BEST MANAGEMENT PRACTICES FOR

SALINE AND SODIC TURFGRASS SOILS

ASSESSMENT AND RECLAMATION

Robert N. Carrow • Ronny R. Duncan

CRC Press
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CRC Press
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Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

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No claim to original U.S. Government works
Version Date: 20111017

International Standard Book Number-13: 978-1-4398-1475-8 (eBook - PDF)

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Preface

THE CHALLENGE

Soluble salts, which can move with gravity-induced movement of water, and salts retained in soils (especially sodium) can adversely influence onsite and offsite natural resources and ecosystems—that is, soils, surface waters, subsurface waters, wildlife, and plant ecosystem sustainability. When a turfgrass site is irrigated with saline irrigation water, salinity management (a) is the most complex stress management issue that the turfgrass manager will confront and (b) requires that daily management for turfgrass performance and site use be tightly coupled with long-term environmental, economic, and social sustainability based on proper science.

One very important lesson that we have learned over the years in dealing with salinity challenges globally is that salinity is often quite subtle in revealing its stress symptoms on plants; but usually by the time those symptoms are recognized, the entire ecosystem is affected. Additionally, fixing the salinity-induced problems usually begins with the secondary plant response and not the primary cause, which means that remediation does not occur rapidly. You must start with the initial sources of salinity additions to the site and develop appropriate reoccurring strategies to overcome the potential limitations.

FEATURES

Barrett-Lennard and Setter (2010, iii) summarized their experience in the vast salt-affected soils of Australia as follows: "It is important to recognize that plant improvement is only part of the solution to the use of salt-land. Better germplasm must be linked to the appropriate management of soils and cropping practices." This quote summarizes the essence of managing turfgrasses or any plant on salt-affected sites—the whole ecosystem must be managed.

The *best management practice* (BMP) concept, considered the gold standard management approach for any individual environmental issue, is used in this book, since it is a whole-ecosystem (holistic), science-based salinity management approach that allows all possible management options to be considered and implemented on a site-specific basis. Features of this book include the following:

- *Provides BMPs addressing both proactive site assessment (initial and ongoing monitoring) and specific individual site management programs* that can be implemented for each type of saline and sodic problem affecting turfgrass performance.
- *Identifies all possible BMP strategies*, including turfgrass and landscape plant selection; irrigation system design; irrigation scheduling and salinity leaching; chemical, physical, and biological amendments; cultivation; topdressing; soil modification; sand capping; surface and subsurface drainage options; nutritional practices; additional cultural practices (plant growth regulators [PGRs], biotic and abiotic stresses, and traffic stresses); and ongoing monitoring. There is no "silver bullet" amendment, treatment, or grass for salinity management—only a holistic BMP approach will be successful and sustainable.
- Includes the role and use of field and laboratory analytical methods for *site assessment approaches for both plant performance and whole-ecosystem assessment* in relation to environmental issues such as soil quality and sustainability, salt disposal, and potential to affect surface and ground waters.
- Since plant and soil nutrient and element deficiencies, imbalances, and toxicities are an integral part of salinity stresses, this book *contains the most detailed information available*

to turfgrass managers specific to turfgrass soil testing (routine and salt package tests), water quality, and plant analyses as well as report interpretation of each of these potential management tools.
- *Presents emerging challenges, technology, and concepts*, including the integration of salinity management into comprehensive site environmental or sustainable management systems; use of halophytic turfgrasses for nontraditional purposes (land reclamation, saline forages, and drainage water reuse schemes); integration of geospatial and geostatistical concepts and technology; and integration of new sensor technology into daily management paradigms.

OUR APPROACH

The *foundational principles* used by the authors in development of this book were as follows:

- *To incorporate both scientific and practical management recommendations (practicum).* Basic scientific principles are necessary to understand specific salinity challenges and to comprehend the logic behind each practical BMP strategy for salinity management.
- *To compile in one source* all the information required *to identify (assessment)* and *manage* the diverse types of salinity stresses.
- *To use a "field problem" approach.* There is not "one" salinity issue but a number of interactive salinity problems, with each salt-affected site encompassing a unique mixture of these multiple challenges. Many times, soil chemical and physical academic courses are not taught from a field problem perspective; but real-world salinity issues that occur on a specific site require a "field problem thought process" that is multidimensional in scope. Color pictures inserted in the center portion of this book will aid in visualizing field problems.
- *To encourage formal and continuing educational programs* in turfgrass science and management at all levels to incorporate more specific *science-based and practical, field problem-solving emphasis on soil salinity and saline water quality*—which are and will continue to be emerging and increasing realities in the turfgrass industry.
- *To encourage the use and development of more salt-tolerant grasses.* Chapter 9 illustrates the science and practicum approach where for individuals interested in turfgrass selection for a salt-affected site, Chapter 9, Section 9.4, titled "Landscape Plants and Salinity Tolerance," is appropriate. Much of the remainder of Chapter 9 plus Section 20.3 ("Grass Selection Issues") are focused on presenting an in-depth review of the current status and challenges for turfgrass breeders, geneticists, and biotechnologists in development of more salt-tolerant grasses in the future.

