions (in coastal area) due to the imbalance of inflow and outflow for sub-surface water. The urbanization has also reduced original permeable ground surface. Pavements, roads and construction of storm water drains to drain the rain water as quickly as possible to natural stream, river or sea to avoid flooding of grounds and disruption in traffic. These surfaces and quick run off gives no scope for percolation of rain water to replenish the sub-surface aquifer causing the dropping of water levels or drying up of wells. In addition to this, land use and land cover changes (involving the large-scale conversion of natural ecosystems) have contributed to the regional and global climate changes, resulting in irregular, reduced, erratic and uncertain rainfalls. Dwindling of water resources coupled with the increased water demand has necessitated the viable alternatives to cater the water requirement. This highlights the need to conserve and augment the renewable natural water resources as last chance for survival, realizing that natural resources are not unlimited if they are exploited beyond certain limit. Conservation and sustainable management practices helps in the restoration of the natural balance. This requires the adoption of basic ecological principles in the management of natural resources to ensure the sustainability. In this context, rainwater harvesting is seen as a viable alternative to augment water resources.

1.1 Natural resources management: Water is a renewable natural resource and plays a pivotal role in the region's development. However, unplanned anthropogenic activities have lead to the scarcity of resources, which has affected the economic, productive, infrastructural and social sectors. Scarcity of water is becoming a limiting factor for sustainable development in many parts of the world. Due to these, infiltration of rainwater into the sub-soil has decreased drastically and recharging of groundwater has diminished. The solution to achieve sustainable development lies in the efficient management of water and other natural resources. Rainwater is the main source of water and annually 300 to 800 mm of seasonal rainfall is lost as surface runoff or deep drainage. Water harvesting can also be achieved by following the watershed-based approaches in ecosystem management using pre-treated catchment and micro-catchment areas to increase the efficiency of runoff and maximize the amount of collected rainfall. Better management of water resources is achieved through water conservation, inter-sectoral water reallocations, water costing, and by using water efficiently. In water stress region, rainfall is collected from areas specifically treated to increase precipitation runoff and stored in tanks or ponds for human and animal consumption and for supplemental irrigation.

1.2 Planning:

If collection and storage are designed carefully, it is possible to cater water demand even in areas with rainfall as little as 400 mm / year. Analysis shows that between 80 to 85 % of all measurable rain can be collected and stored from the catchment area, which includes light drizzle and dew condensation. The run-off from a catchment area is computed (Raghunath,1995) by considering the spatial extent of a catchment (A), catchment coefficient (C, that depends on the land use pattern in the catchment) and rainfall intensity (I) and is given by $Q = C * I * A$ [Where, Q = discharge (m^3), C = co-efficient of run-off, I = total rainfall / annum (m) and A = catchment area (m^2)].

The co-efficient of run-off depends upon the land use pattern in the region. The catchment coefficient for rocky and impermeable: 0.8-1.0; slightly permeable, bare: 0.6-0.8; cultivated or covered with vegetation: 0.4-0.6; cultivated absorbent soil: 0.3-0.4; sandy soil: 0.2-0.3; heavy forest: 0.1-0.2.

The co-efficient of run-off also depends on the shape, size, soil conditions, temperature, and geological conditions of the area of the catchment. However, on the basis of average annual rainfall and land use in the area, the co-efficient can be assumed, which are listed in Table 1.

1.3 Spatial and Temporal Analyses:

Sustainable management of natural resources depends on optimal planning based on spatial and temporal data. In this regard, GIS aids as a dynamic and versatile technology capable of providing information for efficient planning and implementation. The unique feature of GIS is its ability as decision support system and provides answers to the queries through rational and systematic analysis of the situation. This aids planners to take quick decision.

For example, in order to understand the topographic undulation a DEM is generated with the help of GIS. It consists of terrain elevations for ground positions at regularly spaced horizontal intervals. DEM data are arrays of regularly spaced elevation values referenced horizontally to a geographic coordinate system. The grid cells are spaced at regular intervals along south to north profiles that are ordered from west to east. A DEM is a set of points defined in a three–dimensional Cartesian space (x, y, and z) that approximates a real surface. X and Y-axis may be expressed as geographic co-ordinates (i.e. longitude and latitude), whereas Z-axis usually represents the altitude above sea level. The low elevation areas are identified by creating the DEM with the contour data, which helps the decision makers in selecting the sites for setting the rain water harvesting structure.

The repetitive synoptic coverage provided by the space borne sensors (which operates on various bands of electro magnetic spectrum) has been widely used for mapping and monitoring areal extent of natural resources including surface water bodies / reservoirs. This is useful for reliable estimation of storage capacity of the reservoirs and its changes over the years. Ground water surveys through satellite remote sensing have been found to narrow down considerably the areas for detailed ground water exploration.

Management tasks of conserving available resources to meet growing demands and preserving water quality, compatible with socio-economic and environmental constraints have become exceedingly complex. In this context, remote sensing provides spatial data at regular interval and aids as a powerful tool for inventorying and monitoring water resources. Spatial analysis is done to get an idea about the terrain, to identify water logging area (seasonal and annual), and to identify sites for rainwater harvesting.

2.0 OBJECTIVES

Design of structures for optimal harvesting of rainwater using GIS includes

- Creation of the topographical elevation model.
- Identification of suitable sites for locating water harvesting structures using DEM.
- Land use analyses in the catchment.
- Computation of water yield.
- Study of geological and soil characteristics for civil design of the structure.
- Optimal design of rainwater harvesting structure considering the demand.

3.0 STUDY AREA

Indian Institute of Science (IISc) campus has been considered for the present study. The campus limits are enclosed within 13°00'38"N to 13°01'15"N latitude and 77°33'34"E to 77°34'26"E longitude. The area falls in the 57G/12 of SOI topo-sheet of scale 1:50000, 57G of scale 1:250,000. IISc is located in northern part of Bangalore city and Figure 1 gives the map of IISc campus with important landmarks. It is endowed with lush green vegetation and has a green canopy of trees covering the buildings in the campus.

The campus, consisting of five bounds, covers an area of 180 ha. The main campus covers 158 ha. The altitude of campus varies from 914m (from Mean Sea Level) to 942 m. The natural terrain of the campus is rolling and provides good natural drainage. The campus slopes towards three sides (north, east and west) from a central ridge along the middle and along the main road of the campus (Gulmohar Marg). Historical precipitation data of 54 years reveal that, the major portion of rainfall being May-June and thunderstorms during September-October. Bangalore receives mean annual rainfall of 860 mm (Radhakrishnan *et al.*, 1996). Sankey Lake located to the Southeast of the campus. A large drain running all along the eastern side of the campus forms the main feeder of the Sankey Lake.

4.0 METHODOLOGY

4.1 Development of database (spatial and attribute data) for GIS

The Survey of India (SOI) toposheets of scale 1:1000 of IISc campus in 10 sheets and GIS software Geomedia Professional 5.1 and Geomedia Grid were used to build the vector layers of

IISc boundary, boundary with landmarks, buildings, roads, surrounding lakes of IISc, IISc zones based on utilities, tree distribution, canopy cover in IISc based on NDVI ranges, drainage and contours.

A vector layer of vegetation showing all the trees (species wise) in the IISc was prepared through an extensive field survey carried out simultaneously. Contour maps (generated using Geomedia Professional 5.1 and Geomedia Grid) are used to generate slope maps of the area and DEM.

The SOI toposheets (scale 1:1000) were scanned and georegistered in geomedia professional. For georegistration a feature class definition of point feature was made and the original corner points from the topsheets were inserted for that point feature class. Then the scanned toposheet was brought to the geoworkspace working window with the help of insert interactive images. The image is selected through the select tool and source control point and target control points are inserted through the image registration dialog. For each feature class, projection system is defined and the datum and projection is set as per the geographical location of the region and through digitization of the raster image, individual features (like roads, contours etc.) are transformed to vector format.

Different feature class (layers) of IISc was created. This includes boundary, boundary with landmarks, buildings, surrounding lakes, zones based on utilities, tree distribution, canopy cover and contour layer (1m interval) by digitizing toposheets SOI (scale 1:1000).

4.2 DEM generation in GEOMEDIA grid

The contour feature (layer) of one m interval is brought to the geoworkspace working window and new study area is defined and cell resolution and output unit is set for the new study area. The contour features are selected from the legend and are rasterized. Through the edit window the non-void cells values are combined and the values are noted and one third of the noted value is calculated for random sampling. The output unit is set from the information dialog, same as that of the output unit of study area defined. Interpolation of the random sample result layer is done and the interpolated layer is smoothed. The depression (in DEM) is filled for the smoothed layer. The filled depression layer's name with color assignment to the layer was done through the edit window (by selecting the first and last cell in the edit window and right clicking on the selected cells to assign color's through color sequence dialog) of filled depression layer. For DEM, the shaded relief model is made with the filled depression layer and is viewed in the map window.

4.3 Field Investigation

A detailed field survey was undertaken to map trees (with diameter >10 cm) in the campus. Figure: 2 shows tree distribution in IISc campus. The field investigation gave an idea of the terrain, drainage pattern, vegetation cover and other constraints. Apart from this, a detailed field survey was under taken to map trees in various sub catchments. The drainage network of the campus was also studied to find out the possible problems of channeling the rainwater. The slope of the drains was also noted to delineate the catchment for the Pond. The local problems like blockage, clogging of the drains were also noted, so that remedial actions could be taken.

