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Chapter 1: The Evolution of Switchgrass as an Energy Crop

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Chapter 1
The Evolution of Switchgrass as an Energy Crop

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Abstract This chapter discusses the prehistoric origins of switchgrass, its mid-twentieth century adoption as a crop, and late-twentieth century efforts to develop it into an energy crop. The species probably first appeared about 2 million years ago (MYA) and has continued to evolve since, producing two distinct ecotypes and widely varying ploidy levels. We build the case that all existing switchgrass lineages must be descended from plants that survived the most recent glaciation of North America and then, in just 11,000 years, re-colonized the eastern two-thirds of the continent. Moving to historic times, we discuss how switchgrass was first considered as a crop to be grown in monoculture only in the 1940s. Based on scientific reports indexed in a well-known database, interest in switchgrass grew very slowly from the 1940s until it began being considered by the US department of energy (DOE) as a potential energy crop in the 1980s. The history of how switchgrass became DOE's 'model' herbaceous energy crop species is recounted here. Also chronicled are the early research efforts on switchgrass-for-energy in the US, Canada, and Europe and the explosive growth in the last decade of publications discussing switchgrass as an energy crop. If switchgrass—still very much a 'wild' species, especially compared to several domesticated grasses—truly attains global status as a species of choice for bioenergy technologies, it will have been a very remarkable evolution.

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1.1 Introduction

Beating swords into plowshares and spears into pruning hooks (Isaiah 2:4) is a lofty goal. Not so noble but still laudable might be a figurative reshaping of plows into oil derricks and coal tipples. In such a scenario, energy crops would be grown on marginal or non-cropland for conversion into energy forms that reduce dependence on petroleum and coal. The benefits would be multifold. Energy cropping could offset fossil fuel use, thereby extending the supply of non-renewable forms and reducing greenhouse gas emissions. Furthermore, a mature, sustainable, biomass-based energy supply could offer economic and social renewal to many rural areas. We do not reckon that making fuel from the grain of maize (*Zea mays* L.) provides a sustainable path, but we hope that practice is paving the way for a truly sustainable second generation of biomass-based energy crops [1, 2].

Switchgrass (*Panicum virgatum* L.) has garnered much attention as an energy crop in the past few years. This book was commissioned because the body of knowledge on switchgrass-for-energy is implicitly now substantial enough and mature enough to merit such a publication. We think that analysis will hold up to scrutiny, but in this chapter we invite readers to consider that switchgrass is still a very new crop—one that was not planted in monocultures until the mid twentieth century. In a few decades, though, the species has catapulted from obscurity to being the focus for a wealth of good science and to being frequently cited as the feedstock of choice for a second generation biofuels industry.

The rest of this book will deal with the wealth of good science focused on switchgrass; this chapter will explain how switchgrass came to be that focus. We will discuss first the species' biological origins—its evolutionary relationship to other members of the grass family. Then we will document its very recent 'birth' as a crop. Finally, we will discuss how this very new crop has come to be considered the energy crop of choice by so many. The explanation is related partially to the species' biology and agronomy; but it also involves serendipity, a bureaucratic decision, political and economic exigencies, and a 'model' that may have been forgotten.

1.2 The Evolution of Switchgrass

Based on deposits of their distinctive pollen in the fossil record, grasses originated 55 to perhaps 70 million years ago (MYA) [3]. Since then, the grass family (Poaceae or Gramineae) has evolved from rather humble beginnings into forms that dominate significant portions of the planet. Since the much more recent appearance of humans, the grass family's connections to us have become extensive

and, in some cases, essentially symbiotic. Human use and selection in the last 10,000 years have clearly reshaped some grass forms and functions [4], but grasses may have had an even bigger impact on human development. The environment in East African tall-grass savannas 2 MYA may have fostered the evolution of bipedalism, tool-holding hands, and increased intellect in hominids [5]. That, of course, is speculative, but we know without doubt that we are very highly dependent on the grasses today. A few grasses—most notably those that became domesticated during a hundred centuries of interaction with humans [6]—now produce the great majority of the caloric energy consumed in human diets. These might be considered the Olympians within the pantheon of valuable grasses. Some other grasses are not so vital from a human perspective, but they could still be described as belonging within the pantheon of valued grasses because they provide feed for livestock and, hence, additional human dietary components as well as draft power; and still other grasses are valued as sources of fiber, turf, and ornamentation. In this anthropocentric context, switchgrass is clearly already within the pantheon, but it might be poised to join the Olympians—not as food from the gods but as fire brought down from the sky.

1.2.1 Taxonomic and Phylogenetic Relationships Within the Grasses

The approximately 10,000 grass species have been grouped into 600 to 800 genera [7]. The number of genera is in some flux as taxonomists and systematists work to make classification schemes more natural, i.e., to better reflect evolutionary relationships—a task made perhaps especially difficult in the grasses by numerous cases of parallel or convergent evolution [8]. Using morphological and cytogenetic comparisons, the grass genera have been divided into six subfamilies, with various numbers of tribes and subtribes in each [9]. In this classification scheme, *Panicum* is the type genus of both its subfamily (Panicoideae) and its tribe (Paniceae). Fellow subfamily members include *Zea*, *Sorghum*, and *Miscanthus* (each in a different tribe), while the tribe Paniceae consists of about 100 C_3 and C_4 genera, some with familiar names such as *Echinochloa*, *Paspalum*, and *Setaria*—all within the same Setariinae subtribe as *Panicum* [9].

The *Panicum* genus is large and cosmopolitan, with over 450 rather heterogeneous species. The unifying trait within the genus is a distinctive spikelet morphology, but little else seems to hold the taxon together; for example, five different base chromosome numbers, ranging from 8 to 15, occur within the genus [10]. To alleviate the unwieldiness—and likely unnaturalness—of the genus, some taxonomists have subdivided *Panicum* into six or more subgenera and numerous sections [10].

Systematics underwent a revolution in the last quarter of the twentieth century with the advent of technologies that allow comparisons between and within species at the gene level. Instead of focusing on morphological features, such as inflorescences or embryos, this approach looks at DNA sequences. The logic is straightforward: plants share genes that hark back to some putative original plant; transcriptional 'accidents' infrequently but inevitably generate new, enduring base-pair sequences within those genes (and non-coding DNA regions); during and following speciation, varying sequences evolve into different taxa; and, over evolutionary time, unique, new sequences are added to each evolving lineage. Hence, when examining the variations in base-pair sequences of a gene, the more similar the sequences are between two species, the more closely related are they assumed to be. Increasing variation in DNA sequences for a gene indicates greater evolutionary divergence. If molecular studies incorporate large enough stretches of DNA and sufficient numbers of organisms, phylogenetic relationships generally emerge [3].

In the late 1990s, a consortium of systematists from several institutions formed the Grass Phylogeny Working Group [11]. They looked at 62 species representing the breadth of the grass family. The 62 included switchgrass and several other crops, as well as some lesser known but taxonomically important species. Base-pair variations for six nuclear genes as well as chloroplast restriction site data were compiled and analyzed to produce a 'family tree' that showed the most likely genetic relationships of all 62 species. The findings suggested that the grass family might reasonably be divided into 12 subfamilies, including the Panicoideae [11]. The GPWG phylogeny placed switchgrass as a close relative (adjacent branch) of pearl millet (*Pennesetum alopecuroides* (L.) Spreng.), and that pair was next most closely related to maize and *Miscanthus japonicus* Andersson. Of course, these were comparisons only within the 62 species examined, but they suggested a more natural classification for the grass family overall and retained switchgrass firmly within its previously recognized taxa.