SUGGESTIONS FOR READERS

Because salinity management is complex and constantly dynamic and since this book presents both the science principles and the practicum, a reader may find it daunting to attempt to comprehend all aspects. Understanding salinity problems and management requires time. Understanding why salinity issues occur and why specific maintenance programs must be implemented are essential for managing the series of events that seem to cascade in sequence to challenge the sustainability of turfgrass ecosystems. The book is developed so that a turfgrass manager or consultant can obtain a basic understanding of salinity issues by reading Chapters 1 to 3. Then, readers can go to the chapter relating to a specific BMP strategy of interest (e.g., sand capping) without reading all site assessment chapters (Chapter 4 to 8) or management chapters (Chapters 9 to 17). For those involved in the development of a new facility that will be using saline irrigation water, the site assessment chapters and the specific salinity management chapters, even in outline form, will provide a detailed overview of preconstruction planning considerations and possible infrastructure concerns.

May the Lord bless each student, turfgrass manager, and consultant as they pursue a productive career in turfgrass management and science!

Robert (Bob) N. Carrow
Ronny R. Duncan

Acknowledgments

The authors wish to acknowledge contributions from those individuals who provided advice, encouragement, and guidance during the development of this book.

Special thanks for the patience and encouragement of our spouses and families. Thanks to Tim Hiers, golf course manager at The Old Collier Golf Club, for providing the opportunity of a salt-challenged site as a “living laboratory” for defining and refining BMP protocols over the past seven years, for his intense interest in fostering cutting-edge science in salinity management, and for his advice and friendship. We also acknowledge the numerous turfgrass managers and consultants who have provided real-world and site-specific salinity challenges, asked the challenging questions, demonstrated success of the BMP approach for salinity management by implementation, and provided feedback for us. This interaction has allowed the coupling of science and practical management in this book.

Authors

ROBERT N. CARROW, PHD

Dr. Bob Carrow is a professor in the Department of Crop and Soil Sciences at the University of Georgia, located at the Griffin Campus in Griffin, Georgia. After graduation from Michigan State University's (1972) Crop and Soil Science Department, he was a faculty member in turfgrass research and instruction at the University of Massachusetts (1972–1976) and Kansas State University (1976–1984) before coming to the University of Georgia in 1984 as a research scientist in turfgrass stress physiology and soil stresses.

Dr. Carrow has coauthored four books: (a) *Salt-Affected Turfgrass Sites: Assessment and Management* (1998); (b) *Seashore Paspalum: The Environmental Turfgrass* (2000); (c) *Turfgrass Soil Fertility and Chemical Problems* (2001); and (d) *Turfgrass and Landscape Irrigation Water Quality: Assessment and Management* (2009). He was coeditor of *Turfgrass* (Agronomy Monograph no. 32; American Society of Agronomy, 1992). Dr. Carrow is a fellow of the American Society of Agronomy, served as vice president of the International Turfgrass Research Society for ten years, and has written numerous scientific book chapters and journal articles (124) and professional turfgrass trade journal articles (224). He has made over 565 invited presentations on a worldwide basis to turfgrass professionals and 28 to scientific audiences in 38 states and several countries, including Australia, Canada, England, Singapore, Japan, and Guam. He has been a cooperator on the release of three Bermuda grasses, four seashore paspalums, and three tall fescues.

Dr. Carrow's research focus has been in the following areas: (a) precision turfgrass management via mobile spatial mapping for improvement of site-specific irrigation design and scheduling, new water audit approach, salinity management, fertilization, and cultivation; (b) management of salt-affected sites; (c) water conservation and irrigation water quality issues; (d) stress physiology research on drought, saline and sodic soils, low soil oxygen, the acid-soil complex, low light, and nutritional stresses; (e) soil fertility and plant nutrition; and (f) traffic stresses on recreational sites.

RONNY R. DUNCAN, PHD

Dr. Ronny R. Duncan is recently retired after many years as professor of Crop and Soil Sciences at the University of Georgia. From August 2003 to May 21, 2010, Dr. Duncan worked as vice president of Turf Ecosystems LLC, a private consultancy and grass development company that was a subsidiary of Collier Investments, LLC, of Naples, FL. He consults on all turfgrass species regarding water quality problems, soil salinity challenges, and ecosystem agronomics on a global basis.

A premier researcher in the breeding and genetics of turfgrasses, Dr. Duncan continues research interests of edaphic and abiotic environmental stresses on turfgrasses. His expertise extends into salt and salinity-related soil and water problems across all turfgrasses and turfgrass management involving water conservation strategies, water quality problems, and alternative water use on all turfgrasses.