4.3.1 Storm-water pond

Economic and ecological considerations highly favor the creation of a water body inside the campus and divert the storm water generated in the campus to the pond. The water stored in the pond may be used for various purposes such as gardening and for meeting the non-drinking water needs of the adjacent buildings. A small filtration plant near the pond would help in treating the stored water usable for various purposes. A garden may be developed around the pond to enhance the aesthetic appeal. Creation of the water body, apart from providing usable water, is also advantageous from ecological considerations by providing a water source for the number of bird species (about 110 species) that the campus is proud to be a habitat.

The need to conserve water assumes more importance than ever before in the present scenario of water table depletion due to increased demand and over exploitation of groundwater resources. Surface water harvesting has multiple advantages, viz., recharge of ground water and efficient use of rainwater, which otherwise gets wasted or contaminated. This study through spatial and temporal data highlights the parameters to be considered for designing harvesting pond at an appropriate suitable location in the campus. The harvesting pond is designed with a detailed investigation of land use pattern, hydrological analyses, catchment delineation and identification of potential problem areas. The optimal design was arrived at taking into account ecological, economical, social and technical aspects.

4.4 Data analyses

Data analyses involved:

Calculations of the area of sub-catchments and land use analysis,
Computation of water yield in respective sub-catchments,
Suitable location of harvesting structures,
Optimal capacity of the pond.

The sub-catchments were delineated from the main catchment area and coefficients of runoff were given to each according to their catchment characteristics. The daily precipitation data at Bangalore city observatory from 1990 to 1997 were used to arrive at a water yield of the pond. Daily yield was calculated using the rational formula, which was computed for the catchment for all these years. Daily yield was cumulated to obtain the monthly and yearly yields.

Topographical analyses with the help of DEM suggest suitable location of the harvesting structure in the eastern part of the campus, which is currently a marshy region. About 1.5 hectare land is available in this region to construct harvesting structure.

During the early 1960's, there were many lakes around the campus that acted as water storage structures and aided in groundwater recharge mechanism. Anthropogenic stresses have led to conversion of lakes to residential, commercial layouts and public utilities. Recent study shows that about 35 % lakes have disappeared during the last twenty years (Deepa, et al. 1998).

Aswathnarayana-kere and Nagashettihalli-kere in the vicinity of IISc are now non-existent, and have been converted into residential layouts. Figure 3 shows the IISc campus bounded by the existing lakes. Consequently, during peak rainfall season, water from the catchment gets into the low-lying areas adjacent to the IISc campus (like ISRO Head quarters, Vigyanapura, etc.).

The three-dimensional elevation image generated using Geomedia Grid was used to identify suitable location for this rainwater-harvesting pond. Figure 4 shows the DEM of the IISc campus. With an identification of lowest positions in a region, the possibility of channeling water was explored considering the following aspects.

Social	:	Acceptance of pond and usage of its water by people in the vicinity. Proper managerial solution to avoid breeding of mosquitoes.
Technical	:	Remedial measures to prevent water seepage into the soil taking into account the stability aspects of structures in the vicinity.
Ecological	:	Environmental impact assessment to ensure minimum damage to the ecosystem from biodiversity point of view.
Economical	:	To ensure cost effective structure.

All possible locations were identified in the campus. The best option was selected considering above criteria and based on the simplicity of construction and channeling of the storm water. The pond was located at a point where the storm water drained can be channeled without much alterations of the existing drainage network.

After identification of suitable location for constructing harvesting structures (ponds), region was explored to find out the extent of land available. Location and area were decided based on ecologically sound strategies. From the land use map, Figure 5 gives the land use map of IISc campus based on utility (vector layer) of the spatial coverage of possible harvesting structure (pond / reservoir) was prepared. The area available ranges from 1 to 1.5 ha. One and half hectare spatial coverage entails removal of about 15 trees belonging to *Acacia nilotica* species. Considering these two areas and for different depths, capacity of the pond was computed. Volumes were compared with the water yield of the catchment of the campus considering the continuity equation i.e.

Storage volume = Inflow – Outflow - Losses (evaporation, seepage, etc.)

The losses considered were the evaporation from the catchment using the monthly mean of daily evaporation data for Bangalore (Muthreja, 1995). The demand for the swimming pool, gardening was ascertained from the volume of the swimming pool and the volume of the storage tank for gardening respectively.

The average rainfall of Bangalore was computed taking 55 years (from 1940 to 1997- 1948, 1967 were not available) of daily rainfall data from Bangalore city observatory.

Harvesting structure in an available area of 1.5 ha and a depth of about 3 m can hold about 22000 m^3 of rainwater. This is sufficient to meet the requirement of swimming pool, gardening and toilet usage in the campus. The campus swimming pool approximately requires 1000 m^3 of water per refilling. The pool faces scarcity of water during the lean season (i.e. during month of January, February and March). Apart from this, storage structures helps in recharging of the groundwater sources.

The maximum depth available at the proposed site is about 1.5 m. It is desirable to increase this to about 3m, so that the storage may be increased. All round excavation may be taken up to achieve a maximum depth of about 3 m, and to give aesthetic appearance.

Inlet to the pond: The existing main drain that runs in the eastern parts of the campus collects a major portion of the storm water. The lowest point on this drain occurs opposite to the proposed pond location, which could be easily connected to the pond.

Outlet from the pond: An outlet drain of size 1.8 m width and 1.2 m height must be provided at a slope of 1 in 1000, and joined to the existing drain leading to the municipal drain along the eastern part. The invert level of this outlet drain must be the same as that of the inlet drain.

Maintenance of water quality: Adequate care and attention must be focussed on maintenance of clear water in the pond, so that it does not become a source for unhygienic and unpleasant surrounding. Under no circumstances, sewage water and other waste water must be permitted inside the pond. For prevention of mosquito breeding, periodic treatment with lime and/or biological control is required.

5.0 RESULTS, DISCUSSION AND SUGGESTIONS

The base layers of the IISc campus for the analysis were generated using Geomedia Professional 5.1. From the scanned maps of SOI 1:1000 sheets. IISc campus covers an area of 180 ha, of this main campus occupies about 158 ha. Gymkhana bounds is about 10 ha, followed by ASTRA, Post office bound (7.5 ha), KV bounds (3.86 ha) and Staff quarters bounds (0.32 ha)

The two main roads, Gulmohar and Tala Marg run parallel along the middle of the campus as shown in Figure 6. The buildings were classified based on usage as administrative, academic, residential, library and information services, dining facilities, recreation and amenities, sister institutions (NIAS, JNCASR, INSDOC, TIFR), utilities and others (which included unidentified and unused buildings). The Faculty hall or the main building of the campus and other administrative buildings are shown in red color.

The elevation contours (topographic elevation) of the campus was generated by digitizing line features from the scanned maps. The generated contours indicate that, elevation in campus varies from 914 m (along the periphery of the Jubilee garden extension) to 942 m (near C.N.R. Rao circle closer to IISc main gate). The campus slopes towards three sides from the ridge that falls along the Gulmohar Marg (road from C.N.R. Rao circle to TIFR).

The contour map of the campus shows that the campus has a good natural drainage. Figure 7 shows the drainage network of IISc campus overlaid on contours. Hence, the problems of water stagnation in the campus are not grave except for some local problems. In addition, due to the gradient that is available, runoff drains off quickly. The natural drainage drains towards the either side of the main road. The drains are classified on their shape. The drains sloping towards the eastern side joins the large drain flowing towards the Sankey Lake.

The new buildings that were not available in the scanned maps were added using Global Positioning System and the shapes of these buildings are guesstimate. The percentage plinth area of the buildings, tree density, species diversity indices were calculated for each zone and this analysis also helped in arriving at the runoff coefficients.

The location of harvesting structure / storage pond was based on the topographical elevations, existing drainage network, area available and land use / land cover. Campus slopes toward either side from the middle ridge, lending to mainly two drainage directions. The eastern side of the campus has a greater gradient / slope than the western side. The eastern side has positions of low altitude compared to other areas of campus. Moreover, the major portion of the drainage flows to the eastern side. In addition, the large drain flowed along the eastern side (main feeder to Sankey Lake) to which all the eastbound drains lead.

Two areas identified for locating harvesting structures / pond are along the periphery of Jubilee garden having an altitude of 914 to 915 m and at the marshy area on the eastern side having an altitude from 917 to 920 m.

Among these locations, area having an altitude around 914 m was unsuitable because of retrograde natural drainage, lesser area available and difficulty of water being channeled to that area. The campus was also explored for other possible locations. The western side of the campus lacked any suitable site where possible structures could be located.

Moreover, marshy area collects rainwater during monsoon season and wetness is present throughout the year. In view of these, location is selected for the proposed harvesting structure which can cater the water requirement of swimming pool and garden and also be a good recreational spot. The proposed rain water harvesting site is indicated in Figure 8.

The marshy area was selected because it is located in low lying area naturally holding water and this endeavour proposes to modify the existing condition of the area to hold water. The area where the structure is being located has minimum number of trees.

The DEM was generated from the vector contour map using the linear surface interpolation and converted to a raster image. This image was used to visually identify the possible locations for the structure. This confirms the location of proposed harvesting structure in the marshy area (eastern side of the campus). The accuracy of DEM generated from the vector map depends on the no of rows and column selected during the conversion. The DEM was used only for visualisation of the terrain as against the extraction of drainage characteristics.

The spatial extent available for pond would be 1 to 1.5 ha depending on the inclusion or exclusion of the vegetated area around the pond. A depth of 1.5 m can be achieved without any excavation of the present pond bed. The volume of the pond that can be constructed depends on the area available. Table 2 shows the volume of pond for 1 and 1.5 ha for different depths (ranging from 1 m to 5 m).