Molecular phylogenetic comparisons can be used to deduce when specific taxa or traits first appeared in evolutionary time. The notion of a molecular clock is now well appreciated [12]. Variations in base-pair sequences are assumed to accumulate at some inexorable—but deducible—rate, which may vary among angiosperm families [13]; and the number of variants observed can provide an indirect measure of when they began to accumulate. The grass family is considered to be monophyletic, i.e., all grasses are related to a putative original grass species [3]. The molecular/genetic changes that led to the first event of grass speciation caused a first branching point, or node, and each new branch since has followed its own path of incremental changes and accrual of variations in base-pair sequences. If the origin of the first grass can be placed in geological time, phylogeneticists can reason when in evolutionary time various nodes appeared. As noted above, the grass time line is reasoned from the fossil record to have begun 55 to 70 MYA. The molecular clock suggests that the primordial grass lineage must have undergone a total duplication of its genome almost immediately and then remained rather stable until dividing into several subfamilies beginning about 50 MYA [14, 15]; although

some fossil evidence reveals morphological differences equating to some subfamilies may have appeared as early as 65 MYA [16].

For agronomists, one of grasses' most important traits is the ability of species to withstand drought and thrive in full sunlight. Interestingly, that is thought to be a derived trait—not the 'wild type'. Evidence suggests the early grasses were adapted to forest margins and shade, just as some grass species still are [3]. Based on molecular phylogenies, a tolerance of or preference for open habitats evolved in grasses in at least two subfamilies but perhaps only after 20 million years as shade-preferring plants [3, 11, 16].

The family connections between switchgrass and other grass species have been investigated with molecular clock methods. One study looked at inter- and intra-species variation in the DNA sequence of Acc-1, the gene that codes for plastid acetyl-CoA carboxylase [17]. That study and more recent work [13, 18] conclude that present-day switchgrass and maize diverged from a shared ancestor about 22 to 23 MYA. Switchgrass and pearl millet shared a common ancestor until about 16.5 MYA [13]. In a Huang et al. [17] study, while looking at Acc-1 in various switchgrass cultivars, the authors concluded that the gene pool associated with the species now recognized as switchgrass was assembled by about 2 MYA—initially as a diploid—and that the now widespread polyploidization of the species has occurred within the last 1 million years [17]. Based on chloroplast DNA (cpDNA) sequences, Zhang et al. [18] estimated switchgrass diverged from two of its diploid ancestors, *P. hallii* and *P. capillari*, about 5 to 10 MYA, suggesting that the evolution of this tall-growing polyploid required many millions of years to evolve out of a highly heterogeneous mix of diploid ancestors. This divergence occurred as hybridization, natural selection, and polyploidization allowed switchgrass to evolve into unique forms and habitats.

The appearance of switchgrass about 2 MYA was in the midst of the Pleistocene Era, which began about 2.5 MYA and is often described as the 'Last Ice Age'. The new species perhaps originated during an interglacial period, but it would have to endure many glacial episodes over the next 2 million years. We will come back to this point soon.

1.2.2 Evolution of C_4 Pathways

Because it is so important for both productivity and drought tolerance, the evolution of C_4 photosynthesis, which layers CO_2-concentrating mechanisms onto the archetypical C_3 pathway, is of particular interest. Based on phylogenetic observations and species-specific differences in C_4 biochemistry [19], we can conclude immediately that 'the C_4 pathway' is actually multiple C_4 pathways, which have arisen multiple times within the angiosperms, i.e., their appearances exemplify parallel or convergent evolution. A closer look at the grasses in particular suggests that development of C_4ness occurred multiple times just within that family.

1.2.2.1 Where do C_4 Pathways Appear Phylogenetically?

C_4 pathways occur in at least 7,500 angiosperm species found in 19 families—16 eudicot and three monocot [19, 20]. Within taxa where the pathways occur, they are not uniformly present—even within genera. *Panicum*, for example, has C_3, C_4, and intermediate C_3/C_4 members. However, the very large *Panicum* genus is thought by many to be polyphyletic, i.e., not to arise from a single *Panicum* progenitor [3, 10, 20].

The number of separate convergent appearances of C_4 pathways has recently been tallied at 62 [20], with the majority of those lineages in the eudicots. But the grasses have clearly capitalized most on the pathways, with at least 4,500 of the 7,500 C_4 species being grasses [19, 20]. The molecular studies by the Grass Phylogeny Working Group [11] revealed at least five separate appearances of the C_4 pathway just within the 62 species they examined [3]. A systematic comparison of all 10,000 grasses suggests C_4 pathways must have evolved at least 11 separate times in the Poaceae (to include 7 times in just the Paniceae tribe), because C_4 pathways appear in that many different tribes or subtribes with C_3 ancestry [8, 19].

With the multiple, convergent appearances of C_4 photosynthesis, there clearly must be strong selective pressure to develop these pathways. The pathways may provide survival value, or greater fitness, through increased CO_2 fixation rates—especially under brighter, warmer, drier, or saline conditions—and greater water use efficiency. Nitrogen use efficiency also accrues to C_4 species, since they require less RuBisCO, the rather inefficient, sole CO_2-fixing enzyme in the C_3 pathway. Some have noted that C_4 plants might be less subject to herbivory because of their less favorable (for herbivores) protein content and C/N ratio [21]. In a very interesting review of the topic, Sage [19] suggests that the greatest survival value of C_4 pathways—and the reason they developed in so many disparate families—may simply be the relief provided from photorespiratory C losses, which stem from the nature of RuBisCO's kinetics, especially its dual carboxylation/oxygenation proclivity.

1.2.2.2 When did C_4 Pathways Appear?

The distinctive ^{12}C:^{13}C isotopic fingerprint associated with C_4 species begins to be evident in geologic strata dating to 20 MYA; and, by 5 to 8 MYA, C_4 species apparently had become dominant producers in some parts of the globe [19]. This supports the notion that C_4 species (probably dominated by grasses, since they were the pioneer C_4s) were already common in some mid-Miocene ecosystems [19]. Based on molecular clock methods, the first C_4 pathway(s) appeared in the grass family from 24 [14] to 30 [11] or 34 [14, 19] MYA. Based on the presence of intermediate C_3/C_4 species and on genomic evidence from C_3 plants where key genes appear to be evolving in a direction that might favor C_4ness [14], additional species could be only a few steps, albeit perhaps many eons, away from C_4 status.

But when did C_4ness first appear in switchgrass' ancestry? We know, for example, maize and *Sorghum spp*. are in the all-C_4 Andropogoneae tribe and have a presumptive shared C_4 ancestor that lived 12 to 15 MYA [14]. The origin of C_4ness is not so clear with *Panicum*'s ancestry. Because *Panicum* has species with C_3, C_4, and C_3/C_4 intermediate pathways, we might assume that C_4 evolved within the genus sometime after the original *Panicum* appeared. This makes very relevant the earlier speculation that the genus—as it is usually constituted—is not monophyletic, i.e., it does not arise from a single original *Panicum*.

A consensus would appear to be developing that *Panicum*, as currently constituted with its 450+ species, is polyphyletic [3, 10]—even 'highly' polyphyletic [20]. By definition, then, it is impossible to place its various species into definitive lineages and date the origin(s) of the C_4ness. Based on molecular data, it has been proposed that *Panicum virgatum* be retained within the 'true' *Panicum* (*sensu stricto*) along with a few other strictly C_4 *Panicum spp.* [10]. Still open to question is whether C_4ness developed de novo within a smaller, truly monophyletic *Panicum* genus or was inherited from a non-*Panicum* progenitor. The GPWG survey of base-pair sequences in six genes within 62 grass species suggested switchgrass and pearl millet arose from a shared C_4 ancestor [3], but the GPWG analysis was admittedly limited—not surveying any other species within *Panicum* or *Pennisetum*.

