0.10–0.18 have been suggested for dense coniferous forest[4,5]; this would increase the EESF by approximately 25 t C ha^{-1} in the most snow-covered regions.

Here I have considered forestation under present-day conditions, but the effects of future CO_2 rise and climate change are likely to affect the magnitude of both radiative forcing terms, due to dependencies on time-varying quantities such as the atmospheric CO_2 concentration, snow extent and vegetation structure and leafiness. As the atmospheric CO_2 concentration increases, CO_2 fertilization is likely to increase carbon uptake[22] so the magnitude of the negative sequestration forcing should therefore increase, although associated climate changes may exert additional positive or negative effects on sequestration. Warmer temperatures may reduce the extent of snow cover[23], but the leaf area index (LAI) of potential vegetation may increase[24,25], so the albedo forcing could either increase or decrease. The effect of vegetation on surface albedo is not necessarily proportional to biomass, so the net contribution to radiative forcing may not evolve linearly throughout a forest's development; albedo depends on canopy density and architecture, and can become low rapidly, whereas carbon sequestration depends largely on woody biomass which is more gradually accumulated. Other contributions to forcing may also require consideration; for example, the longwave radiation budget could be affected by modified surface emissivity[25], although the sign of such changes is uncertain[25,26].

The work I report here has focused on perturbations to the Earth's radiation budget, which is the fundamental driver of the climate system. Forestation may also influence the climate by modifying the fluxes of heat, moisture and momentum between the land surface and atmosphere. Whereas boreal forests warm their local climate through reduced albedo, tropical forests tend to cool and moisten their local climates by greatly enhancing evaporation. Both may also influence distant regional climates via the atmospheric circulation[9,27]. Assessment of the effect of forestation on climate at a given time in the future will require simulations with a climate model that incorporates vegetation dynamics[25,28] and other atmospheric, terrestrial and oceanic components of the carbon cycle[28], in which forest growth occurs at appropriate rates in relation to changes in atmospheric CO_2 and snow cover. Nevertheless, my results suggest that high-latitude forestation would exert a positive radiative forcing through reduced albedo that in many places could outweigh the negative forcing through carbon sequestration. If afforestation and reforestation are required to decrease radiative forcing rather than simply to reduce net CO_2 emissions, then changes in surface albedo must also be considered. □

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An artificial landscape-scale fishery in the Bolivian Amazon

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Historical ecologists working in the Neotropics argue that the present natural environment is an historical product of human intentionality and ingenuity, a creation that is imposed, built, managed and maintained by the collective multigenerational knowledge and experience of Native Americans[1,2]. In the past 12,000 years, indigenous peoples transformed the environment, creating what we now recognize as the rich ecological mosaic of the Neotropics[3–6]. The prehispanic savanna peoples of the Bolivian Amazon built an anthropogenic landscape through the construction of raised fields, large settlement mounds, and earthen causeways[7,8]. I have studied a complex artificial network of hydraulic earthworks covering 525 km^2 in the Baures region of Bolivia. Here I identify a particular form of earthwork, the zigzag structure, as a fish weir, on the basis of form, orientation, location, association with other hydraulic works and ethnographic analogy.

The native peoples used this technology to harvest sufficient animal protein to sustain large and dense populations in a savanna environment.

The zigzag structure is a particular form of artificial earthwork, found in the seasonally inundated savanna of Baures, Bolivia (Province of Iténez, Department of the Beni) (Figs 1 and 2). Zigzag structures are linear segments of raised earth (1–2 m wide and 20–50 cm tall) that change direction every 10–30 m (Fig. 3). Shrubs, palms, and termite mounds cover the structures. Many zigzag structures cross the savanna from one forest island to another, distances of up to 3.5 km; others terminate 5,000–1,000 m from the forest edge (Fig. 4). Funnel-like openings, 1–3 m long and 1–2 m wide, are present where the structures form a sharp angle (Fig. 5). The structures are associated with small circular ponds. Dense networks of interconnected zigzag structures form enclosures of 10–80 ha. A total of 48.431 linear kilometres of weirs were measured in a sample area of 16.755 km^2 of savanna, a density of 2.891 linear km per km^2.

The zigzag structures are artificial constructions created by raising earth removed from the adjacent savanna. Canals or barrow pits flank some of the zigzag structures. Although overlapping in distribution, the zigzag structures are distinct from the long, wide and straight causeways and canals that cross the savanna between forest islands (Fig. 4). The narrow and irregular zigzag structures would be inefficient for transportation. The zigzag structures do not appear to have functioned as check dams or berms for flood-recessional farming. There is no evidence of crop furrows or field platforms between the structures.