Dr. Duncan's education includes a BS in crop production, an MS in crop science breeding, and a PhD in plant breeding at Texas A&M University in 1977. Current teaching commitments include three popular seminars for the Golf Course Superintendents Association of America. He has taught and/or continues to teach workshops for national and international turfgrass organizations, including the GCSAA, such as his current workshops Seashore Paspalum Turfgrass Management, Greens Management of Seashore Paspalum for Tournament Quality Conditions, Advanced Water Quality Assessment and Management, Turfgrass Water Conservation, and Advanced Salt-Affected Turfgrass Sites: Assessment and Management.

His honors and awards achieved include fellow of the Crop Science Society of America, fellow of the American Society of Agronomy in 1992, and the Excellence in Research Award from Seed Research of Oregon recognizing his turf research, which was given in 1998.

Patents (P) and turfgrasses developed by Dr. Duncan include
‘SeaIsle 1’ seashore paspalum (U.S. PP no. 12,665)
‘SeaIsle2000’ seashore paspalum (U.S. PP no. 12,625)
‘Southeast’ tall fescue
‘Tenacity’ tall fescue
‘Bulldog’ tall fescue
‘Seaspray’ hybrid seeded seashore paspalum (U.S. P no. 7,262,341)
‘SeaIsle Supreme’ (U.S. PP no. 18,869)
‘Platinum TE’ paspalum (U.S. PP no. 19,224)

Dr. Duncan shares his research and knowledge through the writing and editing of more than ten books held in high regard for their technical quality and practicality (e.g., *Seashore Paspalum: The Environmental Turfgrass*), plus more than 200 refereed journal articles or book chapters and publications. The first water quality book for turfgrasses (written by him with two coauthors) was published in 2009.

Section I

Understanding Characteristics of Salt-Affected Sites

1 Basics of Salt-Affected Soils

CONTENTS

1.1 OVERVIEW AND CLASSIFICATION OF SALT-AFFECTED SOILS

1.1.1 Overview of Salt-Affected Soils

While salinity is often thought of as a “soil” issue characterized by the accumulation of high total soluble salt concentrations, it encompasses plant responses as well as effects of topically applied saline irrigation water (USDA-ARS, 2008). Thus, “salinity” is not a single stress or problem, but there are four major salinity issues that are the primary problems that require intensive site-specific attention on an individual basis in response to each stress (USSL, 1954; Abrol et al., 1988; Rhoades and Loveday, 1990; Rengasany and Olsson, 1991; Pessarakli and Szabolcs, 1999; Keren, 2000; Levy, 2000; Qadir and Oster, 2004; Carrow and Duncan, 2010). These four primary “salinity” stresses are as follows:

1. Excessive levels of *total soluble salts*, that is, total salinity causing salt-induced drought stress (Chapter 2)
2. *Na permeability hazard*: excessive levels of Na on the soil cation exchange sites (cation exchange capacity, or CEC) and precipitated as Na carbonates causing soil structure degradation (Chapter 3)
3. *Ions that are toxic to roots or shoots or may cause other problem ion issues* as they accumulate (Chapters 4, 5, and 6)
4. *Actual nutrition concentrations, interactions, and imbalances* caused by nutrients and other ions in the water or soil (Chapters 4, 5, and 6)

1.1.2 Classifying Salt-Affected Soils

Salt-affected soils are very diverse in characteristics and exhibit a combination of the *salinity stresses* previously noted (Rengasamy, 2010a). Classification of a salt-affected soil is based on two major stresses, namely, (a) total soluble salt concentration, which relates to the potential for salt-induced drought stress and subsequent osmotic adjustments internally in the plant; and (b) the quantity of exchangeable Na^+, which relates to the potential for deterioration of soil physical conditions from accumulated Na and for subsequent ion toxicities from excess Na (Table 1.1). Soil pH is also often listed, but is generally not used in the U.S. Salinity Lab (USSL, 1954) classification scheme, which is the most prevalent classification.

Traditionally, the main types of salt-affected soils are broadly classified as saline, sodic, and saline-sodic soils. *Saline soils* have high concentrations of total soluble salts, but relatively low exchangeable Na levels; they are the focus of Chapter 2 ("Saline Soils"). A *sodic soil* is characterized by high exchangeable Na on the soil CEC, but relatively low total soluble salt levels. *Saline-sodic soils* exhibit both high total soluble salt and high exchangeable Na levels. A unique soil problem that is usually found on coastal areas is *acid-sulfate soils*, which are usually saline-sodic in nature. Sodic and saline-sodic soils are the topic of Chapter 3 ("Sodic, Saline-Sodic, and Alkaline Soils").