In order to arrive at the optimal capacity of the proposed harvesting structure / storage pond water demand in the vicinity (such as swimming pool, garden etc.) was explored. The water supply for the Institute swimming pool comes from the Bangalore water supply in addition to well water. There is a shortage of water supply during lean season (December to March). Swimming pool being recycled twice a week its monthly requirement comes to around 4000 m^3. Assuming a pond capacity of 10000 m^3 (if spatial coverage of pond is 1 hectare and depth 1 m), this would be sufficient for two months after the evaporation losses.

The gardening requirement for the Institute is about 6000 m^3 / month. For 10000 m^3 of capacity, this would only be sufficient for 45 days. If the requirement for the swimming pool and the gardening is analysed this would be hardly sufficient for one month.

Instead, a capacity of 15000 m^3 achieved through 1.5 hectare area and a depth of 1 m, can support the swimming pool requirements for three months after evaporation losses. For gardening purposes, it would be sufficient for two months. Both requirements combined would suffice for 40 days. A capacity of 30000 m^3 (if spatial coverage of pond is 1.5 hectare and depth of 2 m), would be adequate to cater both swimming pool and garden annual water requirements. Figure 9 shows the canopy cover of IISc campus based on NDVI ranges.

The possibility of pond water catering to toilet usage in the campus was also analysed. This calculated on the assumption that 50 people each in 50 departments use 20 litres / person / day. This works out to 1500 m^3/month, which is to be supplied throughout the year. The swimming pool, garden and toilet water requirement on campus amounts to 48000 $m^{3.}$ Since there is sufficient yield in this catchment, to harvest this quantity, in an available area of 1.5 ha the depth has to be 3.2 m.

The rainwater harvesting structure could be built as earthen structure like a percolation pond but with adequate inflow and out flow structures. This also results in a cost-effective structure. A small filtration plant near the pond would help in treating the stored water usable for various purposes. A garden may be developed around the pond to enhance the aesthetic appeal. Suitable measures could be undertaken subsequently for maintaining the pond in a good condition, so that mosquito breeding (through biological control-successfully managed elsewhere) and other undesirable conditions may be avoided.

As a rainfall harvesting method to conserve water, another efficient method is to install a roof water harvesting system for each building, which is more cost effective and more efficient in solving the water scarcity in the lean seasons. This water can be used for laboratory usage, toilet usage and for other purposes if some simple treatment is given. This treatment can be simple chlorinating to be bacteriologically safe. Also filtering the water through a sand filter would be appropriate.

6.0 CONCLUSIONS

A comprehensive spatial database has been developed as a tool in aiding decision making for future development. The GIS is used for design of pond to harvest rain water optimally, considering economic and ecological considerations. The surface water stored in the pond may be used for suitable purposes such as gardening and for meeting the non-drinking water needs of the adjacent buildings.

The low-lying area adjacent on the eastern side is most suitable for the water body. Approximately 1.5 ha of low-lying area is available at this site. About 20,000 m^3 of water may be stored in this pond. This site also provides an easy opportunity for diverting a major portion of the storm water generated inside the campus, to the pond. The excess water from the pond may be diverted into the drain going out of the campus through the adjacent CPRI campus.

An outlet drain of size 1.8 m width and 1.2 m height must be provided at a slope of 1 in 1000, and joined to the existing drain on the eastern side leading to the municipal drain along the New BEL road. The invert level of this outlet drain must be the same as that of the inlet drain. It is emphasized that this drain must be of the minimum size mentioned above, and the existing drain that passes through the CPRI campus, to which the outlet drain from the pond is joined must be enlarged to the same cross section (1.8 m x 1.5 m). Adequate care and attention must be focussed on maintenance of clear water in the pond, so that it does not become a source for unhygienic and unpleasant surrounding. Under no circumstances, sewage water and other waste water must be permitted inside the pond.

It is emphasized that a good maintenance of the drainage system is as important as its design and construction. It is necessary that a periodic cleaning of drains, inlets, outlets, culverts etc., is taken up, to remove the muck, weed, solid wastes and other obstacles that may have been deposited, at least once before every monsoon. Like any other service facility, the system will work well when it is needed the most only if it is maintained well even when it is not needed.

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ABBREVIATIONS

BEL- Bharath electronics limited
CPRI-Central power research institute
INSDOC-Indian national scientific documentation centre
ISRO-Indian space research organization
JNCASR-Jawaharlal Nehru centre for advanced scientific research
KV-Kendriya vidyalaya
NDVI- Noramalized difference vegetation index
NIAS- National institute of advanced studies
TIFR- Tata institute for fundamental research

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Table 1: Catchment coefficient for various land uses.

Catchment Type with rainfall and runoff	Run off co-efficient
Dry tracts with annual rainfall 350 to 750 mm, run off 15 to 20 %	0.15 to 0.2
Intermediate Zones rain 750 to 1500 mm, run off 20 to 30 %	0.2 to 0.3
Higher Zone with rainfall above 1500 mm, run off 30 to 55 %	0.3 to 0.55
Roof and paved areas, run off 80 to 90 %	0.8 to 0.9

Table 2: Volume computation for various depths

Area 1 ha		Area 1.5 ha	
Capacity (m^3)	Depth (m)	Capacity (m^3)	Depth (m)
5000	0.5	7500	0.5
10000	1	15000	1
15000	1.5	22500	1.5
20000	2	30000	2
25000	2.5	37500	2.5
30000	3	45000	3
35000	3.5	52500	3.5
40000	4	60000	4

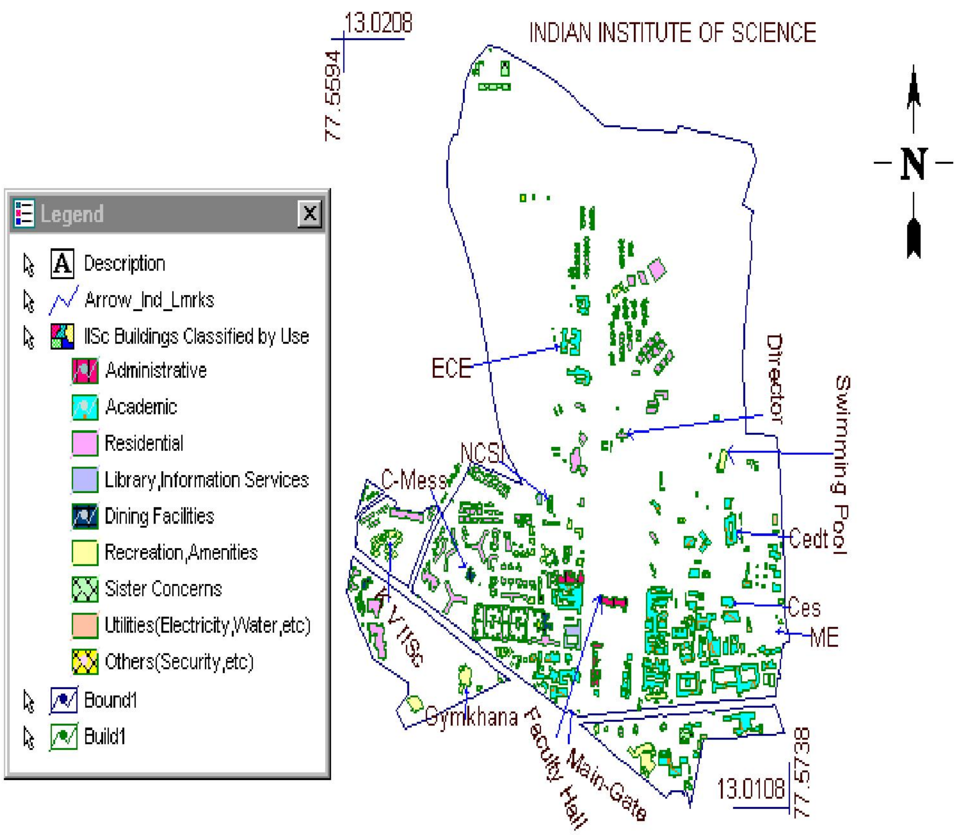

Figure 1: Map of IISc campus with important landmarks.

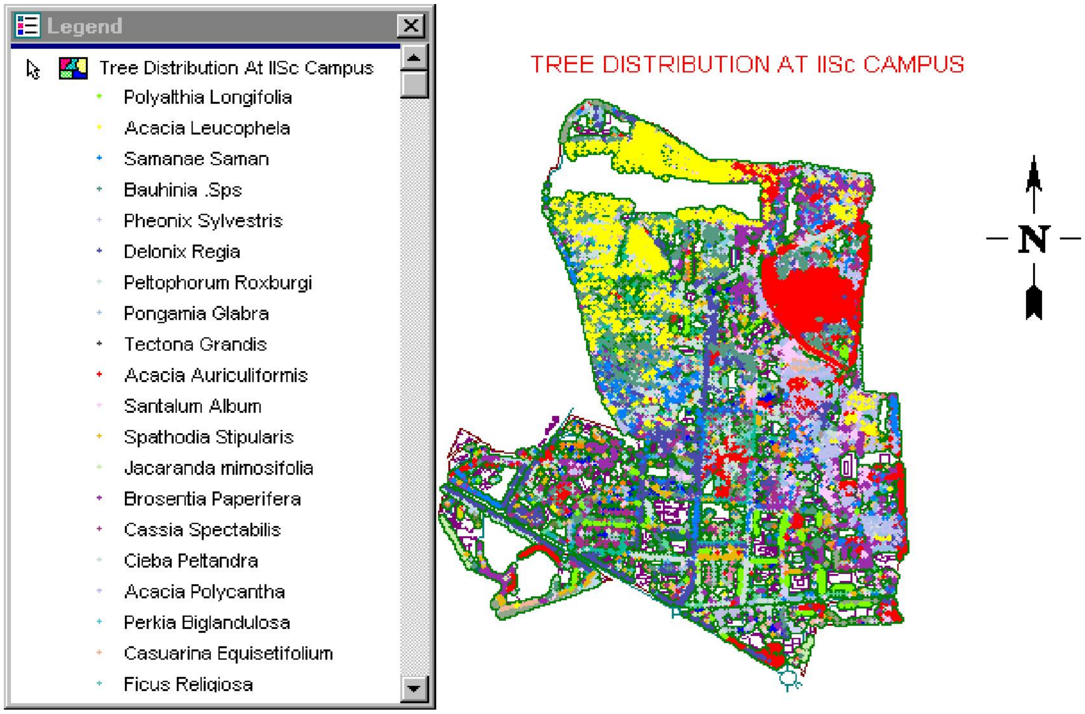

Figure 2: Tree distribution in IISc campus.