On the basis of location, form, patterning, associations and ethnographic analogy, I identify the zigzag structures as fish weirs. Fish migrate to and spawn in the seasonally inundated savannas of Baures during the wet season[9]. Many fish are trapped in water bodies as the floodwaters recede. The zigzag structures provided a means to manage and harvest these fish. The zigzag structures are similar to fish weirs built by native peoples in Bolivia[10–14] and throughout the Americas[15–17]. Two characteristics shared by fish weirs include construction of barriers across shallow bodies of water and V-shaped openings where fish are trapped. Weirs, ranging in length from several to hundreds of metres, are constructed of soil, rock, reed, branches, logs, aquatic vegetation and/or basketry. Superstructures of perishable materials or a dense wall of vegetation probably covered the earthen fish weirs of Baures.

There are important differences between the zigzag structures of Baures and contemporary fish weirs. Most ethnographic fish weirs are ephemeral and rebuilt each season. Traditional weirs are constructed in rivers, streams or permanent bodies of water. In contrast, the zigzag structures are permanent earthworks built across a seasonally flooded savanna. They are also more numerous, longer and more densely placed than ethnographic fish weirs. In addition to controlling and harvesting fish within the savanna, the weirs and large causeways may have been used for water management. The earthworks could have extended the period of inundation by capturing the first rains and holding floodwaters into the dry season[18].

The savanna fisheries of the Bolivian Amazon are productive. Estimates of 100,000 to 400,000 fish have been calculated for a single hectare of abandoned river channel in the savannas[9]. Yields of 1,000 kg per hectare per year have been recorded for shallow ponds in tropical savannas[19]. Large numbers of *Pomacea gigas* snails are found beside the zigzag structures. In addition to fish, these edible snails may have been managed and raised in the weir structures and ponds. In the past, these snails were eaten in Baures and the gastropods are found in precolumbian sites in Bolivia and Brazil[20,21]. The nutritional status of *Pomacea* is probably similar to other tropical snails, low in calories and protein[22]. *Pomacea gigas* reproduce and grow at an impressive rate and an average of 23.8 snails per m^3 is recorded in Bolivian wetlands[23]. The artificial fisheries of Baures potentially produced hundreds of tonnes of edible snails as a secondary food source.

The most common vegetation associated with the fish weirs and ponds is the palm *Mauritia flexuosa*[24–26] (Fig. 3). A single tree can produce up to 5,000 edible fruits each year and a single hectare yields 10–60 t of fruit. The fruits are high in vitamins C and A, oil (12%) and protein (4–5% dry weight). The ground tissue produces large amounts of edible starch. Edible larvae of the palm beetle thrive in the decomposing trunks. In addition, the palm is a favoured food of game animals and fish. The fibres of the fronds and trunks are used for basketry, mats, hammocks, bowstrings, thatch and roof beams. The palm may have been encouraged or even cultivated on the earthworks.

Artificial ponds overlap with the distribution of zigzag structures (Fig. 3). These measure 0.5–2 m deep and 10–30 m in diameter; the largest hold water year round. The ponds teem with fish such as buchere (*Hoplosternum* sp.), yallu, cunaré (*Cichla monoculos*), palometa (*Serrasalmus* sp.), sábalo (*Prochilodus nigricans*) and bentón (*Erythrina* sp), snails, birds, reptiles and amphibians. Contemporary hunters stalk the game animals and birds that congregate at the ponds. Artificial ponds provided a way to store live fish and snails until needed.

The complex of fish weirs and ponds of Baures is a form of intensive aquaculture. The earthworks did not necessarily involve the mobilization of large amounts of labour. I estimate a total of 1,515 linear kilometres of fish weirs in Baures based on a sample of aerial photographs. Using labour estimates for experimental

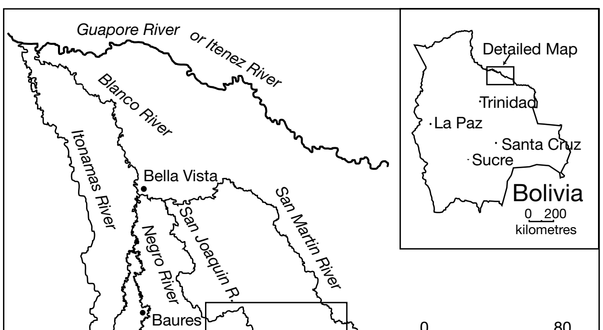

Figure 1 Map of the Baures prehispanic hydraulic complex. It is located between the San Joaquín river to the west and the San Martín river to the east and between 13° 30' and 14° 20' latitude South.