A brief overview of the terminology and criteria used to classify salt-affected soils is presented in Table 1.1, but these will also be dealt with in more detail in the soil-testing chapter (Chapter 4). The first criteria for classifying a salt-affected soil is to determine the soil salinity status, with the best measure of *total soluble salt* concentration being the electrical conductivity of a *saturated soil-water paste extract* (*ECe*). In this method, the soil is brought to saturation, it is allowed to equilibrate to dissolve total soluble salts into the soil solution during a specified time frame, the soil solution is vacuum extracted, and then the electrical conductivity is determined in the extract and noted by the designation of ECe. This is the method developed by the USSL (1954) that most accurately reflects the total soluble salt impact on plants in the field. There are other, less accurate methods using more dilute soil:water extracts, such as 1:2 or 1:5 (soil:water, volume basis), to determine total soil salinity; but these will be discussed in Chapter 4 ("Salinity Soil Tests and Interpretation"). A common unit for ECe is dS/m, and ECe in dS/m can be converted to ppm or mg/kg of salt by the formulas:

$$TDS\ (ppm\ or\ mg/kg) = 640 \times ECe,\ when\ ECe < 5\ dS/m$$
$$TDS = 750 \times ECe,\ when\ ECe > 5\ dS/m$$

TABLE 1.1
Classification of Salt-Affected Soils by U.S. Salinity Laboratory

		Total Salinity	Na Permeability Hazard		
Salt-Affected Soil Class	**Old Classification**	**Soil Electrical Conductivity (ECe, dS/m)[a]**	**Exchangeable Na percentage (ESP, %)[b]**	**Na Adsorption Ratio (SAR)[c]**	**Soil PH**
Saline	White alkali[d]	≥4.0	<15	<12	<8.5
Sodic	Black alkali[e]	<4.0	≥15	≥12	>8.5
Saline-Sodic	—	≥4.0	≥15	≥12	<8.5

Source: U.S. Salinity Laboratory, *Diagnosis and Improvement of Saline and Alkali Soils, Handbook 60*, U.S. Government Printing Office, Washington, DC, 1954.

[a] ECe = electrical conductivity of saturated paste extract.

[b] ESP (%) = percentage NA on soil cation exchange capacity (CEC) sites.

[c] SAR = best determined from Na, Ca, and Mg concentrations in the saturated paste extract.

[d] White alkali = tendency for white-gray salt deposition on the soil surface.

[e] Black alkali = tendency for black color at soil surface from high pH dissolution of organic matter and subsequent coating of the soil.

where *TDS* represents *total dissolved salts*, or sometimes *total soluble salts* (*TSS*) nomenclature is used. Thus, an ECe of 1.0 dS/m represents 640 ppm total soluble salts in the soil. As total salts accumulate in the soil, ECe also increases. A soil is classified as "saline" if total soluble salts are at ECe > 4d Sm^{-1} (i.e., TDS = 2560 ppm) (Table 1.1). The ECe measurement does not distinguish which specific salts are present in the sample, but does provide a reliable measure of total soluble salts.

The second criterion used for classification of salt-affected soils is the *exchangeable sodium percentage* (*ESP*), which relates to the potential for Na-induced deterioration of soil structure (Na permeability hazard) (Table 1.1). Exchangeable Na percentage is the percentage of Na on the CEC in units of cmol/kg or meq/100g. The CEC consists of all exchangeable cations on the soil CEC sites, such as Ca, Mg, K, Na, H, and Al. Determination of ESP depends on an accurate measurement of CEC and is defined as

$$ESP = \frac{(Exchangeable\ Na)(100)}{Cation\ Exchange\ Capacity}$$

While both organic matter and clay colloids have negatively charged CEC sites, the clay CEC sites are especially important for Na-induced soil structure deterioration. As Na percentage increases in the soil, the potential for soil structure deterioration increases. The USSL (1954) classification uses an ESP of >15% to classify a soil as sodic or saline-sodic (Table 1.1).

Sodium status can also be reported as the *sodium adsorption ratio* (*SAR*), where

$$SAR = \frac{Na}{\sqrt{(Ca + Mg)/2}}$$

The Na, Ca, and Mg cation concentrations are determined in a saturated paste extract solution (the same extract as ECe is determined) and are designated in units of $mmol_c/L$ or meq/L. As the Na^+ concentration increases, SAR increases. The quantities of Ca and Mg relative to Na in the soil solution are considered in SAR, while ESP uses only Na, but in terms of Na present on the soil CEC sites.

