The AEZs are defined by a two-way matrix: one axis classifies the regions by LGP and the other by MMT. The definition of the terms used in AEZ classifications are give in Table 3.2. Data on socioeconomic variables are available only by political units, some at national and some at different subnational levels. Since many large countries cover several AEZs, we need to correlate the agroclimatic configuration on a physical geographic basis with available socioeconomic data from subnational political units.

For preparation of the Medium Term Plan 1994–1998, the IRRI developed a database by AEZs using subnational-level socioeconomic data for China and India and national-level data for other countries in Asia. The geographical boundaries used for AEZ delineation can be seen in Table 3.3. The delineation is far from perfect. Several countries have areas that do not belong to the AEZ into which it has been classified. For example, a part of central Myanmar is semi-arid, although all of the country is classified as warm subhumid tropics (AEZ 2), southern Thailand is humid, and central and western Madhya Pradesh (India) is semi-arid, but they are also classified as AEZ 2. Future ecoregional research should be to develop appropriate databases that allow more accurate analysis at the AEZ level.

The pattern of land use for the production of foodgrains in different agroecological zones can be reviewed from Table 3.4. In the semi-arid zones in the Asian tropics, the major crops are oilseeds, pulses and coarse grains such as sorghum and millets, which could be grown with little soil moisture. Wheat and maize are also grown in large parts of the semi-arid zones where irrigation facilities are developed. Wheat and maize are major foodgrain crops in the cool subtropics, and also in subhumid and semi-arid subtropics. Rice–wheat cropping systems predominate in the subhumid subtropics that benefit from adequate rain during summer and a relatively long and dry winter.

Rice is the predominant foodgrain crop in the humid tropics (AEZ 3) and subtropics (AEZ 7) due to abundant moisture. Rice accounts for three-fourths of total cropped land in these two AEZs. But rice is also the most important cereal crop in the subhumid subtropics (AEZ 2) where wheat cannot be grown

Table 3.2. Definition of terms used in the Technical Advisory Committee of the Consultative Group of International Agriculture Research's agroecological zones (AEZs).

AEZ term	Definition
Arid	LGP < 75 days
Semi-arid	LGP 75–180 days
Subhumid	LGP 180–270 days
Humid	LGP > 270 days
Tropics	MMT > 18 °C for all months
Subtropics	MMT 5–18 °C for 1 or more months
Temperate	MMT < 5 °C for 1 or more months
Warm	Daily mean temperature during the growing period of > 20 °C
Cool	Daily mean temperature during the growing period of 5–20 °C

LGP, length of growing period; MMT, mean monthly temperature.

Table 3.3. Geographical delineation of agroecological zones (AEZs) in Asia.*

Agroecological zones	Geographical boundaries
Warm semi-arid tropics (AEZ 1)	Southwestern India (Andhra Pradesh, Karnataka, Tamil Nadu, Maharashtra, Gujarat)
Warm subhumid tropics (AEZ 2)	Thailand, Myanmar, Eastern India (Madhya Pradesh, Orissa, Bihar)
Warm humid tropics (AEZ 3)	Indonesia, Malaysia, Philippines, Vietnam, Cambodia, Laos, Sri Lanka, Bangladesh, parts of India (Assam, Northeastern States, West Bengal, Kerala)
Warm semi-arid subtropics (AEZ 5)	Pakistan, parts of India (Rajasthan, Haryana), parts of China (Helong, Laioning, Jilin, Tianjin, Sandong, Hebei)
Warm subhumid subtropics (AEZ 6)	Northwestern India (Uttar Pradesh, Punjab), Nepal, parts of China (Jiangshu, Anhui, Hubei, Sichuan, Henan, Guizhou, Yunan), North Korea, South Korea
Warm humid subtropics (AEZ 7)	Parts of China (Shanghai, Zehjiang, Fujian, Jianxi, Hunan, Guandong, Guanxi) Taiwan
Cool subtropics temperate zone (AEZ 8)	Parts of India (Himachal Pradesh, Jammu and Kashmir), parts of China (Beijing, Shani, Inner Mongolia, Tibet, Gansu, Ningia, Xinjiang, Quinghai)

* Excludes the Middle East and transitional economies in Central Asia.

because of the warm temperature during the dry season. Rice–pulses, rice–oilseeds or rice–fallow are the major cropping systems in this AEZ.