In short, we do not know when C_4 first appeared in switchgrass's lineage. The answer to that question must await a suitable parsing of the lineage, which must include a sorting out of the *Panicum* genus.

1.2.3 Center of Switchgrass's Origin and Spread Across North America

Switchgrass is a New World species. Its range when Europeans arrived included Central America and eastern North America [22]. It could be found in a wide range of habitats nearly anywhere east of the 100th meridian. After the species arose some 2 MYA [17], it likely radiated and adapted across major portions of the North American continent. However, a priori reasoning suggests that periods of glaciation in the last 2 million years would have driven most of those lineages into extinction or into more southern, ice-free climates. The survivors would presumably have followed the ice northward during interglacial periods, only to repeat the retreat/re-colonize cycle again and again [18, 23].

McMillan [24] posited switchgrass (and other prairie grasses) retreated to refugia during the ice ages and then moved poleward again as the climate warmed. He posited more specifically three regional refugia arose during the most recent glaciation: Lowland (or Southern) Great Plains, Eastern Gulf Coast, and Upland Plains. Recent molecular marker studies examining simple sequence repeats (SSRs) of 18 switchgrass cultivars and accessions [25] have provided tantalizing

support for this three-refugia theory. The latter work provides strong evidence that most—perhaps all—of today's cultivars can be sorted into three groups based on SSRs, with each group harking back to one of the three putative refugia. To follow the line of reasoning, we must first look more closely at the notion of switchgrass 'ecotypes'.

1.2.4 Upland and Lowland Origins, Distinctions, and Connections

Essentially all cultivars, lines, or accessions of switchgrass can be placed into one of two categories: upland or lowland. A few 'intermediate' or 'ambiguous' types, which are not readily assigned to one of these two categories, may represent archaic natural hybrids [23]. The upland and lowland groups are usually described as 'ecotypes', a term from evolutionary ecology connoting genetic variations within a species that allow the ecotypes to be better adapted to particular geographies or habitats. Ecotypes—sometimes also described as subspecies—typically differ in morphology or physiology in ways that make them better suited for different environments, but they are able to interbreed and produce fertile offspring—meeting that classical criterion for a species. More recently, these groupings have also been termed upland and lowland 'cytotypes', referring to the diagnostic DNA sequence data carried in their plastids [26].

Within *Panicum virgatum*, genotypes belonging to the upland ecotype are typically finer stemmed and shorter than those identified as lowlands. As the upland designation might imply, these lines are also generally better adapted to drier and colder habitats, while the lowland ecotype tends to thrive in warmer, wetter habitats. Indeed, most of the lowland lines, e.g., Alamo, are derived from accessions from the southern USA; and the upland genotypes are more generally associated with the northern Great Plains. All identified cultivars from the lowland ecotype are tetraploid ($2n = 4x = 36$), whereas the upland ecotype consists of genotypes that are both tetraploid and octoploid ($2n = 8x = 72$) [25]. Only recently have possible octoploid lowland plants been discovered in a small number of accessions [18, 23]. The two ecotypes, which were initially distinguished by their phenotypes, can now also be grouped into upland and lowland genetic clusters, or cytotypes, using various molecular markers [25, 27]. While crosses between octoploid (upland) and tetraploid (lowland) genotypes are incompatible, tetraploid cultivars from each of the two ecotypes have been crossed and produced fertile offspring, exhibiting significant hybrid vigor [27].

Using molecular clock calculations based on cpDNA sequences, estimates of the upland–lowland divergence range from 0.5 to 1.3 MYA [18, 28]. Because octoploids are extremely rare within the lowland ecotype, it is likely that polyploidization from 4x to 8x occurred after the upland–lowland divergence. Indeed, there is evidence for multiple polyploidization events within the upland lineage, suggesting that this process has occurred frequently. Clear separation of tetraploid and octoploid lineages within the upland ecotype suggests that some of these

octoploid lineages are indeed very ancient [18]. Because 2n gametes are very common in the Poaceae, polyploidization from the 4x to 8x level could have occurred many times in many different lineages of switchgrass. It must be noted that 2n gametes have not specifically been identified in switchgrass, so the mechanism of polyploidization is still unknown.

Key to understanding the evolution of switchgrass is the massive impact that Ice Age cycles have had on habitats that we tend to think of as permanent and immobile. During the past 2 million years, there have been approximately 16 to 20 continental glaciation events in North America, each sufficient to force the complete relocation of the tall-grass prairie and savanna habitats toward warmer climates, e.g., the Gulf Coast. Individual lineages of switchgrass that had evolved to become adapted to more northern areas would have survived by migrating southward (via pollen or seed), or they would have gone extinct. The polyploid nature of switchgrass would have been a key factor in helping lineages to survive, preserving vast amounts of genetic variability within populations, individual plants, seeds, and even individual pollen grains.

Lineages of switchgrass that would have survived the Ice Ages would be those that were endemic to or immigrated southward to areas that allowed their survival during many centuries of glaciation. As suggested by McMillan [24], in the most recent period of glaciation, three areas may have provided ice-free and sufficiently warm growing seasons to serve as refugia for many grassland species. McMillan's logic, which was built on an understanding of climatic geography during the last glacial period, suggested the Lowland (or Southern) Great Plains, the Eastern Gulf Coast, and an area in the Upland Plains were three places that—even in the midst of the glaciation—would have had growing seasons suitable for many of the plants that eventually re-colonized the Great Plains.

Casler and colleagues have looked carefully at the distribution of North American populations of the two switchgrass ecotypes and the morphological and genetic similarities and differences between and within those populations [18, 23, 25, 29, 30]. Other labs (e.g., [31]) have provided similar or additional evidence that the current populations of North American switchgrasses can be placed into a few groups based on molecular markers and that those groups are associated with particular geographies, or provenances.

Zalapa et al. [25] examined SSRs in 18 switchgrass cultivars: 7 lowland (all tetraploid) and 11 upland (two tetraploid and the remainder octoploid). The work found alleles unique to, i.e., diagnostic for, each ecotype and also found alleles that distinguished tetraploid from octoploid members of the upland populations. The analysis revealed also clusters of allelic similarities, or genetic pools, within each of the ecotypes; and, perhaps not surprisingly, those groupings reflected geography of origin. Accordingly, lowland cultivars were grouped by allelic similarities into two clusters; cultivars in one cluster all came from the Eastern Gulf Coast region, and those in the other were all from the Southern Great Plains. The nine octoploid upland cultivars fell into three allelic clusters, or genetic pools, each with a unique provenance: those associated with the Central Great Plains, the Northern Great Plains, and the Eastern Savannah [25]. Zalapa et al. [25] suggest their findings may

provide support for the three Ice Age refugia posited by McMillan [24].[1] Zalapa et al. [25] hypothesized that each of the two lowland allelic (and geographic) genetic pools noted above is descended from McMillan's similarly named refugium, i.e., Lowland/Southern Great Plains and Eastern Gulf Coast. They suggested also that at least two of the upland genetic pools may be the descendants of plants that survived in the Upland Plains refugium. The Zalapa et al. [25] work also offers a reasonable model for arriving at the current situation where octoploids are the more frequent ploidy level for upland cultivars. It builds on the notion that the duplicated genome offers more grist for the evolutionary mill, a notion reflected in the writings of others (e.g., [13, 16]).

More recent studies have identified multiple upland and lowland lineages within the eastern USA [18, 23]. The observation of obvious geographic patterning among upland lineages in the northern USA, combined with a general lack of patterning among lowland lineages in the southern USA, suggests that evolutionary forces have acted on the nuclear genomes of migratory switchgrass, allowing these populations to adapt to a wide range of habitats and climates during the 11,000 years since the last glacial period. Indeed, the allelic patterns of SSR markers identified by Zalapa et al. [25] are sufficiently specific to geographic regions that Zhang et al. [18] were able to identify two 8x upland accessions that were inadvertently transported by the US Army to remote regions of the USA, eventually becoming established and many years later incorrectly identified as 'local' switchgrass accessions.