The ESP procedure for measuring soil Na status depends on an accurate determination of the cation exchange capacity, which is pH dependent. If CEC is determined at a laboratory pH different from field pH (for example, a highly calcareous soil at pH > 8.5), the CEC value could be misleading since some CEC sites are pH dependent. Also, in salt-affected soils, some of the cations not associated with CEC may be dissolved and reported as CEC and, again, cause error. Thus, some scientists have favored SAR over ESP. However, they exhibit similar numerical values over a wide range of sodium levels with SAR somewhat lower in value. The relationship of SAR and ESP in a saturated paste extract is reported as follows (USSL, 1954; Naidu et al., 1995):

$$ESP = \frac{1.475(SAR)}{1 + 0.0147(SAR)}$$

Based on the USSL (1954) classification, a soil would be classified as sodic if the ESP > 15% or the SAR > 12. Soil pH is included in the table, but is only used as an indicator of the possibility of a soil being sodic based on a pH > 8.5. Highly sodic soils can exhibit pH up to 10.2, while saline and saline-sodic soils can have a wide range of soil pH, but are generally at pH < 8.5.

While the USSL (1954) classification scheme for salt-affected soils is the most widely used, Australian and South African scientists often use a lower ESP > 5 or 6 as a critical level for classifying a soil as sodic (Rengasamy, 2010a). One reason for this difference is that in these countries, their sodic soils tend to contain higher clay content, which results in the soils being more responsive to structural breakdown by Na-induced effects. The actual criteria for classifying a soil as saline (i.e., ECe > 4.0 dS/m) or sodic (i.e. ESP of >15; or ESP > 5.0) are less important than recognizing that as total soluble salts or Na accumulate in a soil, there is a continual progression toward salinity or sodicity. For example, when soil samples are collected and submitted for soil testing, the sample depth is often 8–10 cm (3–4 inches) If the ESP for the soil was ESP = 12% of Na on the CEC sites, it would not be classified as a sodic soil; however, if the source of Na ions was the irrigation water, then the actual ESP at the soil surface (3–5 cm) would likely be at an ESP > 15. Thus, when a soil test reveals an ESP > 4 on a clay soil that has clay types responsive to structural degradation by Na and has appreciable clay content (these issues are discussed in Chapter 3, "Sodic, Saline-Sodic, and Alkaline Soils"), it would indicate that aggressive management should be instituted to prevent further adverse effects of Na accumulation because the actual ESP at the surface would be significantly higher due to the continual infusion of Na-laden irrigation water. The Australian and South African criteria for classification of sodic soils are, therefore, more conservative and based on identification of sodic problems before they become a major soil and plant response stress.

1.2 CAUSES

1.2.1 SALT IONS AND COMPOUNDS

Soluble salt ions most common in salt-affected soils are Ca^{+2}, Mg^{+2}, Na^+, K^+, Cl^-, SO_4^{-2}, HCO_3^-, NO_3^-, and CO_3^{-2} (this last one at pH > 9.0). It is the magnitude and balance of these ions (especially imbalances and dominance on the CEC sites or in the soil solution) that are the basis for the various salinity stresses in a particular landscape. These ions arise from the following:

- Dissolution of minerals in the weathering process
- Salt additions by saline irrigation water
- Salts in standard application of fertilizers and soil amendments
- Salts transported into the rootzone by a rising water table (e.g., saltwater intrusion)
- Capillary rise from deeper in the soil
- Seepage zones where saline water moves to another site
- Subsoil migration to lower-topography areas due to gravity
- Flooding, such as in coastal areas
- Saltwater spray
- Use of primary or secondary salinized dredged soils on a site

Inorganic salts can be present in the soil not just as soluble ions but also as compounds that vary in solubility from relatively insoluble (lime) to moderately soluble mineral forms (gypsum dihydrate) (see Chapter 2, Table 2.1). Relatively soluble minerals that can dissolve to release soluble salt ions include (a) various sulfate compounds such as Na_2SO_4, K_2SO_4, $CaSO_4{\cdot}2H_2O$ (gypsum dihydrate), and $MgSO_4$; (b) chloride chemicals, such as KCl, NaCl, and $CaCl_2$; and (c) carbonate or bicarbonate compounds with high solubility such as Na_2CO_3 and $NaHCO_3$. Examples of insoluble salts would be $CaCO_3$, $MgCO_3$, dolomite ($CaCO_3{\cdot}MgCO_3$), anhydrite of gypsum ($CaSO_4$—i.e., without the hydrated water), and soil minerals such as apatites, while dihydrate gypsum ($CaSO_4{\cdot}2H_20$) is a moderately soluble salt.

While the insoluble and moderately soluble mineral forms can influence soils and plants over time, it is the soluble salts that have the most direct and rapid impact on soils and plants, due to their mobility and innate ability to accumulate in soils and plants. When comparing various salt ions versus salt compounds in the soil, individual salt ions can react with other ions to produce salt compounds varying in solubility. The degree of mobility of individual salt ions in response to water movement in the soil is based on whether they reside in the soil solution, as a component of a soluble compound, as a component of an insoluble compound, or on the soil CEC sites that are associated with negative charges on clay and organic matter. Highly mobile ions are Cl, SO_4, and K, while Na, Ca, and Mg are less mobile in the soil.