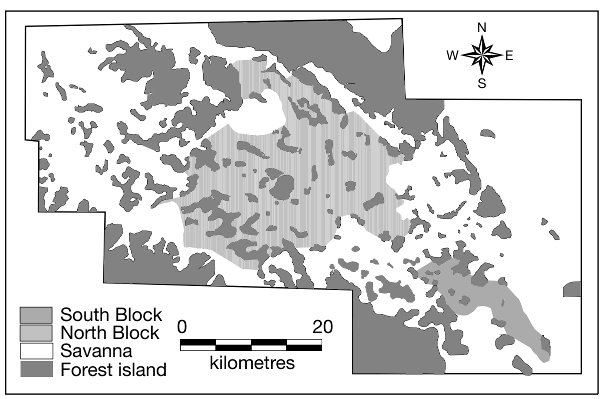

Figure 2 The fish weirs (zigzag structures and ponds). They are concentrated in the North Block (447 km^2 of savanna excluding forest islands) and the South Block (77 km^2). The structures are restricted to savannas near forest islands that are flooded by shallow water.

construction of raised fields (5 m^3 of earth per person per 5-hr day and weirs measuring 2 m wide and 0.5 m tall), the weirs required 300,000 person-days of labour or the equivalent of 1,000 people working 30 days a year over a period of 10 years. Small groups of kin or communities constructed and managed the weirs recorded in ethnographic accounts[10–14]. Similar social groups may have been responsible for the weirs and ponds of Baures.

The weirs also show some evidence of integration at a higher scale. Individual zigzag structures often cross the savanna from one forest island to another (Fig. 4). Assuming each forest island was an autonomous settlement, weir construction may have involved inter-community cooperation. Although individual weirs could operate

Figure 3 Oblique photograph of a fish weir and artificial ponds between forest islands in the savannas of Baures. Fish weirs are the zigzag structures, lower left to upper right; artificial ponds are the circular features surrounded by palms (approximately 20 m in diameter). The diagonal feature (upper left to lower right) is a contemporary path.

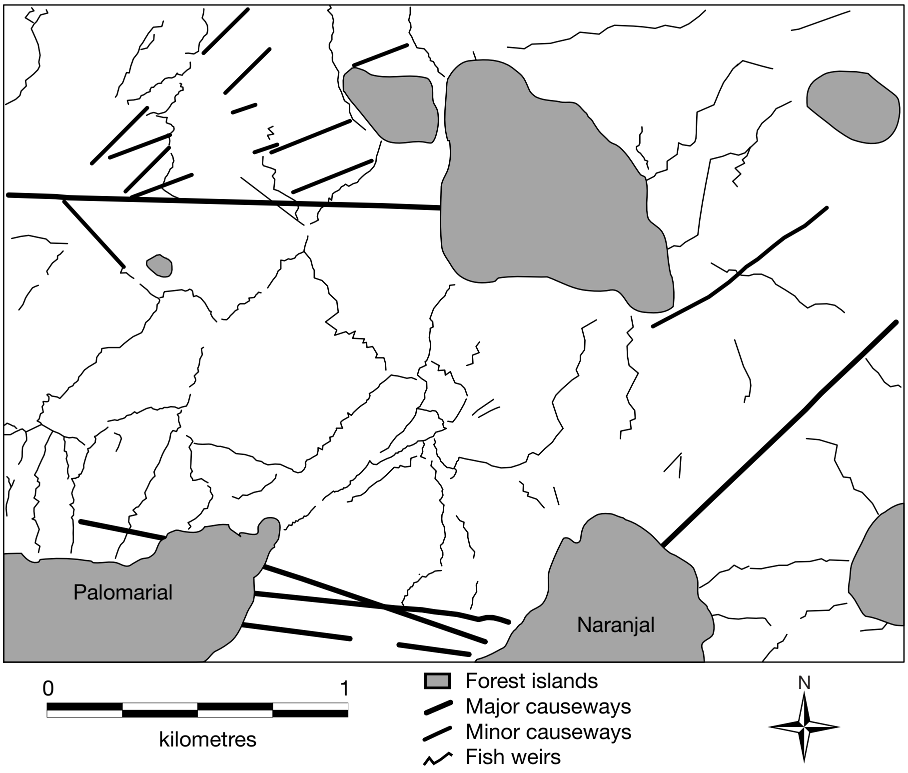

Figure 4 Map of fish weirs (irregular lines) and causeways (straight lines) in Baures. Based on aerial photographs.