One more evolutionary consequence of the Ice Ages was the periodic juxtaposition (in refugia) of upland and lowland lineages for tens of thousands of years, resulting in upland–lowland matings and the establishment of mixed or hybrid lineages, some of which completely defy simple classification [23]. These hybrid lineages are an additional mechanism by which switchgrass enriches and preserves genetic variability to be utilized during and after post-glacial migrations, creating phenotypic variations in flowering time, cold tolerance, and heat tolerance [30, 32] that have allowed it to adapt to such a wide range of habitats.

In sum, we can suggest that our 'modern' switchgrasses, i.e., those that emerged from and radiated after the last Ice Age, may have come from a relatively small number of survivors. Those survivors included a few—maybe only two—groups representing the lowland genetic pool and perhaps a few more groups carrying the upland gene set. What we see today reflects the rather remarkable ability of those few survivors/pioneers to radiate, adapt, and re-colonize two-thirds of a continent in a scant 11,000 years; but 2 million years of switchgrass evolution (which included repeated winnowings and forgings on the anvil of continental glaciation) and development of two ecotypes (with some representatives possessing a quadrupled genome size) clearly set the stage well for a rapid reclaiming of the North American landscape once it was again habitable.

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[1] Casler et al. [30, 32] had adumbrated earlier the colonization of prairie ecosystems by remnants from southern refugia.

1.3 The Agronomic History of Switchgrass

Switchgrass has been a ‘crop’ in the usual sense of that word for only a few decades. Unlike maize, wheat (*Triticum aestivum* L.), rice (*Oryza sativa* L.), and some other grasses that prehistoric humans co-opted into domestication [6], switchgrass has only very recently even been planted or studied in monoculture. *Panicum virgatum* preexisted *Homo sapiens*, of course, but only recently have we begun to take note of it and adapt it to human purposes.

One way to document the rise of switchgrass into human consciousness—or human technology—is to survey the history of publications about the species. We have done that using CAB Direct, the bibliographic database of Commonwealth Agriculture Bureau, which indexes over 9 million entries from applied life sciences fields—entries from 1900 to the present. We searched it for the occurrences of *Panicum virgatum*, switchgrass, or switch grass in ‘all fields’, i.e., title, abstract, key words, or CAB’s coding descriptors and identifiers. As a result, some articles indexing to switchgrass mention it rather coincidentally, e.g., not a host for an aphid, or as one among many species in mixed swards or in multi-species screenings. Along with refereed journal publications, the canvass returns a number of brief abstracts and non-refereed proceedings from agronomy, animal science, and weed science conferences, as well as agricultural experiment station bulletins. On the other hand, some published reports that deal with switchgrass rather extensively (e.g., [1, 33]) do not index to switchgrass, because they do not mention switchgrass in their abstract and the indexer has not included the species as an ‘organism descriptor’. Or, in other cases, switchgrass reports are published in a source—often a book or monograph such as this one—that is not cataloged by CAB (e.g., [34, 35]). So, we know our survey is not an exhaustive or comprehensive list of publications dealing with switchgrass, but we feel confident that it provides a good indication of the overall trend or trajectory for such publications.

As part of our survey, we perused each abstract (and a few full articles) to determine in what context switchgrass was discussed. Was switchgrass a primary focus of the work? For what use/purpose was it being considered? Figure 1.1 plots the total number of CAB-indexed reports referring to switchgrass, the number looking only at switchgrass (or comparing it with only one other species), and the number mentioning switchgrass as a potential energy crop. Accordingly, it documents the ‘birth’ of switchgrass as a crop: first appearing as a subject in scientific investigations about a century ago, exhibiting a long ‘lag phase’, and then entering a vigorous ‘growth phase’ in just the last 20 years.

The volume of work on switchgrass is still very small compared to many other crops. For example, canvassing CAB Direct for citations in 1940 produces 713 hits for *Zea mays*, 395 for *Avena sativa* (oats), and only six for *Panicum virgatum*. The number of publications in 2010 indexing to switchgrass is 165, but that barely outdistances the number of hits for maize in 1929 (and maize provides 5,610 hits in 2010). On the other hand, the 165 switchgrass citations in 2010 compare with just 15 for big bluestem (*Andropogon gerardii* Vitman), a tall-grass prairie species

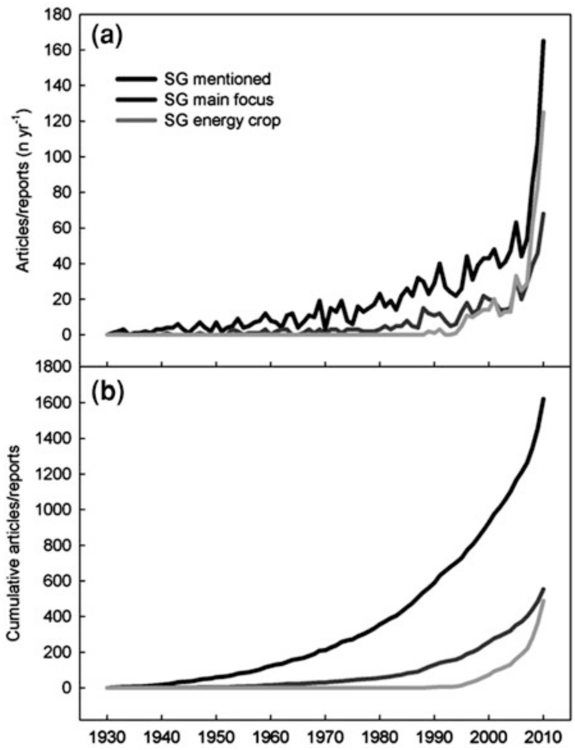

Fig. 1.1 Annual (**a**) and cumulative (**b**) number of CAB Direct citations mentioning switchgrass (*SG*), having *SG* as their major focus, and/or discussing *SG* as an energy crop

that has much in common with switchgrass historically and ecologically; and in only two of those 15 citations is big bluestem a primary focus of the work.

1.3.1 'Prairie Grass' Origins

The first indexed occurrence of switchgrass in the CAB database comes in 1914, where the species is mentioned as not being a host for the aphid about which the article was written. The next appearance is in 1931, in the quaintly named 'Who's who among the prairie grasses' [36], where switchgrass is mentioned as occupying 'less desirable lowland soils'. That publication and most of those few that followed over the next 20 years allude to switchgrass as one of the species in 'tall-grass prairie', 'prairie grasses', 'prairie hay', 'native grasses', 'range grasses', 'mixed grasses', 'warm-season grasses', etc.

Those early papers discussing switchgrass's contribution to grass mixtures include a few peer-reviewed articles and numerous agricultural experiment station bulletins and annual reports. Also appearing at this time are reports on the natural occurrence of switchgrass in various ecosystems. One such report, coming

in 1932 from Massachusetts, is the first CAB-indexed citation where switchgrass is the primary or sole species of interest [37].

1.3.2 Early Studies and Uses as a Monoculture, and the Growth of Reports on Switchgrass

Switchgrass begins to emerge from the anonymity of being 'just' a prairie grass in the 1940s. An article in 1941 looks at differences among various accessions in susceptibility to rusts and is the second paper published with switchgrass as the primary or sole subject of the investigation [38]. A 1947 agricultural experiment station report refers to studies of switchgrass and other prairie grasses done on pure stands established in 1937 [39]. During the late 1940s and 1950s, reports on selection and breeding studies with switchgrass appear in a few agricultural experiment station annual reports. Overall, though, the species receives scant attention. Indeed, through 1960, a total of 123 CAB-indexed reports mention switchgrass, and many of those simply mention its occurrence in various ecosystems.

