An ancient wind-powered iron smelting technology in Sri Lanka

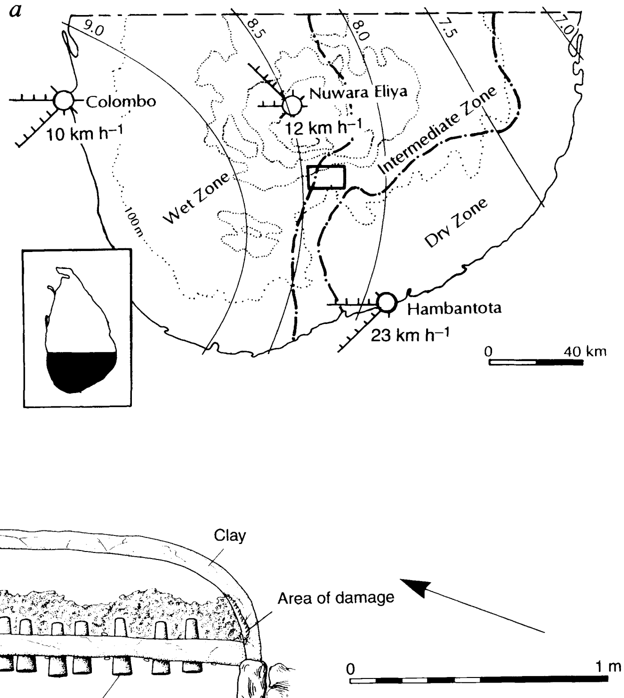
Gill Juleff

Samanalawewa Archaeological Project, Archaeological Department of Sri Lanka, Sir Marcus Fernando Mawatha, Colombo 7, Sri Lanka and University College London, Institute of Archaeology, 31–34 Gordon Square, London WC1H 0PY, UK

Before the development of the blast furnace, iron smelting was achieved by ore reduction at temperatures below the melting point of the metal, forming an agglomerated 'bloom' of low-carbon iron and slag. The forced-draught (bellows-operated) shaft furnace known from archaeological studies is usually regarded as the pinnacle of this early smelting technology[1-3]. Examples of natural-draught furnaces, in which gas buoyancy in a shaft of sufficient height induces a draught adequate to drive the smelting process[4], are also known, but are generally regarded as disappointingly inefficient by comparison[5]. Here I report the discovery and excavation at Samanalawewa, Sri Lanka, of a previously unknown furnace type. The furnaces are all situated on the western margins of hills and ridges, where they are exposed to the strong monsoon winds. Field trials using replica furnaces confirm that this furnace type uses a wind-based air-supply principle that is distinct from either forced or natural draught, and show also that it is capable of producing high-carbon steel. This technology sustained a major industry in this area during the first millennium AD, and may have contributed to South Asia's early pre-eminence in steel production.

Peninsular India, including Sri Lanka, is known for its rich ferrous archaeometallurgy; references, particularly those in classical and Islamic literature, to India as a source of high-quality steels have attracted considerable interest[6-10]. Given the assumed limitations of bloomery smelting, such steels are regarded (with few exceptions) as necessarily the product of secondary refining processes. In South Asia, high-carbon crucible steels are well documented from the eleventh century AD onwards; a form of such a steel, known as *wootz*, was the raw material of mediaeval Indo-Islamic 'Damascus' swords[8,11-15]. The investigation of the technology at Samanalawewa now indicates that comparable steels were produced directly, and in substantial quantities, in sophisticated 'frontal' smelting furnaces driven by wind-pressure.