Ion and nutrient concentrations and mobility in plants are also important in salt-challenged sites. For example, an immobile ion when applied to the turfgrass foliage will not move to lower tissues, including the root system. Thus, if Ca is required in the rootzone of a sodic soil to maintain root viability (to limit Na displacing Ca in root cell walls and causing roots to deteriorate), application to the shoot tissues would not have any effect. Carrow et al. (2001) reported ion mobility within plants as (a) mobile (N, P, K, Mg, and Na), (b) somewhat mobile (S, Zn Cu, Mo, and B), and (c) immobile (Ca, Fe, Mn, and Si).

1.2.2 PRIMARY AND SECONDARY SALINIZATION

Remediation practices to correct salinity stresses and preventative practices to limit recurring salinity stresses are based on a sound understanding of the causes and recognition of the symptoms on the specific site. Salinity caused by soluble salts on a site cannot be ignored, especially when the source of salts is the irrigation water, since soils, plants, and water (surface and subsurface) are all adversely affected with each irrigation cycle (Oster, 1994). *Salinization* (or *salination*) of irrigated land occurs when dissolved salts accumulate in the upper soil layers and impose multiple salinity stresses on the landscape plants and perennial turfgrass ecosystems. Salinization of ground (aquifers) or surface waters occurs when excessive salt loads come into contact with these waters. Causes of soil salinization are classified as (a) *primary or natural salinization* that occurs from natural processes; or (b) *secondary salinization*, which is a result of human activities (Carrow and Duncan, 2010; Duncan et al., 2009). Examples of natural or primary salinization are as follows:

- Accumulation of salts in the soil over long periods of time from weathering of salt-laden parent materials, especially in arid regions where natural leaching is limited by low and often sporadic precipitation. The largest acreage of salt-affected soils in the world is due to this cause, and this would include many turfgrass areas established on naturally salinized soils. In these locations, salt accumulation is normally at the surface, but salt accumulation layers are often found deeper within the soil profile. Subsurface salt zones can contribute to groundwater salinization if the groundwater comes in contact with the salinized zone.
- Old ocean or coastal beds that have evaporated and left salt deposits at the surface or in layers in the soil profile.
- Sea salt carried by wind, rain, or flooding (e.g., storm surges or periodic high tides) onto adjacent land areas.
- Salt movement into the rootzone from a naturally high saline water table or high tidal swells such as in coastal swamps or marshes. Sometimes, the coastal soils are sandy in nature and can be easily reclaimed by leaching. However, coastal marine clays or more fine-textured soils, especially if the clay type is an expansive/contraction 2:1 clay (with high CEC and very susceptible to Na-induced structure deterioration), can be very difficult if one wishes to remove accumulated total soluble salts and Na. As clay content increases, salt removal becomes increasingly difficult.

Secondary salinization results from the activity of humans, especially via irrigation and drainage practices. Understanding the causes of secondary salinization is especially important because preventative measures can often minimize adverse effects. Types of secondary salinization are as follows:

- Irrigation with saline irrigation water where leaching or drainage is insufficient to prevent salt accumulation in the plant rootzone. The percentage of irrigated lands affected by salinization is 20% to 25% in the United States, 13% in Israel, 30% to 40% in Egypt, 15% in China, and 15% to 20% in Australia (Gleick, 1993). For turfgrass sites irrigated with saline irrigation water sources, this is the major cause of secondary soil salinization and is an ongoing management challenge.