The first CAB-indexed paper dedicated solely to switchgrass physiology (and only the third where the species is the primary focus) appears in 1947; it sought relationships between ploidy level and winter survival (but found none) [40]. The total number of indexed studies with switchgrass as their major focus grows slowly. By 1960, 14 such studies have accumulated. By 1970, there are 30; and by 1980, 55. Those reports focusing on switchgrass as a monoculture, i.e., a 'true' crop, deal with a range of topics. Some are reports of cultivar releases, e.g., Blackwell, Caddo, Summer, Pathfinder, and then Kanlow. A 1953 publication provides pioneering data on chemical composition [41]. Some as early as the 1940s discuss switchgrass for erosion control in waterways, and several in the 1960s considered the species' value in reclamation. However, most of the switchgrass-focused reports deal with the species as a forage crop either from an agronomic perspective or from an animal nutrition perspective. All of the cultivar release reports noted above discuss forage value.

Beginning in the 1980s, we observe an up-tick in the study of switchgrass. In that decade, 65 indexed reports appear dealing primarily or solely with switchgrass—more than doubling the previous 50 years' cumulative for this statistic. The focus is still heavily on forage value and breeding, but a few reports deal with reclamation, erosion control, and diseases. At the close of the decade comes the first peer-reviewed article written on switchgrass as an energy crop [42]. Some more background on that publication and further discussion of the trajectory in research studies on switchgrass as an energy crop will be given in Sect. 1.4.1.1.

After a plateau in the early 1990s, interest in switchgrass (as conveyed by indexed publications at least) increases noticeably in the second half of the decade. Reports dealing solely or primarily with switchgrass average eight per year from

1990 through 1994, nearly the same rate as in the 1980s; but the second half of the decade sees an average of 16 articles per year focused on switchgrass. As will be discussed below, that burst of activity is driven largely by the increasingly frequent appearance of reports on switchgrass as an energy crop, but the species continues to be studied for forage and other purposes as well.

In sum, for this section, based on indexed reports in the scientific literature, the history of switchgrass as a crop is very short. Only during the second half of the twentieth century did the species move clearly from being one of the ‘prairie grasses’ to being a crop grown in monoculture. For the first 40 years of its very short agronomic history, the volume of work on switchgrass was small, averaging only about five CAB-indexed mentions per year and averaging less than one report per year dedicated primarily or solely to it. From 1930 to 2010, more than 1,600 reports that index to switchgrass have been published, with more than half of those appearing after 1997. This might suggest that the crop is in the process of joining the Olympian list of ‘most useful grasses’, but let us hold that judgment in abeyance until we have looked at some other matters.

1.3.3 Current and Proposed Uses

The caveat about ‘most useful’ status notwithstanding, we can say without reservation that switchgrass now serves us very well in several roles, i.e., it belongs in the grass pantheon. Its initial adoption as a forage species was probably a logical extension of its millennia-long role as food for ungulates on the Great Plains of North America. In addition to that use, though, it has been adopted or is under consideration for a broad range of other purposes [43], which we will simply summarize:

Established roles/uses for switchgrass:

- Forage for grazing, hay, or haylage;
- Erosion control in waterways, levees, stream margins, etc.;
- Vegetative filter strips (to reduce runoff of soil and nutrients);
- Reclamation/stabilization of sand dunes and disturbed areas;
- Wildlife habitat.

Other roles/purposes under study (or in early adoption):

- Energy feedstock for:
  - Combustion;
  - Conversion to liquid or gaseous forms.
- Fiber or pulp for paper;
- Phytoremediation to include smelter and mining sites;
- Pharmaceuticals, biomaterials, plastics, etc.;
- Value-added ‘by-products’ from biorefineries;
- Substrate for mushroom culture.

1.4 The Origins of Switchgrass as an Energy Crop

A few published articles have discussed the brief history of switchgrass as an energy crop. One [44] is by individuals in the US Department of Energy (DOE) funding agency that initiated studies on switchgrass as an energy crop, but its account begins essentially after the decision has been made to focus on switchgrass. An internal DOE report [45] and a subsequent journal publication [46] provide more of the 'back story' of how switchgrass came to be essentially the sole focus in DOE's efforts on herbaceous energy crops. One of us (DJP) was a participant in the discussions that first brought switchgrass to the attention of DOE, and he has written about the selection of switchgrass [34, 43, 47]. We will summarize and expand on all of these sources in the sections that follow; and some personal observations are provided because we hope they will show how serendipity, pragmatic decision-making, and politics—as well as science, of course—have shaped the narrative of the switchgrass story.

We shall take up our account of the switchgrass-for-energy 'story' beginning in 1984 with DOE's early work on herbaceous biomass species. However, interest in biomass as an energy source certainly predates that. Indeed, biomass use for energy is prehistoric, with wood remaining a primary energy source until the mid nineteenth century. Since then, we have become increasingly dependent on fossil fuels, but many countries—especially in war time—revert to biomass energy sources. In one of the more recent occurrences, the 'energy crisis' following the embargo imposed by oil producing and exporting countries (OPEC) in 1973 spurred interest and work on energy cropping and biomass as a feedstock in the USA, the EC [48], and the UN [49]. Out of those efforts came many reports, including one in the USA that mentions switchgrass as a possible biomass source [50]. However, in our view, there is a loss of continuity (or certainly of momentum) in the biomass-for-energy narrative, when interest in biofuels flagged in the late 1970s, as oil prices returned to 'pre-crisis' levels.

1.4.1 In North America

It is fitting that the first studies of switchgrass as an energy crop were done in North America, but not every energy crop candidate has been first studied in its region or country of origin. For example, miscanthus from southern Asia was first studied as a possible energy crop in England (see Sect. 1.4.2.2). But for switchgrass, the impetus to consider it as an energy crop was as native as the species itself.

1.4.1.1 DOE Extramural Screening Studies

In 1982, the Oak Ridge National Laboratory (ORNL) of the US DOE assumed control of a young program looking at woody species for energy purposes [46].

In 1984, ORNL expanded their biomass-for-energy program and issued a request for proposals (RFP) to screen herbaceous species as energy crops, i.e., species that might produce significant amounts of lignocellulosic biomass. The RFP further stipulated that the work must be done on 'marginal croplands' [46]. In 1985, the first five subcontracts were awarded for what became known as the Herbaceous Energy Crops Program (HECP); and, in the first few years of the HECP, both the 'woody' and 'herbaceous' subcontractors met together periodically to compare biomass production data.

After the five initial HECP subcontractors were identified, ORNL called them together in April 1985. They came from Alabama (Auburn), Indiana (Purdue), Ohio (a private research firm), New York (Cornell), and Virginia (Virginia Tech). Two more subcontractors—Iowa State and North Dakota State—were added to the screening study in 1988 [45]. At that April meeting, each of the five groups shared their list of species to be screened. Each list was appropriate to the region in which the work was to be done, but no species was common to all lists. No benchmark species was there to allow cross-region comparisons of biomass productivity of the over 30 disparate species that would be grown at over 30 disparate locations, each of which was marginal for disparate reasons.[2]

The eight species proposed by Virginia Tech included switchgrass. Their proposal noted that switchgrass is a native that will 'produce better growth and cover on droughty, infertile, eroded soils [which characterized the marginal sites proposed for studies in Virginia] than most introduced grasses'. Dale Wolf, the forage scientist who chose switchgrass for Virginia Tech's proposal, suggested to those present at the 1985 meeting of subcontractors and administrators that the wide natural occurrence of switchgrass should allow it to serve well as the desired benchmark species. His suggestion was adopted, and he subsequently supplied Cave-in-Rock seed from a single source for all subcontractors. For the later-added subcontractors, switchgrass was stipulated as a candidate/benchmark species. So, switchgrass appeared in all seven subcontractors' screening studies—but only after it was added to most. By contrast, 17 candidates from the screening studies were on only one of the seven lists.