The interface between the rice ecosystems and the AEZs is shown in Table 3.5. The irrigated rice ecosystem accounts for 57% of the rice area and 76% of rice production in Asia. It is concentrated mostly in the subtropics and the semi-arid tropics. The irrigated ecosystem in the subtropics is gradually losing land to urbanization and industrialization. Farm yields are approaching the ceiling of average yields obtained in experimental stations. It is characterized by intensive use of agrochemicals with potential adverse effects on human health and the sustainability of the natural resource base. The unfavourable rice ecosystems (rainfed lowland, upland, deepwater and coastal wetlands) are predominant in the humid and subhumid tropics (AEZs 2 and 3). These are ecosystems where modern rice technologies have yet to make an impressive impact. Expansion to marginal land has been an important source of growth in rice production. Strategic research is needed for these regions to ease

Table 3.4. Relative importance of foodgrain crops by agroecological zones, 1991

Agroecological zones	Percent of total area						
	Rice	Wheat	Maize	Coarse grains	Pulses	Oilseeds	Total
Warm tropics							
Semi-arid	18.5	3.4	2.0	36.1	16.2	23.8	100.0
Subhumid	51.3	9.3	6.2	7.6	15.4	10.2	100.0
Humid	75.4	1.7	12.9	0.3	3.7	6.0	100.0
Warm subtropics							
Semi-arid	9.4	38.0	15.6	12.7	17.9	6.4	100.0
Subhumid	35.7	29.4	10.8	4.8	10.0	9.3	100.0
Humid	75.6	3.6	3.3	0.1	7.3	10.2	100.0
Cool subtropics	3.1	45.3	20.5	6.[illegible]	14.0	10.8	100.0

Source: FAO agrostat database, and national statistical publications for China and India.

Table 3.5. The interface between agroecological zones and rice ecosystems, 1991

Agroecological zones	Total rice cropped area (million ha)	Percent of total rice area in each rice ecosystem				
		Irrigated	Rainfed lowland	Rainfed upland	Flood-prone	Total
Warm tropics						
Semi-arid	9.68	75.0	12.4	10.8	1.8	100.0
Subhumid	28.94	23.3	53.9	10.6	12.1	100.0
Humid	44.52	42.2	32.0	10.3	15.5	100.0
Warm subtropics						
Semi-arid	7.47	99.7	0.0	0.3	0.0	100.0
Subhumid	23.91	76.6	13.8	5.2	4.4	100.0
Humid	18.35	92.1	6.4	1.5	0.0	100.0
Cool subtropics	0.4	100.0	0.0	0.0	0.0	100.0
Total	133.27	56.9	26.7	7.7	8.7	100.0

Source: IRRI rice statistics database.

constraints to growth in productivity imposed by abiotic stresses, drought, flooding, waterlogging and problem soils.

Population pressure and the natural resource balance for agricultural production in the four AEZs under study can be seen in Table 3.6. The most severe pressure of population on land resources is in the humid subtropics (AEZ 7), where 1 ha of arable land supported almost 11 persons as early as the beginning of the 1960s. With population growth at 2.0% per year over the last three decades, arable land per capita has now declined to less than 0.05 ha. The growing demand for food in this ecoregion has been met by expansion of irrigation facilities, which permitted multiple cropping with foodgrains, and adoption of the high-yielding modern varieties. In this ecoregion, the foodgrain area accounts for 158% of arable land; thus, a substantial portion of the area is multiple cropped under foodgrains.

The availability of land is somewhat better in the subhumid tropics, where at present four to five persons are supported per hectare of arable land. But the quality of this land is poor, and the development of irrigation has been limited. Less than one-third of the area under rice is currently irrigated. Due to dependence on erratic monsoon rains, farmers still grow mainly traditional varieties of grains, and agricultural productivity remains low. Data on the potential for irrigation development is not available by AEZs. But the fact that irrigation coverage remains lower in the tropics than in the subtropics in spite of the lower availability of foodgrain per capita (see Table 3.6) reveals greater economic and environmental constraints to the development of land under irrigation. Returns on investment in large-scale irrigation projects in the subhumid tropics may be low since these regions experience a monsoonal climate requiring only supplemental irrigation during the wet season (hence the capacity utilization of irrigation systems is low). During the dry season there is not enough surface water available for irrigating the rice crop. Abundant, yet poorly distributed, rainfall is the norm, and floods may be as severe a problem as drought.