Samanalawewa lies in hilly terrain between the lowland plains and central highlands of Sri Lanka (Fig. 1*a*). Its climate is dominated from June to September by desiccating winds associated with the southwest monsoon, which brings rain to the Wet Zone and *föhn* winds to the Intermediate and Dry zones[16] (Fig. 1*a*). A plentiful supply of ore is ensured by numerous small hill-top deposits of secondary iron oxyhydroxides, common throughout southern Sri Lanka[17,18]. Archaeological surveys, undertaken since 1988 as part of a hydro-electric scheme from which the area takes its name, have identified[19] (within an area of 60 km^2) 139 iron-working sites spanning 2,000 years. The technology described here is evidenced by 77 'west-facing' smelting sites, which form the largest component of the record. These are



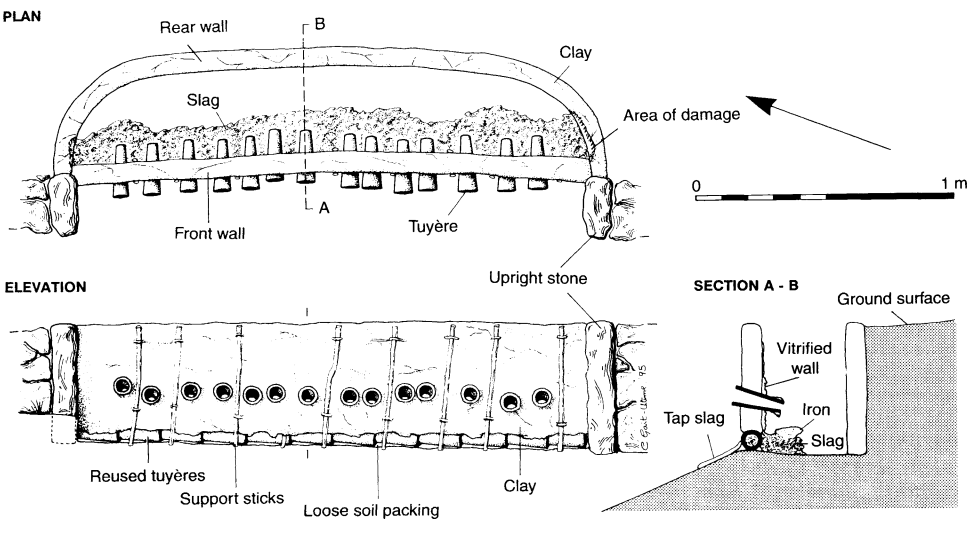


FIG. 1 *a* Map of southern Sri Lanka showing the project area (within rectangle) and major climate divisions. Contour interval is 500 m unless marked. Also shown are July wind and pressure statistics for three meteorological stations, including percentage frequency of wind direction (in divisions of 10%), average wind speed (km h^{-1}) and pressure isobars (above 1,000 mbar)[29]. Data collected from the study area over four monsoons (1990–92 and 1994) reveal a pattern of near-mono-directional, high-velocity winds of mean speed 31.5 km h^{-1}. Prevailing winds are west-northwest and west, although incident winds vary with local topography. *b*, Furnace used in smelting trials, reconstructed from archaeological data, comprising two elements; a semi-permanent rear wall and a temporary front wall. The rear wall is aligned north–south and curves westwards at each end to terminate with upright stones. The front wall, constructed between the two upright stones, is rebuilt with each smelt. From archaeological examples, furnace lengths (north–south axis) range from 1.2 to 2.3 m, while depth-in-plan (east–west axis) shows little variation, averaging 0.4 m. Furnace height, from base to rim of rear wall, is no more than 0.5 m. The supporting framework of sticks incorporated here into the front wall was the only feature for which there was no archaeological evidence. The front wall is designed to withstand the aggressive action of vitrification and slag formation during smelting, and to be broken at the end of the smelt. Greatest durability is imparted by the pre-fired, reused tuyères at the base where molten slag collects. These tuyères had already been used in the conventional manner, that is, as refractory conduits through which air entered the furnace. Multiple tuyères are generally equated with non-bellows furnaces. The re-used tuyères also act as a self-tapping mechanism, allowing slag to flow out of the furnace. Here the front wall was constructed abutting both rear wall and upright stones, whereas in archaeological examples it abuts the upright stones only. The stones thus serve as buffers between the two walls, helping to leave the rear wall free of damage in all but the extreme 'corners'.

all situated on the western margins of hill-tops and ridges, and the coincidence of the strongest incident winds during the monsoon with the locations of slag waste concentrations gave the first clue to wind utilisation.