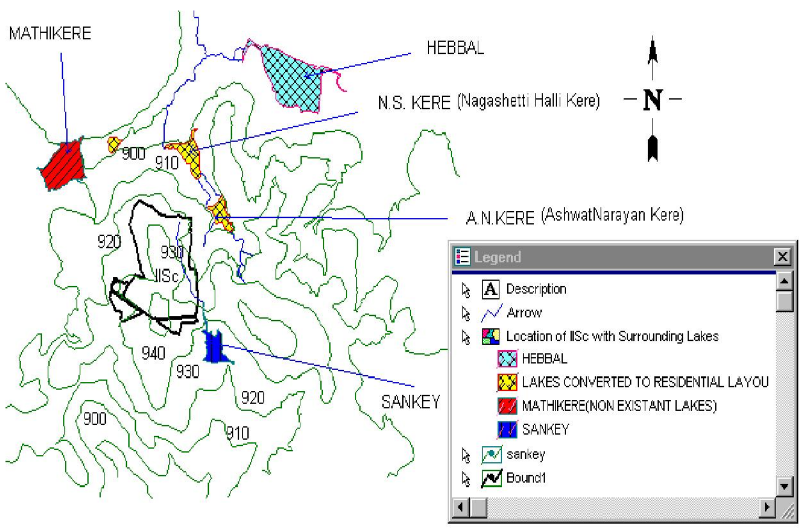

Figure 3: IISc campus bounded by the existing lakes.

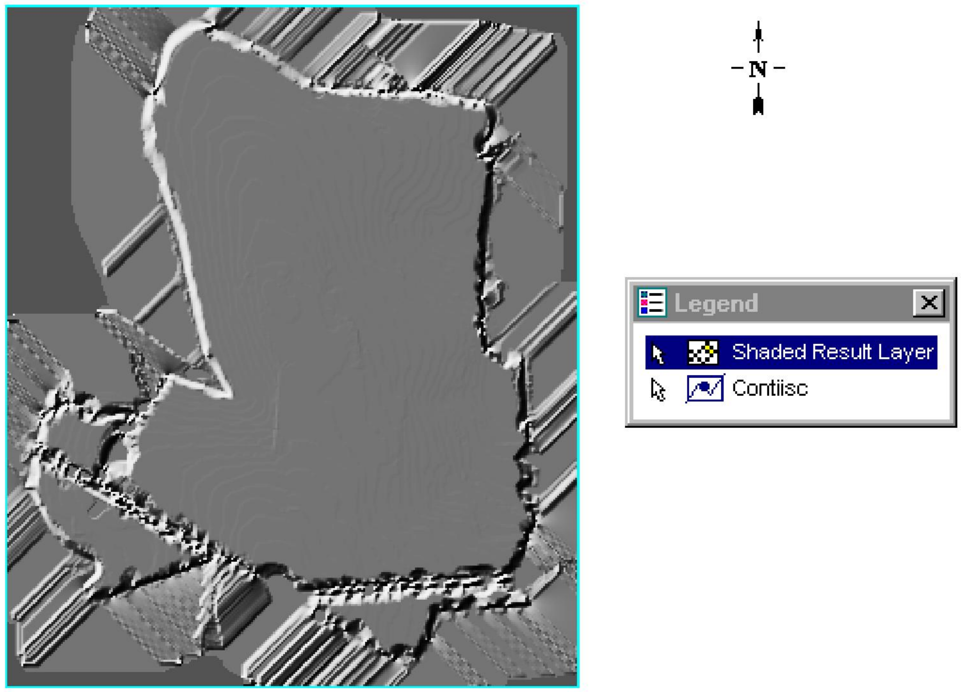

Figure 4: Digital Elevation Model of the IISc campus.

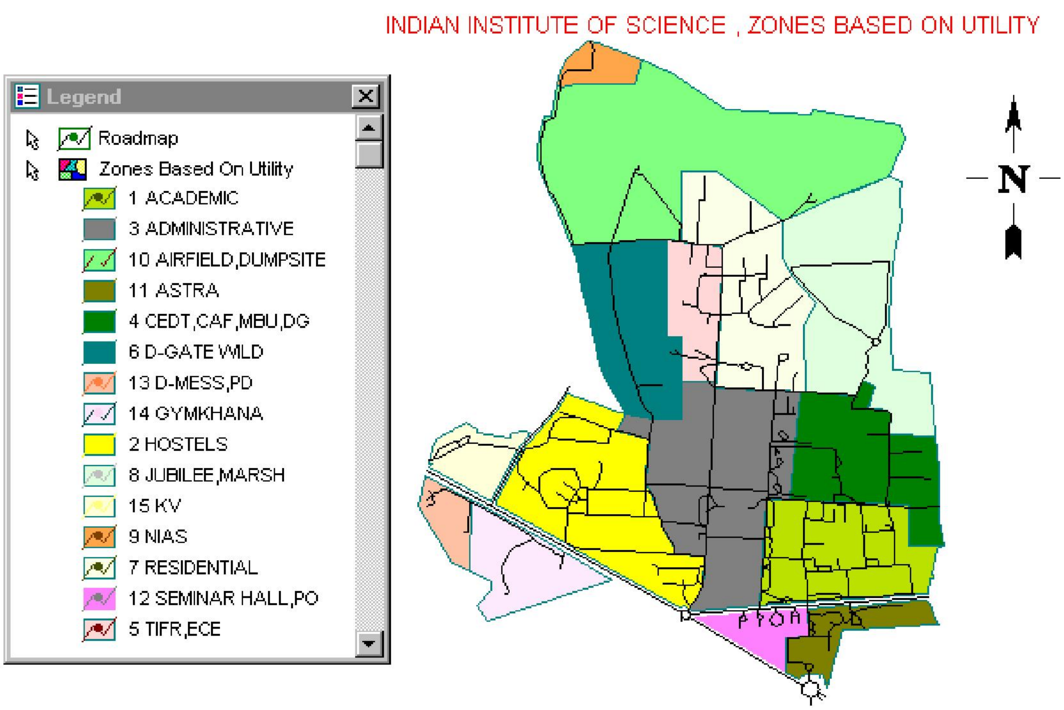

Figure 5: Land use map of IISc campus based on utility.

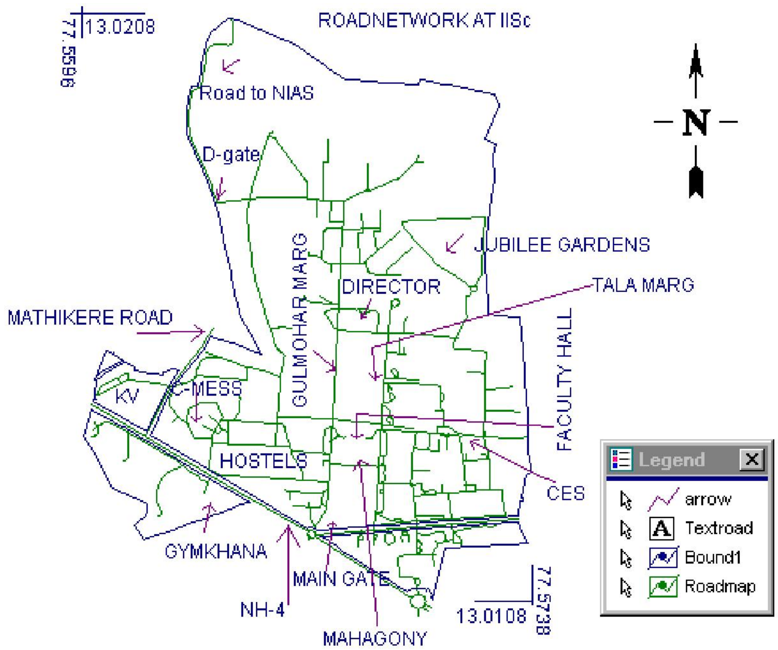

Figure 6: Road network of IISc campus.

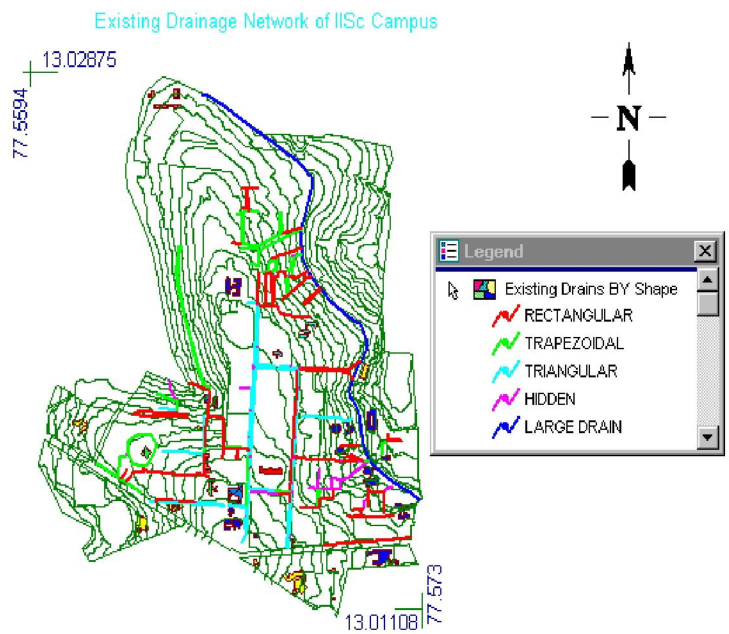

Figure 7: Drainage network of IISc campus overlaid on contours.