The initial round of subcontracts called for a 5-year study to allow each of the screened species to come to full production and to experience a range of growing seasons.[3] With the addition of two more subcontractors in 1988, the total number of species screened grew to 36 plus two polycultures, and the total number of sites was 31 [45]. When the final reports of the screening studies were compiled, switchgrass had proven itself to be one of the most prolific producers of biomass across most of the locations.[4] It, in fact, did well soon enough in the 5-year cycle

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[2] Each group would plant their list of candidates at from two to eight sites. (Data in this and the next few paragraphs were compiled from Wright [45]).

[3] Most were perennials, but that was not a requirement of the RFP.

[4] Switchgrass did not fare so well in Ohio perhaps because the marginal sites there were poorly drained.

that some of the subcontractors did switchgrass-specific studies looking at management techniques (Virginia Tech) and screening cultivars (Auburn) [45].

Partly because of the long-term nature of the screening studies and perhaps because biomass production for energy purposes was not yet a 'standard' topic for editors of agronomic publications, the first papers on switchgrass as a model species were slow to appear. Only two switchgrass-based and DOE-credited reports appeared during that first 5-year cycle. Both came out of Purdue and included the paper mentioned above [42]. However, annual reports and final reports from all of the subcontractors and ORNL HECP staff were submitted in a timely fashion.[5]

1.4.1.2 Intramural Efforts at ORNL and Other DOE Agencies

In the early 1990s, HECP was subsumed into the Bioenergy Feedstock Development Program (BFDP), reflecting some reorganization within ORNL and merging woody and herbaceous biomass programs under this new name and management. As of this writing, feedstock development efforts in DOE remain based in ORNL's Environmental Sciences Division (part of ORNL's Energy and Environmental Sciences Directorate) with a program name of Renewable Energy Systems. In addition, work on microbial conversion of biomass into biofuels is housed in the directorate's Biosciences Division as the Bioconversion Science and Technology Program.[6]

A very significant body of work on switchgrass has and continues to come from ORNL scientists. Besides intramural studies on microbial conversions of switchgrass biomass, ORNL staff have examined molecular markers and basic physiology of switchgrass and the species' potential for sequestering carbon. Several on the ORNL staff have also looked at the economics of large-scale switchgrass production. Much of that body of work—as well as annual and final reports from subcontract work—can be accessed at ORNL's website.[7]

Other DOE laboratories outside of Oak Ridge are also engaged in work on switchgrass as well as other biomass species. Much of the biomass conversion work has been done at the Solar Energy Research Institute (SERI), which was formed in 1977 and was reorganized and renamed the National Renewable Energy Lab (NREL) in 1991. NREL is the home of the National Bioenergy Center; and, along with ORNL and three other national DOE laboratories, it supports the efforts of DOE's umbrella Biomass Program. As the name implies, NREL deals with more than biofuels, but their portfolio includes efforts aimed at development and commercialization of biomass conversion technologies, i.e., biorefineries.

5 http://www.ornl.gov/info/reports/

6 http://www.ornl.gov/sci/ees/organization.shtml

7 http://www.ornl.gov/info/reports/

1.4.1.3 DOE Extramural 'Model Species' Studies

Switchgrass, which was somewhat serendipitously chosen as the benchmark species for HECP's initial 5-year, 7-state, 36-species screening studies, did so well in those studies that ORNL's BFDP subsequently invited proposals to study only switchgrass. The RFP described switchgrass as a 'model species' [44–46]—perhaps an implicit reservation or caveat that switchgrass might ultimately prove less productive than some of the thousands of species that had not been screened. However, it was a very reasonable notion that lessons learned from studies of a model species could be applied or adapted to other promising biomass species when they might appear. The decision to focus on a single herbaceous species was made at a time when ORNL's budgets for biofuels work were shrinking, suggesting that the decision to focus on a single herbaceous species was perhaps at least partially a pragmatic one, based on fiscal constraints [45, 46]. ORNL narrowed their focus on woody biomass to a single model species at this time also [45]. The upshot of the switchgrass-as-a-model-species decision was that DOE essentially stopped looking for new herbaceous energy crops after the first 5-year screening study.

A second and then a third 5-year round of DOE-funded extramural subcontract work—now focused solely on switchgrass—began in 1992 and 1997. In 1992, several long-term varietal and management studies were initiated, some of which ultimately received 10 years of DOE support (e.g., [51, 52]). Field studies on cultivar selection, improving establishment, and management for biomass production (especially fertilization and harvest management when grown for biomass) were performed at Auburn, Iowa State, Texas A&M, and Virginia Tech [44]. During DOE's 'model species' funding cycles, switchgrass breeding efforts were supported at Oklahoma State and the University of Georgia, as were tissue culture and transgenic work at the University of Tennessee [44]. Also included in these rounds of DOE/ORNL funding were collaborations with USDA personnel based at various public universities and USDA facilities, included the very productive program at the University of Nebraska [44].

During this era, papers discussing switchgrass as an energy crop authored by DOE subcontractors, ORNL scientists, and collaborating USDA personnel began to appear with increasing frequency (Fig. 1.1). These papers represented the bulk of papers being published on herbaceous biomass species at the time, and they typically discussed switchgrass as a 'model species', 'energy crop candidate', 'potential energy crop' etc.; but the 'model' designation seemed to fade from consciousness (along with 'marginal croplands') as more and more reports appeared on switchgrass—especially as non-DOE efforts increased. Essentially all of the first several papers dealing with switchgrass as an energy crop can be traced to DOE/ORNL efforts and support, but that would change quickly at the beginning of the twenty-first century.

1.4.1.4 Transition of Support from DOE to DOT, USDA, and the Private Sector

Shifting US politics and administrations cause the switchgrass story to take a right-hand turn in 2002. The DOE/ORNL/BFDP program had issued a new RFP for switchgrass studies in 2001 and was in discussion with potential subcontractors when funding was withdrawn based on 'decisions made within DOE' [44]. Work continued within DOE, but no more funding went to outside parties. Interestingly, towards the end of the same administration, switchgrass was given a boost into the public consciousness when it was mentioned in the 2006 State of the Union message to the US Congress and citizens. That reference triggered much interest from the news media, resulting in a flurry of telephone calls and e-mails to the relatively small fraternity of scientists then working on switchgrass; and it probably brought first knowledge of the species and its bioenergy potential to millions. It was almost certainly the impetus for a spate of magazine and newspaper articles.

Following the loss of DOE funding for extramural research on switchgrass-for-energy, the US Department of Ariculture (USDA) began slowly and then more vigorously to assume leadership. For example, the USDA Agricultural Research Service (ARS) developed a national intramural program on Bioenergy and Energy Alternatives that includes major studies with switchgrass at several USDA facilities.[8]

Some of the initial post-DOE funding for efforts on switchgrass came through the Sun Grant Program, which was enacted legislatively in 2002 and overseen by the US Department of Transportation (DOT) with substantial inputs from both USDA and DOE. Various regional studies on switchgrass and other bioenergy species were developed and funded (and continue to be funded) by Sun Grant.[9]

Also stepping into the biofuels arena increasingly in the first decade of the twenty-first century has been the private sector. Some major petroleum companies have invested in biofuels research, in some cases via centers established at universities. A number of new companies that hope to capitalize on switchgrass's and other species' bioenergy potential have also appeared. Most of them have their own cadre of research scientists, but they have also contracted work out to scientists at various public and private institutions. Another major participant in switchgrass-for-energy studies has been the private, not-for-profit Noble Foundation in Oklahoma, which has expanded its long-standing efforts on forages into studies aimed specifically at the energy crop potential of switchgrass.[10]

During this time of change in funding sources and administrative oversight of bioenergy efforts, there were also quantitative and qualitative changes in the trajectory of publications on switchgrass. Since the first two switchgrass-for-energy citations in 1989, the number of reports dealing with that topic has grown rapidly.