Because metal products were rarely abandoned at their site of manufacture, slags are the principal indicators of furnace type and process for most research in extractive archaeometallurgy. In this case, the dominant forms are large, highly distinctive, sub-rectangular blocks of furnace slag. In these, slag has solidified against a horizontal line of reused tuyères; one tuyère telescoped into another to form the foundation of a straight furnace wall (Fig. 1*b*). To resolve the nature of the furnaces in which these slags formed, excavations were undertaken at one of the larger west-facing sites. The stratigraphic sequence of the site, covering $\sim 3,000\,\mathrm{m}^2$ on a ridge aligned north–south, revealed regular, episodic activity devoted exclusively to smelting. Eight radiocarbon dates from charcoal place[20] the use of the site between the seventh and early eleventh centuries AD. Approximately 20% of the site volume was investigated, revealing 41 furnace structures, all precisely positioned along the western brow of the ridge and oriented to face the incident wind. Furnaces conform to the basic two-component design shown in Fig. 1*b*. Rear walls were well preserved *in situ* whereas front walls were reconstructed from associated scatters of slag and clay fragments from the dismantled structures. Vitrification patterns and damage to rear walls caused by slag removal indicated maximum temperatures along the front wall and in the two furnace 'corners'.

From survey data, and by extrapolation from quantitative sampling during excavation, the product output from the known sites is conservatively estimated at $\sim 3,500$ tonnes. Indications are that the industry, clearly successful, well organized and probably centrally controlled, was not restricted to Samanalawewa but extended into adjoining areas. Evidence from a single site within the area suggests the technology had roots in at least the third century BC (G.J., manuscript in preparation). Having reached a zenith in the ninth century, the industry disappears from the archaeological record in the eleventh century, probably as a result of incursions from South India which brought political and demographic upheaval, and eventually the end of Sri Lanka's Dry Zone civilisation[21].

'Wind-blown' iron smelting has not been reported with conviction from any part of the world and the possibility of such smelting had been largely discounted; the principal objection was based on the tacit assumption that the action of the wind would emulate that of bellows—that is, by blowing directly into the furnace (via tuyères)—and that gusting and calms, no matter how short, would produce an uncontrollable system liable to irreversible 'freezing'[10]. In addition, it was difficult to imagine that reducing conditions could be maintained in such an 'open' structure. To address these questions replication trials were carried out in July 1994, including three full smelts (trials 3, 4 and 5). Two new furnaces were constructed (Fig. 1*b*) at a west-facing site, ensuring that their orientation replicated that of archaeological furnaces at the site. Ore (79–87% $\mathrm{Fe_2O_3}$) was collected from local deposits, and charcoal prepared from timber of a single species, *Syzygium spathulatum*; one of the three *Syzygium*s exploited preferentially for charcoal from the third century BC onwards. Wind speeds were recorded throughout, and during trial 5 furnace temperatures were measured using an optical pyrometer (Fig. 2). Progressive changes were made in ore/fuel ratios, from 1 : 1.5 to 1.5 : 1. In trials 4 and 5, the ore was roasted for 30 minutes over a charcoal fire before placing it (charging) into the furnace and, in trial 5, ore size was halved, from ~ 30 mm.