independently of other weirs, the presence of an integrated network of causeways, canals, weirs and ponds suggest a higher order of water management[8,18]. As a permanent food-producing infrastructure, the weirs must have been valuable real estate. The networks of causeways and canals may have promoted communication and alliances between individual communities exploiting the fish weirs. Groups in the Colombian Amazon jealously protect and guard riverine fisheries, valuable resources that are owned and inherited by clans and chiefly lineages[16]. The presence of moated, and presumably palisaded, settlements on many of the forest islands suggests potential tension over the fisheries and other resources[27].

Colonial accounts describe the use of causeways in Baures for communication and transportation between settlements[7,10,12,27]. Weirs in lakes and streams are described[10,12], but there is no mention of the zigzag structures in the savanna. To date the fish weirs, I excavated a large causeway directly associated with zigzag structures[28]. Burned wood from the base of the causeway fill was radiocarbon dated to 335 years BP (before present) ± 20 (OS-17293) or an uncalibrated calendar date of AD 1615 (AD 1595–1635). The corrected date at 68.2% confidence is AD 1490 (0.26) AD 1530; AD 1560 (0.74) AD 1630. Depending on the context, the sample may date or predate the original construction. The Spanish did not control the Baures region until 1708; thus, the earthwork probably predates European occupation.

The earthworks of Baures are an example of creation and active management of an anthropogenic landscape by native peoples. The linear causeways and canals were a sophisticated means of regulating water levels within the savannas to enhance and manage seasonal aquatic resources. The network of fish weirs provided a means of controlling and harvesting fish, in addition to enhancing the habitat and availability of aquatic and terrestrial fauna. The artificial ponds were a means of concentrating and storing live fish, providing drinking water and improving game habitats. Palms growing on earthworks provided additional foodstuffs and materials. Using this simple, but elegant, technology, the people of Baure converted much of the landscape into an aquatic farm covering 500 km^2. Rather than domesticate the species that they exploited, the people of Baure domesticated the landscape. The fish weirs and ponds produced abundant, storable, and possibly sustainable yields of animal protein. Thus, they were able to sustain large dense populations in what many would consider a marginal environment. □

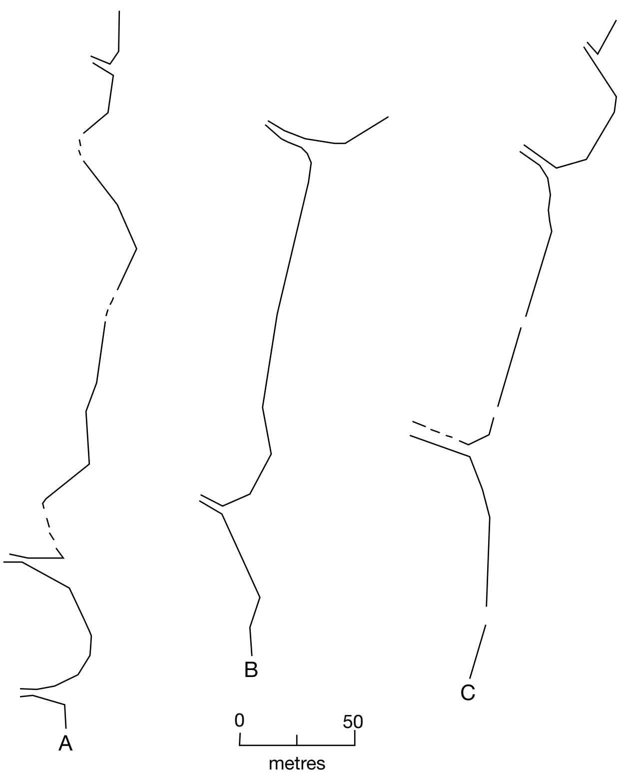

Figure 5 Plans of fish weirs (zigzag structures). Small parallel openings in the weirs are present every 50–200 m.

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