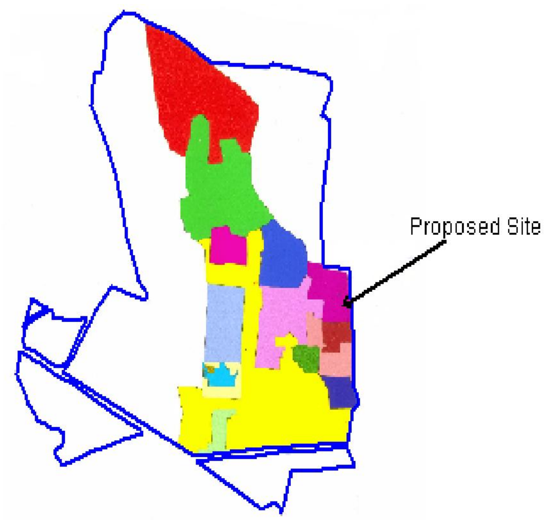

Figure 8: Rain Water Harvesting Site in IISc.

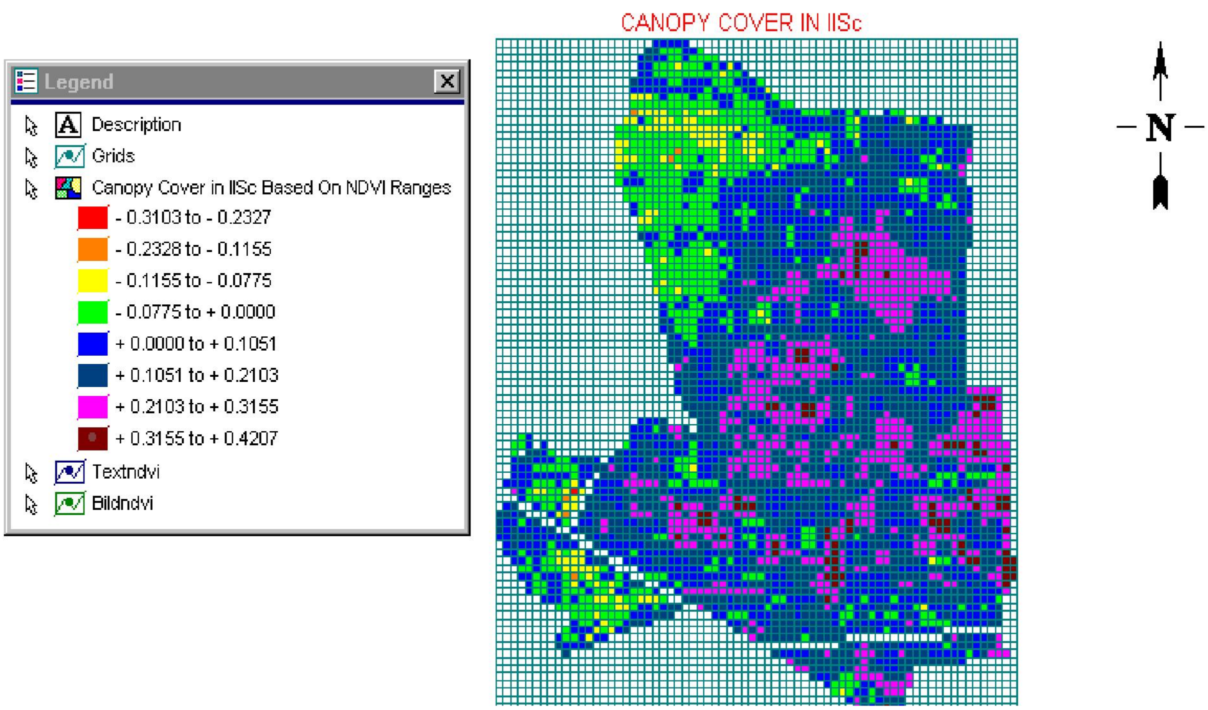

Figure 9: Canopy Cover of IISc Campus based on NDVI Ranges.

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Mini Forest - An experiment to evaluate the adaptability of Western Ghats species for afforestation

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Abstract

Saplings of forty nine species of trees from Western Ghats forests were planted on a 1.5 hectare tract of Deccan plateau (in the campus of Indian Institute of Science, Bangalore) and their performance monitored for 23 years. The objective was to evaluate their adaptability to a habitat and conditions apparently alien to these species. The study was also meant to understand the linkages of these trees with the surrounding environment. Contrary to the belief that tree species are very sensitive to change of location and conditions, the introduced trees have grown as good as they would do in their native habitat and maintained their phenology. Further, they have grown in perfect harmony with trees native to the location. The results show that the introduced species are opportunistic and readily acclimatized and grew well overcoming the need for the edaphic and other factors that are believed to be responsible for their endemicity. Besides ex situ conservation, the creation of miniforest has other accrued ecosystem benefits. For instance, the ground water level has risen and the ambient temperature has come down by two degrees.

Keywords: Western Ghats, Ecological Services, Mini forest

It is general belief that tree species are adapted to such specialized natural conditions that they are unsuitable for translocation, particularly to planting in urban environs. Contrary to this opinion, it has been observed in the present study that trees have a remarkable ability to adapt to change in locations which are totally alien, a fact that was demonstrated by scores of exotic species naturalised and flourishing in parts of the world other than the region of their origin or nativity (Sankara Rao, 2008, 2009, Hanumaiah *et al*., 1967). There has been an almost continuous process of introduction of alien trees into Karnataka state, especially to Bangalore (Hayavadana Rao, 1930). The success of some of these is startling. They have come from a very wide range of geographic regions of the world. Within a short time, these species such as Paper mulberry (*Broussonetia papyrifera* Vent.), Tabebuias (*T. aurea*, *T. chrysotricha*, *T. impetiginosa*, *T. pallida*, *T. rosea*), Leucaena (*Leucaena latisiliqua* (L.) Gillis) and some Australian Acacias (*Acacia auriculiformis* Cunn. ex Benth.) have come to dominate Bangalore's tree flora and become the principal cause for a number of native species in the city edging towards local extinction. There is a growing concern that we should be helping to maintain our native woodland species in afforestation programmes in denuded land and in cities which are suffering from a continuous process of attrition, particularly in the urban spaces in the face of modern developments.

Flora of India belongs to diverse vegetation types. Virtually every kind of vegetation supported tree species, small and big, deciduous and those that remain leafy most part of the year. The species diversity is enormous and as such, there is no dearth for selection of species among these native trees for afforestation and urban greening. There is also the impending danger of climate change, which is likely to affect some of our native tree species, and their phenology, and thereby effecting further regeneration and continuity of the species, which would result in loss of diversity. It might therefore become necessary to bring different wild indigenous species to other locations and also into city confines where they might have better opportunity to thrive under a watchful eye. With this conservation strategy in mind, creation of miniforest was mooted three decades ago at the Centre for Ecological Sciences (CES), Indian Institute of Science (IISc), Bangalore and tree species of Western Ghats forests were sought to be evaluated for their performance in the Deccan plateau region of which Bangalore is a part. A small vacant space (about 1.5 hectare) that was beset with scrub vegetation opposite

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to the CES in the campus of Indian Institute of Science was chosen for planting tree saplings from the forests of the Western Ghats that came to be known as the miniforest. Saplings (480 no's.) belonging to forty nine species (Table 1) which were raised at the CES Field Station Nursery at Sirsi, Uttara Kannada district were obtained and planted along with few species already existing on the plot with a spacing of 3 x 3 m.

Figure 1: Picture showing the type of terrain on which the miniforest was raised

Table 1: List of species in the miniforest

Sl No	Species
1	*Adenanthera pavonina* L.
2	*Adina cordifolia* (Roxb.) Hook.f. ex Brandis
3	*Ailanthus triphysa* (Dennst.) Alston
4	*Albizia amara* (Roxb.) Boiv.
5	*Alstonia scholaris* (L.) R. Br.
6	*Areca catechu* L.
7	*Artocarpus heterophyllus* Lam.
8	*Artocarpus hirsutus* Lam.
9	*Artocarpus lacucha* Roxb. ex Buch.-Ham.
10	*Bambusa arundinacea* (Retz.) Willd.
11	*Bombax malabaricum* DC.
12	*Broussonetia luzonica* Bureau
13	*Butea monosperma* (Lam.)Taub.
14	*Calamus prasinus* Lak. & Renuka
15	*Calophyllum apetalum* Willd.
16	*Calophyllum inophyllum* L.
17	*Cananga odorata* (Lam.) Hook. f. & Thoms.
18	*Canarium strictum* Roxb.
19	*Ceiba pentandra* (L.) Gaertn.
20	*Chukrasia tabularis* A. Juss.
21	*Commiphora wightii* (Arn.) Bhand.
22	*Duabanga grandiflora* (Roxb. ex DC.) Walp.
23	*Elaeocarpus serratus* L.
24	*Elaeocarpus tuberculatus* Roxb.
25	*Entada rheedei* Spreng.
26	*Ficus benghalensis* L.
27	*Ficus racemosa* L.
28	*Garcinia indica* (Thouars) Choisy
29	*Holigarna grahamii* (Wight) Kurz
30	*Holigarna arnottiana* Hook. f.
31	*Hopea ponga* (Dennst.) Mabb.
32	*Lagerstroemia lanceolata* Wall. ex C. B. Clarke
33	*Lophopetalum wightianum* Arn.
34	*Madhuca longifolia* (Koenig) Macbr.
35	*Mallotus philippensis* (Lam.) Muell.-Arg.
36	*Mangifera indica* L.
37	*Memecylon umbellatum* Burm. f.
38	*Mimusops elengi* L.
39	*Mitragyna parvifolia* (Roxb.) Korth.
40	*Pajanelia longifolia* (Willd.) K. Schum.
41	*Sterculia guttata* Roxb. ex DC.
42	*Syzygium cumini* (L.) Skeels
43	*Syzygium laetum* (Buch.-Ham.) Gandhi
44	*Terminalia arjuna* (Roxb. ex DC.) Wight & Arn.
45	*Terminalia crenulata* Roth
46	*Vateria indica* L.
47	*Vitex altissima* L.f.
48	*Xylia xylocarpa* (Roxb.) Taub.
49	*Ziziphus rugosa* Lam.