Each smelt followed the same procedure, beginning with a two-hour preheat, burning charcoal only, followed by the gradual addition, over ~ 3.5 hours, of pre-weighed, alternately layered, ore/charcoal charges (total ore 81, 95 and 126 kg respectively). Tap slag formed readily, within an hour of the first ore charge, the time decreasing with successive smelts, and flowed through the line of re-used tuyères at the base of the front wall. After a further 1.5 hours charging charcoal only, the stockline was allowed to burn down from rim to half furnace height (~ 1.5 h). To end the smelt, the front wall was pushed inwards and the furnace contents (charcoal, slag, metal and the broken front wall) dragged westwards out of the furnace. Increasing ore/fuel ratios, ore roasting and reduction in ore size all contributed to enhanced reactivity

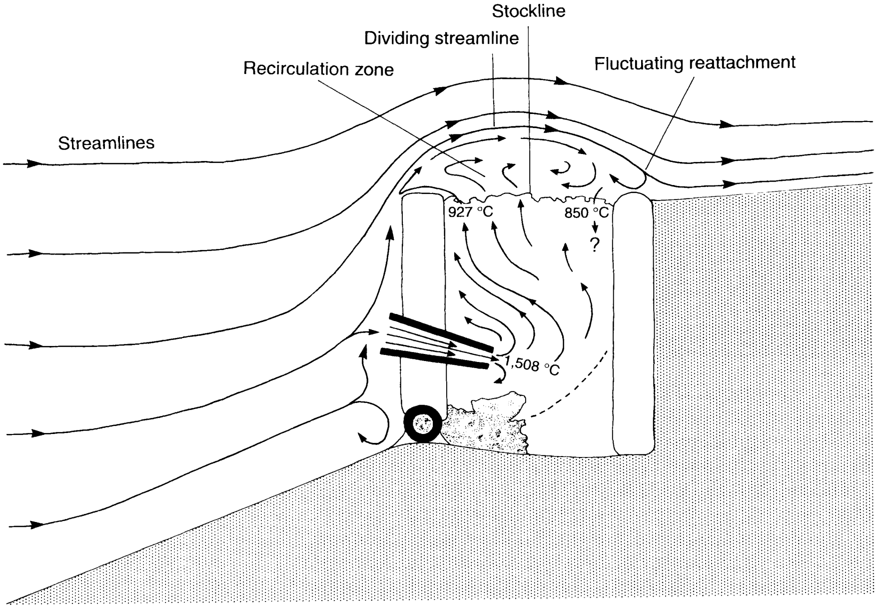


FIG. 2 Furnace cross-section showing observed and postulated airflow, and maximum combustion zone and furnace-top temperatures recorded during trial 5. Wind close to ground level, flowing upslope, reaches maximum acceleration at the crest of the hill where it encounters the furnace. As it is forced over the front wall, boundary layer separation occurs creating a recirculation 'bubble', capping the top of the furnace; low pressure within the bubble draws the dividing streamline downwards again until it reattaches at a point close to the rear wall. Within the bubble, which preserves low pressure, heat and reducing conditions, trapped combustion gases (clearly visible at night) flow along the north–south axis of the furnace perpendicular to the incident wind. The point of lowest pressure occurs towards the outer lip of the front wall and airflow within the furnace is towards this point, producing the smelting curtain or 'front' seen along the front wall. This 'front' remained dimensionally stable (at about one-third of furnace depth-in-plan) throughout the smelts and, although increasing wind speed intensified its incandescence, it did not increase its penetration into the charcoal bed. This observation demonstrates that there is little effect from wind blowing directly into the furnace, which in turn affords the system a measure of stability; its response to changes in wind speed is slow, negating the effects of gusting. In trial 5, a 1.5-hour period of low wind speeds ($< 15\,\mathrm{km\,h^{-1}}$) caused only a gradual lowering of the mean combustion zone temperature from 1,454 to 1,336 °C. (The temperatures reached in trial 4 (mean wind speed $44\,\mathrm{km\,h^{-1}}$), although not measured would have been in excess of those noted here.) Increased combustion at the front wall also results in a physical gradient allowing charcoal and ore to fall towards the front, rather than falling, unreacted, to the back of the furnace. The front wall, and in particular its outer lip, would be critical in creating the desired airflow and pressure regime and was probably modelled with greater precision in ancient times.

and yields with successive trials. The most successful charging regime was achieved in trial 5, yielding 17 kg metal despite low wind speeds (mean 22 km h^{-1}). The strongest winds prevailed during trial 4 (mean 44 km h^{-1}), giving the highest fuel consumption (2.2 kg per h per tuyère). Replication by the trials of characteristic features of the archaeological slags, furnace wall vitrification patterns and post-smelt debris arrays gives veracity to the interpretations drawn from the experiments.