AEZs 2 and 3 (the subhumid and humid tropics) have clearly less favourable grain-production environments than AEZs 6 and 7 (the subhumid and humid subtropics). Because of a more favourable land : person ratio, the production of foodgrains per capita was actually higher in the subhumid tropics than for other AEZs before the onset of the green revolution. But the subtropics benefited more from the diffusion of the green revolution technologies than did the tropics (Tables 3.7 and 3.8). In both the humid and subhumid subtropics, the productivity in foodgrain cultivation increased much faster than population. The impressive growth in rice yield has helped the humid subtropics to divert rice land to other crops since early 1980s, and meet the growing demand for non-grain foods without overexploitation of the limited land. Over the past three decades per capita production of foodgrains increased by about 100 kg year^{-1} for AEZs 6 and 7, and by about 53 kg year^{-1} in AEZ 3, but remained unchanged in AEZ 2. As a result, food insecurity and poverty in the subhumid and humid tropics increased more than in the subtropics. Compared to AEZ 7, which is in the most favourable position with respect to food security, the per capita energy intake is about

Table 3.6. Population pressure, foodgrain production and incidence of poverty in Asian agroecological zones, 1990.*

Agroecological zones	Share of arable land (%)	Share of population (%)	Arable land/ capita (ha)	Foodgrain production per ha of arable land (tons ha^{-1})	Foodgrain production/ capita (kg $year^{-1}$)	Foodgrain cropped area as % of arable land	Calorie : poverty intake ratio (kcal % of capital)
Warm tropics							
Semi-arid	15.6	10.3	0.20	1.22	240	95.0	226,854.1
Subhumid	18.3	10.1	0.23	1.39	260	90.6	213,952.1
Humid	19.4	22.0	0.11	2.24	256	86.0	237,038.1
Warm subtropics							
Semi-arid	19.2	16.2	0.15	1.99	304	94.3	250,823.7
Subhumid	17.8	25.3	0.09	4.16	377	133.3	254,928.6
Humid	4.5	11.5	0.05	6.64	331	157.5	274,219.2
Cool subtropics	5.3	4.6	0.15	2.02	300	82.8	250,819.5
Asia	100.0	100.0	0.13	2.40	310	101.2	245,333.4

* Excludes middle east and transitional economies in Central Asia.
Source: FAO agrostat database, and national statistical publications.

Table 3.7. Sources of growth (% per year) in foodgrain production in Asia, 1961–1991

Agroecological zones	Area	Yield	Production
Subhumid tropics	0.84 (0.06)	1.49 (0.13)	2.33 (0.15)
Humid tropics	0.84 (0.04)	2.34 (0.08)	3.18 (0.08)
Subhumid subtropics	1.45 (0.05)	3.43 (0.11)	4.88 (0.14)
Humid subtropics	0.07 (0.13)	3.08 (0.12)	3.15 (0.17)

Estimated by fitting semilogarithmic trend lines on time series data. Figures within parentheses are standard errors of estimated growth.

600 kcal lower in AEZ 2 and 372 kcal lower in AEZ 3. In 1990, nearly 52% of the people in AEZ 2 lived in poverty, compared to only 19% in AEZ 7 (see Table 3.8).

The overwhelming importance of rice in the humid and subhumid tropics and subtropics (see Table 3.4) clearly indicates that for ecoregional foodgrain research to have the desired impact, the primary focus must be on rice-based production systems. Rice will continue to dominate agriculture in Asia well into the next century. Efforts to recover degraded resources and increase sustainable productivity of the overall resource base in the humid and

Table 3.8. Sources of growth (% per year) in rice production, 1961–1991

Agroecological zones	Area	Yield	Production
Subhumid tropics	0.56 (0.05)	1.38 (0.14)	1.94 (0.16)
Humid tropics	0.69 (0.03)	2.39 (0.08)	3.08 (0.08)
Subhumid subtropics	1.07 (0.11)	2.96 (0.11)	4.03 (0.16)
Humid subtropics	0.19 (0.13)	2.99 (0.11)	3.18 (0.17)

Estimated by fitting semilogarithmic trend lines on time series data. Figures within parentheses are standard errors of estimated growth.

Table 3.9. Rice area in different ecosystems in eastern India.