- Irrigation with saline irrigation water where surface drainage does occur, but results in salinization of groundwater (aquifers).
- Irrigation with groundwater from saline strata, which is often located below the drinking water strata and often is exposed to some degree of progressive ocean water infusion.
- Irrigation with saline irrigation water, especially in arid or semiarid regions, where evaporative demands continually surpass leaching requirements and irrigation system capability, resulting in upper soil profile salt accumulation and layering.
- *Dryland salinity* is a type of secondary salinization and is a major problem in Western Australia (Pannell and Ewing, 2006) and other areas in the world with similar ecosystems. Land clearing (native deep-rooted trees and shrubs) coupled with the introduction of more shallow-rooted agricultural crops (nonirrigated or irrigated) can result in a rising water table that eventually leads to secondary salinization and waterlogging of the surface soil profile. The deep-rooted vegetation changes result in more water draining past the rootzone since the root systems for agricultural crops are more shallow compared to perennial native vegetation. The drainage water can result in a rising water table that, in turn, mobilizes soluble salts that are located below the rootzone but above the normal water table. If the salt-laden water table rises (upconing of excess salts) into the rootzone or the capillary fringe is within reach of the plant rootzone, rapid and serious secondary soil salinization can occur, often resulting in plant death since the salinity tolerances of those plants are not adequate to withstand this upward surge in localized rhizosphere salt accumulation. Moreover, the groundwater also is often salinized.
- Salt-laden leachate waters intercepted by tile drains may deposit salts into surface water or shallow groundwater strata.
- Drainage water reuse and other *water reuse schemes* (i.e., reuse of water for irrigation purposes) where the water may become increasingly salinized. Water reuse (water recapture and subsequent recycling) on a specific site and these reuse schemes will become more common in the future on turfgrass and landscape sites as water conservation becomes a greater mandated issue. Examples of water reuse on a site-specific basis where salinity in the irrigation water may contribute to secondary salinization and, therefore, must become a management concern are as follows. (a) *Onsite drainage water reuse* is an area of greater interest in some locations where water that has percolated through the soil into tile lines and then tile drainage water is recollected from a containment site for direct blending and/or reuse for irrigation on various areas of the property. This is a form of recycled water use but without additional treatment except for what occurs during soil percolation before collection and reapplication. Tanji and Kielen (2002) and Oster and Grattan (2002) provide detailed discussions for the management of drainage water when reused for irrigation. (b) *Onsite reclaimed water reuse* is where harvested water is collected from stormwater or sewage drainage lines coming off a property, such as a golf course complex surrounded by a housing development or business complex; treated at an onsite treatment facility (i.e., onsite reclamation); and then reused for irrigation and other suitable purposes on the site. In this instance, the drainage line water is usually not coming from the soil drain lines where water percolated through the soil, but from the surrounding surface stormwater and sewage or water drain lines and catchment facilities. (c) *Onsite stormwater collection* is from surface runoff and/or stormwater drain lines from the site that go directly into a collection lake without the discharge intermingling with sewage water in the sewage lines. And (d) *Other water reuse schemes* involve water collected on or near the site and then reused for irrigation. This could be as simple as using swimming pool water for irrigation, air conditioner condensate for landscape plant drip irrigation, or more complex sources such as using industrial water from cooling towers for landscape irrigation (Gerhart et al., 2006).

Much of the attention for secondary salinization of lands by irrigation and drainage practices has focused on rural agriculture land (Rhoades et al., 1992; Ayers and Westcot, 1994; Oster, 1994; Grattan and Oster, 2003; Qadir and Oster, 2004); but with more saline waters increasingly used for landscape irrigation in urban areas with increasing population growth, urban secondary salinization is receiving more attention (Wilson, 2003). Another trend has been the increased interest in the potential effects of salinity contamination of freshwater (drinking water) ecosystems such as aquifers (Hart et al., 1990; Nielsen et al., 2006).

Pillsbury (1981, 54) noted the impact of salinization in history and why the historical lessons must not be forgotten:

> Many ancient civilizations rose by diverting rivers and irrigating arid lands to grow crops. For such projects to succeed, human beings had to learn to work cooperatively toward a common objective. The most fruitful of the ancient systems was created at the southeastern end of the Fertile Crescent, the broad valley formed by the Tigris and the Euphrates in what is now Iraq. From there civilization spread eastward through present-day Iran, Afghanistan, Pakistan, and India and thence into China, where ever rivers disgorged through valleys of recently deposited alluvial soil. At its peak of productivity, each irrigated region probably supported well over a million people. All these civilizations ultimately collapsed, and for the same reason: the land became so salty that crops could no longer be grown on it. The salts that were washed out of the soil at higher elevations became concentrated in the irrigated fields as the water evaporated from the surface and transpired through the leaves of the growing crops. Although floods, plagues and wars took their toll, in the end the civilizations based on irrigation faded away because of salination.

Thus, history and current experience illustrate that the use of highly saline irrigation water greatly enhances the potential to degrade soil, plant, and water resources unless definite infrastructure improvements and skilled management practices are implemented. Accumulation of excess soluble salts and sodium in the soil is more rapid as irrigation water quality declines, unless salts are continuously managed. Adequate infrastructure provides the necessary “tools” for the site manager to address salinity stresses; in other words, the infrastructure tools include surface and subsurface drainage systems; adequate water sources in terms of quantity and quality; irrigation system design for distribution uniformity; irrigation scheduling; sand capping, when needed; irrigation water treatment technology; sensor technology to proactively monitor salts and water; adequate salt disposal systems; appropriate cultivation equipment; the blending of variable saline water sources in order to reduce the overall salt load being applied to the turfgrass ecosystem; and others. With these tools, management must target soils, plants, and water deposition on the site for holistic environmental protection (Rhoades et al., 1992; Duncan et al., 2000, 2009).