The trials demonstrated visibly that high temperatures and smelting reactions are concentrated immediately inside the front wall (Fig. 2). From this, and observations of gas flow at the top of the furnace, it appears that the system is driven by wind flow over the front wall creating a low-pressure zone at the top of the wall. This results in a steep pressure gradient between the external tuyère mouth and the top of the furnace, which then pulls air through the tuyères. Fluid-mechanics calculations, based on wind velocities measured during trial 4 and using conservatively estimated parameters, predict a pressure drop of the order of 50 N m^{-2}. In contrast, gas buoyancy, as in a natural-draught furnace, has little or no effect in this furnace, of only 0.35 m height (tuyère nozzle to furnace rim); the relevant calculation predicting a pressure drop of < 3 N m^{-2} (D. J. Wilson, personal communication). The air supply mechanism described gives continuous aspiration, as compared with the intermittent pumping of bellows, which is recognized as decisive in achieving the high temperatures needed to promote carburization.

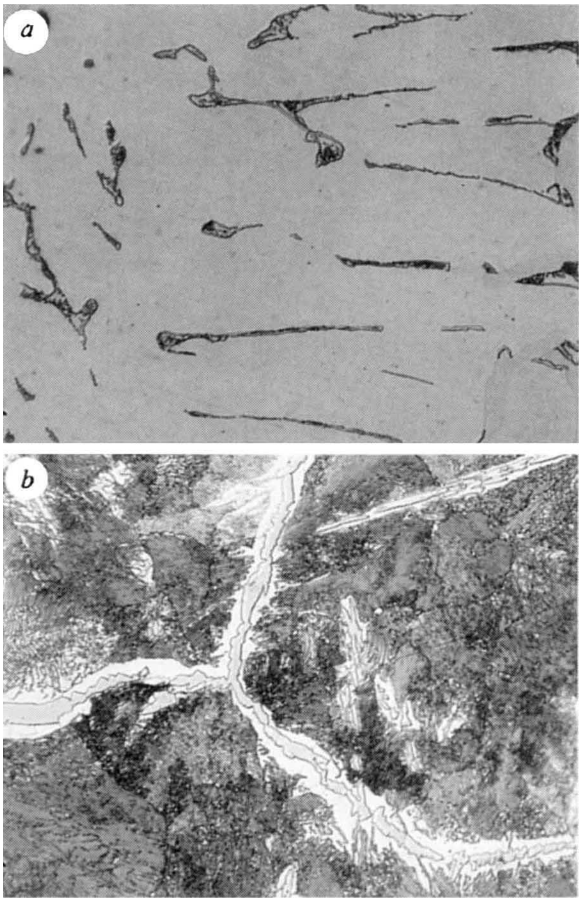


FIG. 3 *a*, Optical micrograph of low-carbon iron with estimated 0.1% C, consisting of ferrite with a small amount of pearlite. The sample shown was etched with nital; magnification ×710). A 270-g fragment of similar material, from trial 4, was forged by local blacksmiths into a bar weighing 125 g, demonstrating that approximately half comprised entrapped slag. *b*, Optical micrograph of hypereutectoid steel typical of that from the top of the furnace slag, showing proeutectoid cementite (Fe_3C) on grain boundaries, in pearlite matrix. The pearlite is both lamellar (extreme left) and degenerate with some spheroidization (elsewhere). The estimated carbon content within this sample is 0.6 to >1%, with the area shown being >0.8% C. The sample shown was etched with nital; magnification, ×710 (M. L. Wayman, personal communication). The mechanism by which the metal lowest and longest in the furnace has absorbed carbon to such an extent has yet to be investigated, but parallels may be drawn with the mechanisms described for the *Tatara* process[24]. Together, the products from the trials suggest successful, but not fully optimized, smelts. Given further experimentation, it is possible to envisage better consolidation of all the reduced metal, more uniform carburization, and complete metal/slag separation.