State	Irrigated	Upland	Rainfed lowland		Deepwater	Very deepwater	Total
			0–30 cm	30–50 cm	(50–100 cm)	(>100 cm)	
Assam	203	215	892	472	385	100	2,267
Bihar	1,512	531	1,698	465	382	672	5,260
Orissa	1,062	691	1,743	486	400	150	4,532
Madhya Pradesh	608	1,349	2,695	–	–	–	4,652
Uttar Pradesh	982	714	1,884	290	234	555	4,659
West Bengal	1,324	883	1,685	470	383	677	5,422
Total	5,691	4,383	10,597	2,183	1,784	2,154	26,792

Source: IRRI, 1992.

Table 3.10. Extent of the subecosystems of shallow rainfed lowland rice in eastern India.

State	Shallow rainfed lowland subecosystems (ha × 10^3)				
	Drought-prone	Drought- and submergence-prone	Favourable	Submergence-prone	Total
Assam	–	–	450		892
Bihar	948	750	–		1,698
Orissa	700	500	275		1,743
Madhya Pradesh	2,695	–	–		2,695
Uttar Pradesh	784	1,100	–		1,884
West Bengal	660	350	300		1,685
Total	5,787	2,700	1,025		10,597

Source: IRRI, 1992.

1.5 tons ha^{-1} in the uplands, 0.9–2.4 tons ha^{-1} in the rainfed lowlands and 0.9–2.0 tons ha^{-1} in the deepwater and very deepwater areas. The first priority ecosystem in eastern India is the rainfed lowlands, because of its area, larger dependent population and potential for yield increase.

A meso-level analysis of rainfed rice ecosystems was conducted in the Bahraich and Faizabad districts of Uttar Pradesh, Hazaribagh district of Bihar and Raipur district of Madhya Pradesh. Characterization of the rice environments of the Faizabad district (total area of 451,100 ha and rice area of about 181,000 ha) was done with satellite remotely sensed data, selective field checks and auxiliary data. Maps (1 : 250,000 scale) were prepared to delineate physiographic units, land-utilization pattern, soils, flooding and drought. Information on climate, ground water, irrigation sources, landholding and input use was integrated with the maps.

The classification of rainfed rice environments showed that about 40% of the area in the Faizabad district is favourable rainfed lowland, 51% is drought-prone lowland, 2% is submergence-prone lowland and 4% is submergence- and drought-prone lowland. Apart from drought and submergence, soil sodicity was identified as the priority research area in the district.

Detailed meso-level analysis was done in the Masodha block of the Faizabad district. The block covers about 21,000 ha (total land area) and has about 8000 ha of rice area. Rice-growing environments in terms of physiography, land use, soils, flooding, drought, ground water and irrigation were studied in detail using remote sensing and conventional data. The major part of the block is classified as a shallow favourable rainfed rice subecosystem. Meso-level analysis showed that about 14% of the block area is affected by flooding, 10% by sodicity and 2% by waterlogging. Only 32% of the ground-water potential has been developed so far. Recharge-draft analysis showed that about 1600 ha m of ground water is still available for irrigation.

Table 3.9. Rice area in different ecosystems in eastern India.

State	Irrigated	Upland	Rainfed lowland		Deepwater	Very deepwater	Total
			0–30 cm	30–50 cm	(50–100 cm)	(>100 cm)	
Assam	203	215	892	472	385	100	2,267
Bihar	1,512	531	1,698	465	382	672	5,260
Orissa	1,062	691	1,743	486	400	150	4,532
Madhya Pradesh	608	1,349	2,695	–	–	–	4,652
Uttar Pradesh	982	714	1,884	290	234	555	4,659
West Bengal	1,324	883	1,685	470	383	677	5,422
Total	5,691	4,383	10,597	2,183	1,784	2,154	26,792

Source: IRRI, 1992.

Within each of the upland, rainfed lowland and deepwater ecosystems in eastern India, target environments were characterized at the micro-level to set research priorities within and among dominant farming systems. Ninety sites were analysed.

Rapid rural appraisal techniques, which included agroecosystems mapping and diagnostic surveys, were employed at all sites. The analysis focused on spatial, temporal, resource flow and decision patterns. The methodology involved a two-tier training program for researchers on how to set research priorities using agroecosystems analysis. The research diagnosis and prioritization at this level were conducted by multidisciplinary teams, with continuous involvement and interactions from groups of farmers.

At all sites, the static factors studied were land types, land use, source of water supply and soil properties. The dynamic factors were field-water depth and rainfall; cropping pattern and crop calendars, crop yields, varieties and management practices; insects, diseases and weeds; production costs and returns; labour supply pattern, assets, income distribution, landholding size and demography by social class and gender.