The area encompassing Western Ghats is recognised as one of the most eco-sensitive regions of the world and is one among the 34 biodiversity hotspots on the basis of its species richness (Myers, *et al.*, 2000).

Western Ghats run along the West coast of India from the Vindhya-Satpura ranges in the North to the southern tip of the peninsula to a stretch of 6000 km, covering an area of nearly 1, 59,000 sq. km and consist of mountains ranging from 50 m to 2695 m in height. Western Ghats receive an average of 6000 mm of rainfall every year. The vegetation is quite diverse, broadly having evergreen, semi-evergreen, deciduous, scrub forests, sholas, grasslands and bamboo clumps. Factors including sunlight, rainfall, humidity, altitude, topography and location contribute to the uniqueness of this habitat, its animal and plant diversity. Plants such as *Holigarna grahamii* (Wight) Kurz, *Garcinia sp.*, *Mitragyna parvifolia* (Roxb.) Korth., *Lophopetalum wightianum* Arn., *Syzygium leatum* (Buch.-Ham.) Gandhi, *Entada rheedei* Spreng., *Calamus prasinus* Lak. & Renuka and the like represent evergreen, semi evergreen and moist deciduous species of the Western Ghats (Pascal and Ramesh, 1987, Pascal, 1988). These species generally thrive in Western Ghats with the unique climatic and edaphic factors and are not generally found thriving in other plateau regions.

It is observed that in less than 25 years, the experimental plot, now termed 'Miniforest' on account of the limited area, is transformed into a lush green forest on a terrain that was originally a scrub vegetation of the Deccan plateau type with apparently conditions alien to most of the species that have been introduced. The miniforest, in this respect, presented an opportunity to study the adaptations and succession of the Western Ghats forest species (Table 1) in comparison with native species existing in the area. The species composition that emerged in the experimental plot is quite interesting. Majority of them are the Western Ghats species whereas the others, the native to scrub vegetation, both found growing in perfect harmony, in spite of the difference in rainfall (850 mm), humidity, temperature and soil conditions for the former species (Fig 2). The miniforest trees exhibited normal robust growth, flowered and set fruit as they would do in their native habitat. Some of the trees, for example *Mitragyna parvifolia* (Roxb.) Korth., *Chukrasia tabularis* A. Juss., *Duabanga grandiflora* (Roxb. ex DC.) Walp., *Garcinia indica* (Thouars) Choisy, *Holigarna grahamii* (Wight) Kurz, *Lophopetalum wightianum* Arn. *and Syzygium laetum* (Buch.-Ham.) Gandhi (Plate 1) have grown as well as they would do in the evergreen forests.

Figure 2: A view of Miniforest

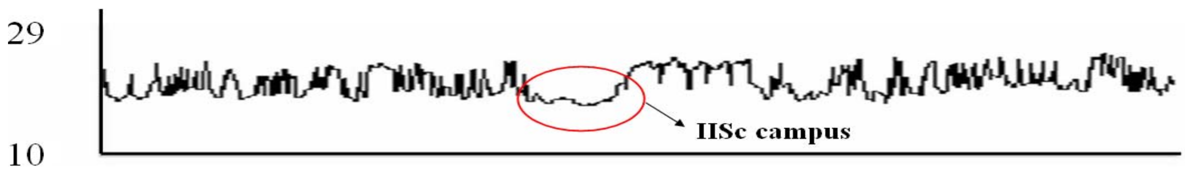
A gigantic liana *Entada rheedei* Spreng., that was not known to grow outside the moist forests has thrived very well and spread prolifically to nearby areas (Ramesh Maheshwari et al., 2009) and flowered since 2001(Fig 3). *Calamus prasinus* Lak. & Renuka, being a rattan, which is rarely reported to survive in drier tracts, has also grown considerably well exhibiting normal flowering (Gopalakrishna Bhat, 2003). These observations provide evidence that most of the trees of the Western Ghats forests are opportunistic and grow under factors largely different from those believed to be responsible for their endemicity. A microclimate prevails in the plot, the miniforest. There is a slight dip in temperature, an increase in humidity and humus enrichment on account of the survival of many moist evergreen species and their good canopy cover. The miniforest plot is kept undisturbed. Progressively, the area developed rich micro- and macro-fauna, from insects, frogs, snakes to birds and smaller mammals like the most elusive Slender Loris. Smaller plants such as mosses, algae, fungi, ferns, herbaceous plants and climbers have grown well adapting to the change. The entire plot is amazingly transformed into the type of a habitat that prevails in the moist forests of Western Ghats.

Other ecological benefits have resulted from creating the miniforest. Temperature profile analysis through the computation of Land Surface Temperature (LST) was carried out using LANDSAT ETM thermal data shows that the temperature in this area is at least 2 degrees lower than the surrounding regions (Fig 4). The water table at this location was in the range of 60-70 m depth before creating the miniforest. Present monitoring of water table shows the level of water is

Figure 3: A gigantic liana *Entada rheedei* Spreng.(with fruits)

at about 3 to 3.5 m below the ground. This indicates that land cover dynamics play a decisive role in recharging the groundwater sources. Four families of Slender Loris (*Loris tardigradus*) inhabiting here is an indication of total wilderness prevailing in the miniforest, further confirming the ecological richness of the habitat.

Figure 4: Temperature profile of IISc campus (Transect passing through miniforest)



***Syzygium laetum* (Buch.-Ham.) Gandhi**

***Lophopetalum wightianum* Arn**

***Holigarna arnottiana* Hook. f. (Fruiting)**

***Garcinia indica* (Thouars) Choisy (Fruiting)**

Figure 5: Evergreen species of miniforest

The results further show that the experiment of the miniforest can be replicated to create such green pockets in and around other urban spaces. This kind of green patch not only can be an arboretum for evergreen tree species but also serves as a home for several refuge fauna and adaptable species. The patch will also serve as an efficient carbon sink, trapping free carbon in the atmosphere, bringing the temperature to less than a degree, thus helping in mitigating climate change issues. Similar experiments also can be valuable in establishing germplasm banks to offset any loss of species in the wild due to climate change and other factors.

Acknowledgement
We are grateful to the Ministry of Environment and Forests, Government of India and Indian Institute of Science for the sustained financial and infrastructure support. We thank Dr. D M Bhat, CES Research Station at Sirsi for providing saplings. Mr.Venkatiah and Ms.Venkatalakshmi helped during the initial stages in the regular upkeep of the arboretum. Mr.Raghavendra Rao, Mr Venkatappa, Mr.Manjunath and Mr.Murugeshachar voluntarily helped in fencing the area and also for regular monitoring.

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Structural characteristics of a giant tropical liana and its mode of canopy spread in an alien environment

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To circumvent the practical difficulties in research on tropical rainforest lianas in their natural habitat due to prevailing weather conditions, dense camouflaging vegetation and problems in transporting equipment for experimental investigations, *Entada pursaetha* DC (syn. *Entada scandens* Benth., Leguminosae) was grown inside a research campus in a dry subtropical environment. A solitary genet has attained a gigantic size in 17 years, infesting crowns of semi-evergreen trees growing in an area roughly equivalent to 1.6 ha. It has used aerially formed, cable-like stolons for navigating and spreading its canopy across tree gaps. Some of its parts which had remained unseen in its natural habitat due to dense vegetation are described. The attained size of this liana in a climatically different environment raises the question as to why it is restricted to evergreen rainforests. Some research problems for which this liana will be useful are pointed out.

Keywords: *Entada*, lianas, natural habitat, plant growth, rainforest.

A LIANA is a woody plant which is rooted in the ground, but needs the physical support of a nearby tree for its weak stem and branches to lean and ascend for exposing its canopy to sunlight. Based on transect sampling in rainforests, it has been estimated that climbers or lianas comprise about one-fifth of all plant types[1] (trees, shrubs, herbs, epiphytes, climbers, lianas and stragglers). Investigations on lianas in tropical rainforests are hindered by dense vegetation; even their gross morphology has neither been adequately described nor illustrated. Therefore, if a rainforest liana can be successfully grown in a research campus, this can be considered a breakthrough as opportunities can be opened up for various types of research – such as biomechanical characteristics of its specific parts, tropic responses, host preference, climbing mechanism, nitrogen fixation, type of photosynthesis (C3 or C4), root pressure, reproductive biology, mechanism in invasive growth and morphological response upon contact with support trees. With these objectives, seeds of *Entada pursaetha* (Mimosoideae, Leguminosae) were sown in a research campus in Bangalore – a city in Deccan Plateau – with an average elevation of 918 msl and mean annual precipitation of 950 mm, chiefly during the monsoon period from July to October. A single plant has unexpectedly attained a gigantic size in less than 17 years, with its canopy infesting the crowns of nearby trees. Although data on the ontogenetic changes of this genet are unavailable because of the passage of time, we attempt an interpretation of its growth characteristics and reconstruct the events in *Entada* development from its extant morphological organization. We point out some questions vital to understanding the evolution of the lianoid forms.