In characterizing this furnace, the term 'frontal', expressing both smelting zone and overall furnace geometry, is used to distinguish it from the axial symmetry of the shaft (and blast) furnace. This frontal configuration provides the largest smelting zone for a given furnace volume and allows variable capacity: once depth-in-plan (east–west axis) is optimized for the expected air supply regime, the furnace can be substantially enlarged by lengthening the structure. Two ancestral Sri Lankan furnace forms show progressive evolution of the 'frontal' concept, namely the third century BC Samanalawewa example, and the first century BC to third century AD examples from Sigiriya[22]. Both have front walls that increase in length, over time, from 0.5 to 0.95 m, the depth-in-plan remaining at ~ 0.5 m. Similar frontal design is recognizable in other furnaces not driven by wind, for example, the natural-draught furnaces of Burma[23] and the bellows-operated *Tatara* of Japan[24], both used for iron smelting. The latter is one of the very few pre-modern processes capable of producing usable quantities of high-carbon steel. Whether historical connections exist between these Asian technologies deserves investigation. As the data stands, the west-facing furnaces seem to represent an independent development with no known parallels in India, the assumed cultural well-spring of Sri Lanka.

Metal products from the trials divide into two general types, stratified within the furnace: an upper layer of detached 'blooms', and a lower layer of well consolidated metal still adhering to the furnace slag (Fig. 1*b*). No metal was found embedded in archaeological slags, and incomplete metal/slag separation was a shortcoming in the trials. Metallographic analysis (Fig. 3) of the detached metal reveals generally low-carbon iron in forms typical of the varying stages in bloomery smelting[25]. In contrast, and unexpectedly, the metal attached to the slag (comprising ~50% of the metal produced) is relatively slag-free and predominantly high in carbon, and can be classed as high-carbon steel. Carburization, although heterogeneous, is sufficiently extensive to indicate a sought-after product rather than fortuitous occurrence. This finding has important bearing on a ninth century Islamic reference[8,14,26], describing the use of *Sarandibi* (Sri Lankan) steels in sword-manufacture. Whereas previously it was assumed that this referred, by extrapolation from later accounts, to crucible steel, it now seems probable that the material in question was 'furnace steel'. Sri Lanka's well established Indian Ocean trade links makes distribution of products from the west-facing sites entirely feasible, and dated artefact finds from Sri Lanka[27] and the east coast of Africa[28] demonstrate that high-carbon steels were in circulation at the time. The data presented here provide the earliest dated field evidence from South Asia for the industrialized production of high-carbon steel. ☐

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Evolution of extreme specialization within a lineage of ectomycorrhizal epiparasites

K. W. Cullings*, T. M. Szaro & T. D. Bruns

Department of Environmental Science, Policy, and Management, University of California, Berkeley, California 94720 USA

MONOTROPES (Monotropoideae, Ericaceae) are achlorophyllous, epiparasitic plants that receive all of their fixed carbon from green plants through a common ectomycorrhizal association rather than by a direct parasitic connection (Fig. 1)[1,2]. Using molecular identification methods we show that some monotropes are highly specific in their fungal associations and at least one species, *Pterospora andromedea*, is specialized on a single species group within the genus *Rhizopogon*. Phylogenetic analysis of the Monotropoideae shows that specialization has been derived through narrowing of fungal associations within the lineage containing *P. andromedea*. High specificity is contrary to past predictions for the Monotropoideae and for plant communities in general, raising many questions about the roles of mycorrhizal specificity in ecosystem function.