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8 http://www.ars.usda.gov/research/programs/programs.htm?np_code=307

9 http://www.sungrant.org/

10 http://www.noble.org/Research/Biofuels/index.html

In the 1990s, 57 appear; and from 2000 to 2010, another 429 are added to the CAB database. Not all of those are dealing solely with switchgrass; some only compare it briefly with another species of interest; but it seems in many cases that switchgrass is the standard—the benchmark again—against which other biomass species are being compared. Interest in switchgrass for other purposes certainly does not go away during this time, but the great majority of reports with switchgrass as the main focus are looking at it for its bioenergy potential. For example, as of this writing, over 100 CAB Direct entries in 2011 index to switchgrass, and three-quarters of them mention it as an energy crop.

1.4.1.5 Canadian Efforts

Switchgrass is native to southern portions of Canada, and Canadian workers became involved in switchgrass-for-energy studies early on, but it was largely a one-institution project based at McGill University. In 1993, workers at McGill planted a screening study that looked at five species of warm-season grasses, to include 12 cultivars or lines of switchgrass [53]. They followed phenology and yields for two post-establishment seasons and reported biomass on a per-plant basis. They concluded that several cultivars of switchgrass and one of cord grass (*Spartina pectinata* L.) were the most productive. A simultaneous study at the same location looked at phenology and allometry of nine switchgrass cultivars and one line of big bluestem [54]. It showed again potential for these warm-season grasses in a short-season locale. Those screening studies were followed by several studies focusing specifically on switchgrass: looking at management, seed physiology, energy yield, and chemical composition. Taken together, these works represent a significant body of knowledge on the potential of switchgrass-for energy (or other) purposes in southern Quebec.

After the flurry of studies done at McGill, Canadian work on switchgrass-for-energy was taken up and expanded to an international scale by scientists at Resource Efficient Agricultural Production (REAP) Canada, which is located on the McGill campus. That organization has championed in Canada and elsewhere the adoption of switchgrass as an energy crop. They are particularly interested in—and are fostering commercial ventures that employ—the concept of growing switchgrass for conversion into densified units (e.g., pellets) that can be used for heating [55]. Their web site[11] has a comprehensive list of their work and recommendations, which include growing guides and information about pelletizing and burning switchgrass.

[11] http://www.reap-canada.com/

1.4.2 In Europe and Elsewhere

1.4.2.1 A Brief History of Switchgrass in Europe

If the North American history of switchgrass as an energy crop can be considered brief, the same is all the more true in Europe. It is notable that the first European studies on switchgrass-for-energy were done at the famed Institute of Arable Crops Research (IACR)—formerly known as Rothamsted Experimental Station—when scientists there planted plots of upland and lowland switchgrass in 1993 [56, 57]. One year later, A. Biotec, an Italian private research institute located in Cervia (southern Italy) undertook pioneering studies on switchgrass in the Mediterranean region. These English and Italian studies revealed an adaptability of switchgrass to both northern and southern European conditions. However, because of lower productivity compared to other biomass crops, switchgrass was initially deemed to be a less suitable crop for energy conversion than some other species. In southern Europe, switchgrass produced significantly lower biomass yields than giant reed (*Arundo donax* L.) and sorghum (*Sorghum bicolor* L.), while in northern Europe it was less productive than miscanthus and some short-rotation coppices such as poplar (*Populus spp.*) and willow (*Salix spp*.).

Nevertheless, the promising results with switchgrass beginning to come from North America in the 1990s paved the way for a 1998 to 2001 European project specifically focused on switchgrass: 'Switchgrass as an alternative energy crop in Europe' [58]. This project effectively coordinated research activities on switchgrass in Europe and extended trials over a wide range of European latitudes, soils, and climates. In addition to trials in the Netherlands and UK, studies were established in southern Europe: Trisaia, Italy (40.09' N, 16:38' E), Aliartos, Greece (38.22' N, 23.10' E) [59], and Bologna, Italy (44.43' N, 11:47' E) [60].

In general, the results from this first pan-European switchgrass project confirmed a yield advantage of lowland over upland ecotypes; but, in some cases, it also revealed lowlands' susceptibility to cold stress, which considerably limited their productivity. Some lowland plantings failed, especially in Germany, western UK, and Ireland. This was likely due to a particularly harsh winter, since there were other cases of successful lowland plantings with high yields in more northern countries.

Other studies carried on as part of this first European switchgrass project assessed economic and environmental impacts of switchgrass [61, 62], variety choice [63], nutrient composition [58], modeling [64], thermal conversion (combustion, gasification, and pyrolysis), ethanol production [61, 65], and industrial non-energy uses [66, 67]. Studies by Monti et al. [68] and Minelli et al. [69] examined tillage and weed control methods for improving switchgrass establishment and provided sustainability strategies aimed at the use of machinery and herbicides.

Collectively, these projects led to several conclusions: (1) switchgrass can be grown over a wide range of European latitudes, although the level of biomass

production may not always be satisfactory; (2) production of up to 25 Mg biomass ha^{-1} is possible, with higher yields generally seen when planting lowland cultivars in more southern latitudes; (3) seed propagation is valued by farmers, as it significantly reduces their investments compared to vegetatively propagated grasses and short rotation coppices; (4) switchgrass is particularly vulnerable during establishment, but, once established, it requires relatively low use of chemicals and farm resources.

A weakness of the first European (and American) switchgrass projects was the absence of farm-scale studies under truly operational conditions. Nearly all production data—and subsequent economic and environmental analyses—were in fact extrapolated from plot trials, which it is generally conceded often produce inflated yields. Studies at farm and field scales were therefore undertaken in a subsequent 2001 to 2005 project, 'Bio-energy chains from perennial crops in southern Europe' [70], which compared switchgrass, miscanthus, giant reed, and cardoon (*Cynara cardunculus* L.) grown in the Mediterranean region. The University of Bologna led the work on switchgrass and planted Europe's first field-scale experiment (ca. 9 ha), where interdisciplinary studies were carried out, e.g., geo-statistical [71], economic [72], agronomic [73], and agro-environmental [74].

One of the main findings of this Italian work was that, under real-world operational conditions (using common farm machinery), up to 30% of switchgrass biomass can be left in the field. However, much of that loss could be reduced through simple machinery adjustments. Therefore, switchgrass generally achieved acceptable biomass yields, and its management required very few investments in terms of additional machinery or implements. Along with these important operational advantages, switchgrass could also provide significant environmental and economic benefits compared to other energy crops [74]. The advantages seen in Italy, however, were not always seen in other Mediterranean countries. For example, in Greece the productivity of switchgrass was much lower than that of giant reed, and in Spain the productivity of cardoon was clearly higher than switchgrass. Therefore, no clear picture emerged on which crop should be used for energy in the Mediterranean area. Indeed, just as in the USA, it may well be that some species will out-perform switchgrass as biomass producers in specific locales.