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Materials and methods

Entada pursaetha DC has been reported from Silhet (now Bangladesh), Manipur, the Andamans and Nicobar Islands and the Eastern and the Western Ghats in peninsular India[2–4]. Seeds of *Entada* were collected from the Western Ghats (lat. 13°55′–15°31′N, long. 74°9′–75°10′E) about 55 km from the Arabian Sea, at an elevation of 700–800 msl. The region receives 450 cm or more annual rainfall, and during post-monsoon period the wind speed is 8–10 m/s. Following mechanical cracking of the hard testa, the seeds were kept in a coarse cloth bag and floated in pond water for about 20 days before sowing at various places in the campus. Of the seven seeds sown, one buried in the soil close to a tree of *Bauhinia purpurea* (Caesalpinioideae, Leguminosae) has grown into a liana, spreading its canopy on a miniforest of the semi-evergreen tropical trees, in an area roughly equivalent to 1.6 ha. Since its climbing parts are mostly hidden among the crowns of support trees, locating their interconnections and estimating the spread area of this liana required observations over a period of time, especially when the identity could be confirmed by examination of its flowers and fruits. Here we focus on some features of *E. pursaetha* (hereafter referred to as *Entada*) of value to liana biology.

Figure 1. The tree-form of *Entada pursaetha*. ***a***, Self-supporting trunk (thick arrow) in proximity to *Bauhinia purpurea* (Leguminosae). The pleats comprising upright trunk uncoil at or above breast height (thin arrow) and diverge as separate branches (thin arrows) that lean on the surrounding support trees. ***b***, Festoons of secondary branches suspended from support trees. *Entada* has overtaken and oversized *B. purpurea*.

Results and discussion

The superstructure of *Entada* is comprised of a mix of structures of a tree and a woody climber, and some unique structures. Its erect trunk is comprised of anti-clockwise-twisted pleats. Its climber part comprises of hammock-like, twisted, woody stems. The structure that has spread its canopy from one support tree to another are long, leafless, cable-like stems (stolons) that navigated aerially approximately 15 m above the ground, differentiating foliage upon accessing a living tree.

Freestanding trunk

The *Entada* trunk has a girth of 2.1 m at the base and 1.7 m at breast height and is organized as helically twisted pleats (Figure 1 *a*). Although we missed out the ontogenic changes, the self-supporting trunk may have resulted from orthotropic vegetative offshoots that developed from the base of the sapling. This is plausible because according to the noted researcher of rainforests, P. W. Richards[5], 'tropical rain-forest trees often produce coppice-shoots very readily when the main trunk has fallen or decayed … a new formation of coppice-shoots grows up round the secondary main trunk'. We assume that in its juvenile phase *Entada* formed circumnutating offshoots from the base, allowing mutual contacts and eventually fusing to form a mechanically-independent trunk. Circumnutation is a common property in climbers that enables contacting a potential support in the vicinity[6–8]. Sectioning of this solitary specimen for wood anatomy was not possible. However, a reason for considering the *Entada* trunk as comprised of basally formed conjoined, offshoots is because the pleats unwind at 1.5–3 m above the ground and diverge as branches either in vertical or horizontal directions. No other liana is known with a trunk constructed similarly, although the Neotropical liana *Croton nuntians* (Euphorbiaceae) in French Guyana is freestanding and resembles a young tree, but becomes unstable and leans on surrounding vegetation for support[9].

Anticlockwise twists in climbing parts

The uncoiled trunk pleats have branched out into hammock-like, highly twisted, woody branches (Figure 1 *b*). Yet, no above-ground part has twined around a support tree or its branches; hence *Entada* is not a twiner. Rather, its branches mostly lie on the host branches for support and are occasionally entangled into them. A striking feature of *Entada* are the climbing branches shaped into an 'Archimedes screw' (Figure 2) with pronounced tangential thickening. The significance of this patterning is unknown. Recently, a theory has been put forward for the formation of twists in stems subjected to bending stress[10].

The predominantly anticlockwise helices in *Entada* prompted us to examine the direction of coiling in climbers growing in a nearby miniforest in the campus. Anticlockwise ascend was observed in all climbers. Edwards *et al.*[11] reported anticlockwise twining in plants at 17 sites in nine countries in both the northern and southern hemisphere. An exception is the yam *Dioscorea*, where species have been classified on the basis of stems twining to the left or to the right[12]. The handedness of growth depends on the orientation in which cortical microfibrils are organized under the control of *spiral* gene[13]. However, it is not known whether helical microtubule arrays are the cause or the consequence of organ twisting.

We have not observed any thorns, hooks, spines or stem tendrils that could facilitate anchoring of *Entada* to the supporting tree. Rather, physical support is gained by occasional placing of its branches on those of support trees. At best, *Entada* may be classified as a straggler.

Figure 2. The climber-form of *E. pursaetha*. ***a***, Hammock-like branches with twists (arrow). ***b***, Major types (arrows) of branches, numbered 1 to 4. Note Archimedes screw patterning in branch # 3.

Figure 3. ***a***, *Entada* in a decumbent orientation against a wall is distinguished from other species of woody climbers by white and yellow inflorescence. ***b***, A 2 ft long pod.

Some of its overhanging leafy branches that were exposed to full sunlight during March–April (before monsoon rains begin) produced inflorescence (Figure 3).

Invasion and spreading strategy

Thus far, all previously reported lianas spread their canopy by means of ground stolons which then climb on available support. *Entada* is unique: it has formed specialized, cable-like, aerial stolons (Figure 4) that have extended near-horizontally into air, crossing gaps and spreading canopy from the primary support tree onto the crowns of other support trees (Figure 5). The length of these aerial stolons exceeds 15 m; and there is no evidence of a support tree being present between the inter-support distances, because of a dividing tarred road. Hence investigations are required as to how *Entada* sensed the availability of support trees across tree gaps, the time and rate of elongation of stolons and the chemical cues directing their aerial trajectory towards the available crown. Indeed, it was the aerial stolons traversing a road junction over a lamp post which attracted the attention of two authors to an unusual plant type growing in the campus. Following contact with the crown of support trees, the stolons have branched and much of their twisted woody branches appear to support each other (self-support), with this being augmented by the branches that have infiltrated into the trees. A stand of bamboo culms accessed across a gap due to a road is bent down to a greater degree than the uninfested culms, either because of the weight of *Entada* or because *Entada* exerted a force to pull them down. Structural adjustments that are required to counter stress and strain as a consequence of tension due to pull need investigation.

Figure 4. Mode of spread in *E. pursaetha*. ***a***, Leafless aerial shoots navigating across a gap towards tree canopy. ***b***, Horizontally extending shoots traversing a gap between trees and bypassing an inanimate support (lamp post) in a road junction in their trajectory towards living trees. Since this photograph was taken, the aerial stolons (cable-like stems) have been cut as these were posing a hazard to vehicular traffic.

Figure 5. Invasive growth. Aerial stolon (arrow) crossing tree gap to spread on crown of tree canopy.

Since the aerial stolons are oriented towards a vegetated tract across a tarred road without crisscrossing (Figure 4), a possibility is that other than phototropism, some volatile chemicals produced by the 'host' trees not only provided a cue for the development of cables, but also directed their extension towards trellises. This speculation is supported by a recent finding that volatile compounds, α-pinene, β-myrcene, 2-carene, *p*-cymene, β-phellandrene, limonene, (*E*,*E*)-4,8,12-trimethyl-1,3,7,11-tridecatetraene and an unidentified monoterpene released by tomato plant guide the dodder vine, *Cuscuta pentagona*[14]. Rowe and Speck[15] have illustrated 'searcher branches' in a woody liana *Strychnos* sp. (Loganiaceae), having a cable-like appearance and extending horizontally 3–4 m across the canopy gap to locate new support. Upon contact with a neighbouring tree, the *Entada* cables (stolons) differentiated normal foliage, viz. compound leaves with thick leaflets. The branches of *Entada* have infiltrated and entangled with that of *Bauhinia purpurea*, *Cassia spectabilis*, *Broussonetia papyrifera*, *Tebebuia rosea*, *Eucalyptus tereticornis*, *Tectona grandis* and *Bambusa* sp. However, we have not observed *Entada* on dead branches of standing trees, raising the possibility of requirement of living support trees for infestation. Since coiling, bending or flexing and differentiating into morphologically distinct parts occur in response to contact, the phenomenon of thigmomorphogenesis appears to be important in the infiltration and spread of *Entada* on living trees.

We have not observed new cables (aerial stolons) being formed in the four years since regular observation of *Entada*, suggesting that there could be periodicity of years in triggering its development. Some bamboos behave similarly[16]. A contentious explanation is that the aerial stolons were formed in response to some unusual weather trigger. Perhaps, more likely is periodicity in their development. Possibly these were stiff as the culms of bamboo, and extended rapidly across tree gaps. Based on an estimate of its spread size and the timescale, it appears that *Entada* could be amongst the fastest growing plants; rivalling the bamboos in which the culms grow almost 4 ft in a 24 h period (www.lewisbamboo.com/habits.html). The fast growth rate of stolons against gravity will enable them to take mechanical risk[17].