The geographic area was zoned into agroecosystems and the problem and opportunities elucidated in each major agroecosystem. Highest priority was given to the agroecosystem with the largest rice area. The research problems were then prioritized on the basis of the physical extent (coverage), number of affected households, complexity, severity (crop-loss estimates), frequency of occurrence, importance of the affected enterprise in the farming system and the farmers' perceptions of the problem.

All site studies within each sub-ecosystem and ecosystem were pooled and compared to identify commonality of problems and opportunities. This provided an empirical picture of the entire ecosystem, which served as a basis in formulating a need-based research agenda and the allocation of resources at the national, regional and zonal level (IRRI, 1992).

V. Rice Research Prioritization: Beyond a Commodity Approach

The two most well-developed methods for rice research prioritization have examined the allocation of resources from a commodity approach. They have either attempted to estimate an optimal allocation among the rice ecosystems (Barker *et al.*, 1985) or among alternative rice-crop (i.e. genetic) improvement problems (Herdt *et al.*, 1987). Analyses of prospective allocation of research resources by rice ecosystem emphasized the direct marginal contributions to rice production that are likely to accrue to research effort expended in one or another ecosystem. They use congruence rules that are dominated by the value of current production.

Herdt *et al.* (1987) pointed out that research problems tend to fall into one of three types: (i) constraints to achieving currently possible yields (constraints research); (ii) increasing the level of potential yields (potential productivity); and (iii) maintaining current yields (maintenance research). Increasing awareness of environmentally damaging negative externalities in crop production has resulted in greater research resources directed toward technologies that will reduce these external costs, which is a form of maintenance research. The widespread interest in sustainability translates into greater relative emphasis on maintenance research to avoid negative external costs due to new technology, or due to the lack of it.

Environmental externalities have been embedded in the cost–benefit approach (Herdt *et al.*, 1987). As ecosystems analysis improved our understanding of the rice environments, it became obvious that some major negative externalities are omitted from such exercises. Their inclusion would have significant effects on resource allocation, because the nature of the externalities, and their gross value differ among the ecosystems.

Negative externalities in the lowland rice ecosystem include such problems as ground-water pollution with high fertilization, pesticide residues and their danger to the health of human applicators. In the upland ecosystems, rice production on sloping lands with inappropriate farming practices results in accelerated soil erosion and soil degradation. In the upland ecosystem there are two major classes of negative externalities. First, massive sediment loads from the uplands devalue investments in irrigation systems in the lowlands, particularly storage reservoirs, and increase the maintenance costs of irrigation canals at primary and tertiary levels (P.L. Pingali, personal communication). The accelerated sediment deposition in river systems increases the flooding hazards and costs of flood prevention. Second, the degradation of the upland resource base, particularly soil quality and biological diversity, indicates a loss in the value of the land resource stocks over very large geographic areas. These stocks may be valued in terms of the current land productivity lost due to a degraded land base, and future costs in rehabilitating it to provide significant production and protection functions. These costs to society are large. Unlike for lowland rice, the aggregate land area on which upland rice is grown is many times larger than the amount of rice area in any given year.

Thus, the aerial extent of the negative externalities of upland rice is not adequately reflected in tallies of current crop area by ecosystem. The crop is shifted among fields in permanent as well as fallow rotation systems, and is therefore grown on a large proportion of the total area of acid tropical uplands. Thus, upland rice cultivation's effects on the lowland resource base greatly exceeds its effects on the land where it is grown in a given year.

Upland rice research in many environments is directed to reversing the process of land degradation due to inappropriate land use and and management. In such a framework it is important to recognize that the objectives of upland rice research differ from mainstream rice research in general. Given the impact of the negative externalities of upland rice cultivation on the lowlands, it is likely that a more definitive resource accounting would point toward greater relative attention to the uplands in research fund allocation than its share of global rice area and rice production suggests (P.L. Pingali, personal communication).

Adequate data do not exist to make reasonable estimates of the negative externalities. The relative gains to society from research that decreases the degradation of the land resource stocks can be explicitly embedded in these analyses. This also implies greater attention to AEZs as a basis for research prioritization; as the TAC of the CGIAR has attempted (TAC, 1990). Incorporation of these issues into formal research prioritization will undoubtedly stimulate further acceleration in ecosystem analysis work.

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