Ectomycorrhizae are mutualistic associations between a vascular plant root and a fungus; they are the dominant nutrient-gathering organs in most temperate forest ecosystems[3]. These mutualisms vary from general to specific, but when specificity occurs it is one-sided: fungal species may be specific to a single plant species or genus, but plants typically have dozens or even thousands of fungal associates[4,5]. Plant specificity has been assumed to inhibit the ability of establishing seedlings to form new mycorrhizal associations[6,7], and because monotropes are entirely dependent on these associations, it has been suggested that they should be generalists[6]. This view was supported by a previous survey of monotrope associates that was based primarily on proximity of these plants to fungal sporocarps[8].

To test the hypothesis that monotropes associate with many unrelated fungi, we used three different complementary polymerase chain reaction-based methods to identify fungal associates of four of the most common monotrope species: *Pterospora andromedea*, *Monotropa hypopithys*, *Monotropa uniflora*, and *Sarcodes sanguinea*. Results show a variety of fungal associates and levels of specificity within the monotropes (Table 1). *Sarcodes sanguinea* appears to be a generalist that associates with at least three unrelated families of fungi. Although our sampling of *Monotropa* species was more limited, our results indicate that both may be specialists. *Monotropa hypopithys* was associated only with suilloid fungi, a monophyletic group that includes *Rhizopogon* and *Suillus*[9,10], whereas *M. uniflora* individuals collected from widely divergent habitats were all associated with fungi in the Russulaceae. *Pterospora andromedea* was found to be an extreme specialist. All 31 individuals, collected from a broad geographic region, were associated with the *Rhizopogon subcaerulescens* species group (Table 1). These results indicate a higher level of ectomycorrhizal specificity for *P. andromedea* than has been reported for any ectomycorrhizal plant. In comparison, *Alnus rubra*, which is considered to be exceptionally specialized, associates with 30 fungal species, many of which are only distantly related to each other[11].

We can reject the idea that specificity of *P. andromedea* is based on a lack of opportunity to associate with other fungi for the following reasons. (1) Ectomycorrhizal fungal diversity is very high within small pine monocultures; even adjacent root tips are frequently colonized by different fungi[12]. (2) Suilloid fungi, though they produce numerous fruiting bodies in such forests, often account for a very low percentage of the colonized tree roots[13,14]. (3) In the five locations where *P. andromedea* occurred with *M. hypopithys* or *S. sanguinea*, the latter two species were associated with different fungi (Table 1). (4) We analysed host tree roots present within the root ball of one *P. andromedea* and adjacent tree roots within 0.5 metres of three other *P. andromedea* plants and found that *R. subcaerulescens*, though present on the

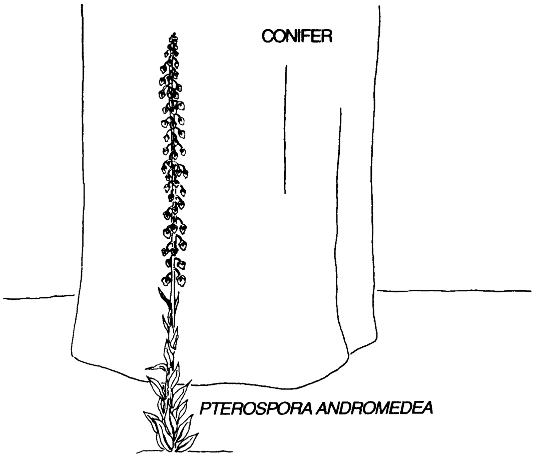

FIG. 1 Schematic summary of mycorrhizal epiparasitism in the Monotropoideae. Carbon fixed by the surrounding trees is transferred via a shared mycorrhizal fungus to the achlorophyllous monotrope: no direct connection between the two plants exists. The monotropes discussed in this paper have a compact root ball of mycorrhizae. The tree mycorrhizae, which are more diffuse in arrangement and more diverse in fungal associates, are often found within the root balls of the monotropes but are morphologically distinct.

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*Present address Department of Biology, San Francisco State University, California 94132, USA