Cable-like stolon along the ground surface with ascending apex was illustrated in a palm *Desmoncus orthacanthus*, growing in the rainforests in South America[18] and in rhizomatous shrub *Xanthorhiza simplicissima*, growing in the Botanical Garden in Freiburg, Germany[19]. However, data on its rate of extension was not given. Penalosa[7] reported a liana *Ipomoea phillomega* in the rainforest of Mexico, with leafless, creeping stems (stolons) on the ground that extend up to 30 m at a mean rate of 13.6 cm/day, and turning upwards in a *S*-shaped manner upon contact with a potential support and twining around a support host in sunny clearings. The climber *Clematis* *maritima* changes its morphology when growing on aboveground areas and on sand[17]. We have not observed surface-growing stems in adult *Entada*. Its aerial stolons changed morphology upon accessing a support tree, suggesting that in addition to light and circumnavigational movement, contact-induced differentiation of foliage is important in mechanistic explanation of *Entada* spread on crowns of support trees as a straggler. Trellis availability is a major factor determining the success of canopy-bound lianas[20].

Hydraulic supply

The parent and the interconnected daughter canopies of *Entada* are founded on a single germinated seed and hence on a single root system. Since the aerial stolons ultimately connect to the rooted trunk, these must constitute the hydraulic system for the entire canopy.

When aerial stolons (cables) extending across a road junction, posing hazard to motorists were cut, colourless, watery sap trickled from the cut cables. This suggests that water is translocated by root pressure, requiring development of non-destructive methods for investigation of its underground parts. Apparently, the twists in plant structure do not resist the movement of water, making *Entada* a good material for investigations of pressure-generating capability for water movement, compared to a tree. Following severing, the daughter canopies differentiated by aerial stolons and distributed on surrounding trees dried, confirming that the aerial cables constitute the hydraulic supply system and the structural form for the spread of the canopy on support trees.

Ecophysiology

Occasionally, a terminal leaflet in the pinnate compound leaves of *Entada* is modified into a forked tendril (Figure 6 *b*). Tendril development may be influenced by the amount of light filtering through the canopy, and its function may only be to orient the leaf for maximal absorption of sunlight by the canopy in natural habitat under cloudy conditions. A visual comparison of the density of *Entada* foliage with that of the surrounding trees suggests that this liana invests more of photosynthetically fixed carbon in woody branches, which have a capacity to resprout after breakage.

The first sighting of a single 12 inches long, green pod was in May 2003, and again in 2005 and 2008. It therefore appears that fruiting in the alien environment is a rare phenomenon, for unknown reasons. Although being a leguminous plant, *Entada* is assumed to be self-pollinated, the lack of a pollinator species could account for its rare fruiting. Further observations are required to determine if flowering and fruiting in the daughter canopies is synchronized with that of the interconnected parent canopy. Brandis[2] described fruits of *E. pursaetha* as 2–4 ft long and 3–4 inches broad. An *Entada* pod in the Phansad Wildlife Sanctuary (about 152 km from Mumbai) was found to be nearly 6 ft long. *Entada* pods are therefore among the largest legumes.

The ability to produce large pods with rather large seeds[2,3] suggests a high photosynthetic rate. It is believed that lianas have a fast growth rate because of their high photosynthetic rate due to elevated CO_2 in the canopy[21]. Contrary to popular belief, liana density and growth are unrelated to the mean annual precipitation[19,21,22]. Schnitzer[22] reported that lianas grow nearly twice as much as trees during the wet season, but more than seven times that of trees during the dry season. This observation was corroborated by Swaine and Grace[23]. In view of the requirement of seedling material for experimental investigations in the laboratory, the reproductive biology of *Entada* assumes special importance.

Regeneration

Aerial stolons (diameter approximately <10 cm) that had begun to cause obstruction to vehicular traffic were cut. Two to four metre long cut pieces of woody stems (diameter 20–30 cm) were gathered and left in the open. In about 4 weeks the cut stems sprouted one to 1½ m tall shoots with stiff, erect stems producing foliage (Figure 6). Since sprouting occurred during the dry season, this observation signifies that *Entada* stores considerable water inside the stem tissue. However, the cut stems did not root, and the sprouts dried after the rains ceased. However, the ability of cut stems to resprout has implication in its natural habitat where strong wind and rain prevail: The branches that are unable to resist wind-induced breakage or those that are unstable under their own weight may fall on the ground and function as ramets (vegetatively produced, independent plants). This raises the question of the specific contribution of the ramets (broken and fallen branches that resprout and form roots) versus the genets (single individual plants from sexually formed seeds) in the composition of *Entada* thickets in its natural habitat. In Panama, Putz[20] noted the propensity for lianas to sprout vigorously from fallen stems. Based

Figure 6. Regeneration in *E. pursaetha*. ***a***, Sprouting of shoots in cut, aerial stolons and attached branch. ***b***, Forked leaf tendril (arrow) showing anticlockwise twining.

Table 1. Summary of salient characters of *Entada pursaetha*

Observation	Phenomenon implied
Seeds required scarification and incubation in pond water for germination	Mechanical dormancy
Free-standing, upright trunk formed by conjoining of basally sprouted branches	Circumnutation of coppices and thigmomorphogenesis
Anticlockwise twists throughout mature plant body	Morphological plasticity
Branches lean on support trees	Discrimination of living support?
Navigation towards canopy of support trees across large gaps by leafless aerial stolons (remote sensing)	Perception of chemical cues
Time taken by genet to spread canopy on neighbouring trees <17 yrs	Rapid growth
Aerial stolons produce foliage following contact and infiltration into support trees	Thigmomorphogenesis
Infrequent fruiting despite profuse flowering	Dependency on a pollinator?
Pod >2 ft, seeds large	High photosynthetic rate, large maternal investment
Terminal leaflet modifies into tendril	Interception of light filtering through canopy and response to quantity and quality of light
Maintained greenness and spread over 1.6 ha despite seasonal drought	Deep root system, high root pressure

Table 2. Research problems for which an introduced *Entada* can be especially valuable

Research area	Description
Biological species invasion	Tracking the timetable, speed for navigation of aerial stolons towards support trees. Navigation of aerial stolons – evidence for chemical cues.
Plant biomechanics	Measurement and comparison of root pressure, transpiration rate, ascent of water to canopy, causes of anticlockwise twists and helical geometry and flexural rigidity of stems, xylem architecture and water transport, and correlation of anatomical parameters of different stem types with structural bending modulus. Reasons for the formation of ‘screw’ type reaction wood (Figure 2).
Plant morphogenesis	Mechanoperception of support trees and differentiation of foliage, germination of seeds, seedling morphology, and role of circumnutation behaviour in seedling for construction of self-supporting trunk.
Plant physiology, horticulture	Rooting of ramets, growth rate and response to light, estimation of compensation point.
Plant population genetics	DNA analysis for differentiation of ramets versus genets
Plant microbiology	Benefit from nitrogen-fixing ability. Possible benefit to trellises from symbiotic nitrogen-fixing ability of leguminous liana
Plant reproductive biology	Causes of irregular fruit set, quantitization of viable seeds produced/individual
Ecophysiology	Mechanisms in photosynthetic acclimation to light changes in canopy because of density of foliage, determination of compensation point
Plant ecology	Periodicity in formation of navigating aerial stolons, timetable of their development and speed of extension, the estimation of life-span, comparative analyses of inorganic nutrients (N, P, K, Ca, Mg) in soils in the campus and the wetlands (natural habitat).

on seedling excavations, Putz found that 90% liana species in the understorey were ramets.

Paradox of growth in alien environment

The factors that may explain an alien liana thriving in a place which receives only about 95 cm annual rainfall and where the soil surface (red earth) is generally dry, except for the monsoon months (May–September) are:

(1) Foremost, a safe mode of infiltration on available support trees by means of aerially formed stolons, thereby avoiding risk of injury from trampling by grazing animals.

(2) Nutrient-rich soil in the campus (the soils in rainforests is generally nutrient-poor because of the leaching of nutrients by rains through the millennia[5,24]).

(3) Presumed deep root system of *Entada* allowing access to water table, or water which seeped down from a

nearby stream. This is in keeping with a report[25] that root systems in excavated liana seedlings of *Davilla kunthii* (Dilleniaceae) in eastern Amazonia were more than eight times longer than the aboveground stem.

(4) Higher solar illumination[26].

(5) Absence of herbivores or pathogens and less competition for resources as more area is available for aerial spread, root growth and nutrient absorption, unlike in dense vegetated tropical forests.

Finally, what explains the distribution of *Entada* in coastal sea areas and river banks? Water may play a key role for dispersal as well as for breaking of dormancy of big, heavy *Entada* seeds. The presence of aquatic microorganisms and the lytic enzymes leached from them would soften the testa.

Despite the extensive spread of *Entada* genet in an alien environment, we are hesitant in attributing this as 'success', since ecologically 'success' is a measure of reproductive efficiency, namely the number of individual genets or ramets per unit area and density of liana growth[26]. Success of introduced *Entada* can only be assessed if it becomes naturalized by production of new genets or ramets.

Conclusion

A solitary *Entada* genet introduced in a research campus has provided an opportunity to observe new morphological features in a giant liana (Table 1), raising questions and ideas on the ecology of the lianas and the biomechanics of lianoid forms (Table 2). Some of the lead questions that have arisen from its regular observations are: (1) How did the liana construct the self-supporting trunk? (2) How does the liana sense availability of support tree from distance? (3) How do the aerial, cable-like stolons navigate precisely for infiltrating into the tree canopy? (4) How does the liana apply force to pull down a support (bamboo)? (5) What mechanisms liana uses to perceive and avoid an inadequate support in its trajectory? (6) How might have the liana growth habit evolved? (7) What is the lifespan of liana? (The general belief being that lianas have a long life-span). (8) Does *Entada* require a living tree for support?

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