Following the first two multi-year European projects, a number of new national (e.g., LignoGuide in France, and BioSeGen in Italy) and multi-country projects were launched (Fig. 1.2) to look at switchgrass—in many cases along with other species. Agronomic studies at different scales or levels increased, especially in western Europe, but they moved eastward as well (Fig. 1.2). Some European projects that have emphasized the possibilities of switchgrass as an energy crop are: (1) On-Cultivos (2005–2012), which has set out to define, promote, and develop a sustainable market of energy crops; (2) Babilafuente (2007–2022), which hopes to demonstrate the commercial feasibility of a second-generation ethanol plant in Spain; (3) 4FCROPS (2009–2011), which has analyzed potential land allocation and prospects for switchgrass in Europe; (4) BIOLYFE (2010–2013), which has addressed second-generation cellulosic ethanol, including

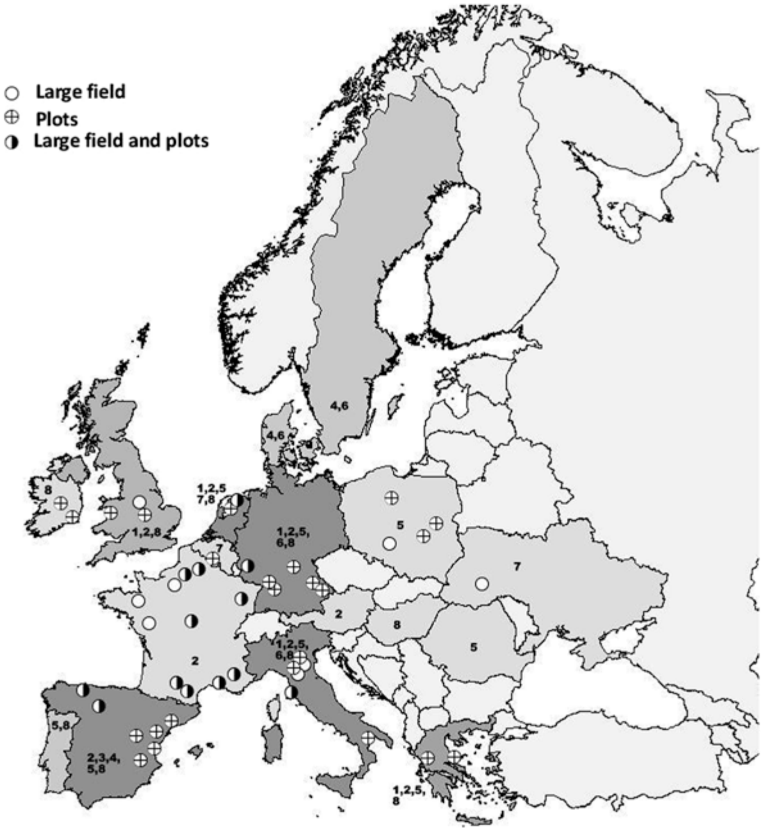

Fig. 1.2 Switchgrass trials in Europe. Data gathered from the literature and by personal communications. Numbers inside each country identify which of the following European projects that country has participated in: *1* Switchgrass (1998–2001); *2* Bioenergy chains (2002–2005); *3* On-cultivos (2005–2012); *4* Babilafuente (2007–2022); *5* 4FCrops (2009–2011); *6* BIOLYFE (2010–2013); *7* Pellets-for-Power (2010–2013); *8* OPTIMA (2011–2014)

upstream and down-stream processes, such as pretreatment steps; (5) Pellets-for-Power (2010–2013), which is aimed at developing switchgrass on 1 to 5 million currently underutilized hectares in the Ukraine and other countries of eastern Europe: (6) OPTIMA (2011–2014), which is dealing with the development of perennial grasses in the Mediterranean basin, particularly on marginal lands.

These continuing research efforts and the reports coming from them have 'raised the profile' of this non-native species in Europe, such that switchgrass has become an increasingly frequent subject for scientists, farmers, and entrepreneurs. By virtue of its frequent appearance in scientific and popular reports, switchgrass has come to be considered as one of the most important energy crops in Europe—much as happened in the US.

To summarize, the results to date from various European studies suggest that switchgrass is broadly adapted to many of Europe's countries. However, there is still great uncertainty on whether lowland or upland ecotypes should be used in northern European countries. Biomass productivity is clearly the most important determinant in selecting energy crops in Europe. For this reason, the expectations for switchgrass as an energy crop are still significantly lower compared to other perennial and annual grasses which may out-yield it: giant reed, sorghum, and miscanthus in southern Europe and miscanthus in northern Europe. The advantage of switchgrass compared to other competing perennial grasses mainly lies in its integrated assessment, i.e., by weighing all the operational, economic, and environmental aspects. In its favor, switchgrass is propagated by seed and requires very little investment in terms of farm machinery and agricultural inputs. In comparing several biomass crops, Monti et al. [74] and Fazio and Monti [75] found that the environmental loads and the annual equivalent cost per unit biomass were the lowest in switchgrass. The ongoing projects will likely contribute to raising the awareness of switchgrass benefits in Europe by emphasizing the integrated assessment in terms of farming systems and economic and environmental sustainability.

1.4.2.2 Switchgrass Studies in Other Countries

The number of non-North American and non-European countries in which switchgrass has been studied is growing. In a tally done in 2005, the species had been investigated or was reported as in use in 11 countries [43]. The list now stands at more than 20. Among the first reports of adoption of the species outside of North America was one from Australia considering switchgrass-for soil conservation uses [76]. Besides the North American and European nations already noted, the countries producing studies on switchgrass include: Argentina, Australia, China, Colombia, Japan, Korea, Mexico, Pakistan, Poland, Sudan, and Venezuela. In most cases, especially for the more recent citations, the studies deal with switchgrass-for-energy.

1.5 Conclusions

The story of switchgrass, which began 2 MYA in the first quarter of the Pleistocene epoch (the Ice Ages), does not intersect with human science and technology until the middle of the twentieth century. Initially the species was of interest to us primarily as a member of prairie ecosystems, but it began slowly to gain attention as a potential forage crop and then for other uses when grown in monoculture. Less than three decades ago, we began to consider it for bioenergy purposes.

Switchgrass came out of the Ice Ages' climatic upheavals and into our scientific era as two distinct, polyploid ecotypes, each possessing a range of morphologic,

physiologic, and genetic differences. The species' legacy of having endured repeated glacial and interglacial episodes combined with the greater genetic plasticity afforded by its polyploidy likely explain switchgrass's ability to rapidly re-colonize North America after the last glacial episode; and those same factors likely produced a deeper, wider genetic pool from which we can now draw traits to serve us for a variety of purposes today.

The history of switchgrass-for-energy begins in 1985 with its selection as the benchmark species for a US DOE herbaceous energy crop screening study. Switchgrass proved to be among the top biomass producers of the 36 crops considered, and in 1991 DOE designated it a 'model species' for further study. Since DOE was the primary US agency supporting biomass-for-energy work at that time, the next decade produced a significant amount of work on switchgrass as a model energy crop, while no other herbaceous lignocellulosic species were being considered in a systematic way. When DOE funding for extramural work on switchgrass ceased in 2002, other public, as well as private, organizations kept the work moving and even accelerating. But in the transition, the notion of 'model' may have become blurred or even lost altogether. As a result, switchgrass has perhaps become a de facto biomass species of choice. At the very least, it is regularly held up as a benchmark against which other energy crop candidates are being considered.

Incontrovertible data show a remarkable rise of interest in switchgrass as a bioenergy crop in the last quarter century. If that trajectory is maintained, switchgrass could well become what some have already ascribed to it—the biomass species of choice for many systems. We feel that its biology, especially its phenotypic and genetic variability, may well make it more than just a good model species. In time, it may be grown over millions of hectares to serve as a transformer of the sun's energy into forms that reduce our dependency on fossil fuels. If that happens, it should, indeed, be allowed to join the handful of species that constitute the Olympians within the grass pantheon.

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