The influence of saline irrigation water will be greatest on the site to which it is regularly applied, but application can impact the surrounding environment. Since the percentage of saline-irrigated turfgrass land area versus total community area in most instances is small, this localization aids in reducing the potential for large-scale adverse environmental impacts on localized community surface and subsurface waters as well as secondary salinization of site-specific community landscapes and waters. However, in some locations with numerous golf courses or other large irrigated turfgrass and landscape sites, salinity impacts for turfgrass and landscape areas can be potentially significant if the salinity is not properly managed at all community levels. For example, in arid regions, golf courses or other landscape sites may be major customers for reclaimed water from the public water treatment facilities, but these reclaimed waters may contain appreciable salts passed through the treatment facility. In these instances, the public water treatment facility and government entities must realize that salts coming into the treatment facilities (such as from ion exchange salt-based water softeners or home- or business-specific reverse osmosis units) are a public responsibility involving potential secondary salinization and not one that can be passed to the current end user—the turfgrass or landscape ecosystem—without compromising the environmental sustainability of the ecosystem. The effluent and the specific effluent constituents must be disposed of in an environmentally compatible manner by the treatment facilities regardless of the end-use customer; and if there is no end-use customer, the effluent disposal could end up in surface waters or subsurface aquifers (Clean Water News, 2007). If undue excess salt levels are passed through to public or private landscape areas for irrigation, the applied salts soon become a community problem from the deterioration of natural resources: soils, surface waters, subsurface waters, and plant ecosystem sustainability.

1.3 SCOPE OF SALINITY PROBLEMS

1.3.1 Land Area

Australia and Asia have the greatest area of salt-affected soil with 38% and 34%, respectively, of their land area degraded by salinity; but saline and sodic soils are found on all continents (Table 1.2) (Zinck and Metternicht, 2009). The 2303 million acres (932 million ha) of salt-affected area in the world represent about 7% of the earth's continental surface area, with saline soils comprising 43% of the total and sodic soils 57%. For reference, Texas contains 172 million acres.

Of the 568 million acres (230 million ha) of irrigated lands in the world, about 20% or 114 million acres are salt affected (Pitman and Lauchi, 2002). There are many causes contributing to the primary salinization or secondary salinization of soils, but human activity accounts for the secondary salinization of approximately 189 million acres (76.6 million ha), or 8.2% of the total salt-affected land area.

1.3.2 Management and Environmental Challenges

The scope of salinity issues goes beyond the land area of these soils and entails increasing management and environmental challenges. On turfgrass and landscape sites, soil salinity stresses have increased in scope and concern in recent years due to several factors. One factor is political and societal pressures for water conservation, resulting in turfgrass sites increasingly using poorer-quality, variable saline irrigation water to alleviate the demand for potable water sources (Marcum, 2006; Carrow and Duncan, 2008). Saline irrigation water sources include saline groundwater (water that is naturally saline, salt affected by salt leaching, drainage water reuse, salt affected by rising water tables, or seawater intrusion into aquifers), brackish surface water, stormwater runoff, recycled water (i.e., reclaimed or effluent water), and seawater or seawater blends. Increasingly, more governmental units are mandating the use of reclaimed water or saline groundwater for larger turfgrass sites (Marcum, 2006). This is a trend expected to continue on a worldwide basis so that in

TABLE 1.2
Global Distribution of Salt-Affected Soils (Million Ha)

Area	Saline Soil	Sodic Soil	Total	Total (%)	Human-Induced Salinization (%)
Australasia	17.6	340.0	357.6	38.4	1.2
Asia	194.7	121.9	316.5	33.9	68.8
America	77.6	69.3	146.9	15.8	5.7
Africa	53.5	26.9	80.4	8.6	19.3
Europe	7.8	22.9	30.8	3.3	5.0
World	351.2	581.0	932.2	100	100

Source: Adapted from Zinck, J. A. and G. Metternicht, Soil salinity and salinization hazard, in G. Metternicht and J. A. Zinck (Eds.), *Remote Sensing of Soil Salinization*, pp. 3–20, CRC Press, Boca Raton, FL, 2009.

the future, irrigation water applied on turfgrass and landscape sites will often be more saline than in the past (Miyamoto et al., 2005; Miyamoto and Chacon, 2006).

A second force increasing salinity as an abiotic environmental stress on turfgrass sites is the development of salt-tolerant grasses (Chapter 9), which allows use of more variable saline irrigation sources (Duncan and Carrow, 2000; Marcum, 2002; Loch et al., 2003). While salinity tolerance may be genetically improved in various turfgrass species, this scientifically improved trait only allows the turfgrass manager time to make appropriate management decisions, but it does not negate the absolute and continuous requirement for managing any salt deposition from saline irrigation water on the specific site for long-term environmental sustainability. Halophytic turfgrasses (i.e., salt-tolerant grasses) and landscape species generally strictly regulate salt ion uptake, thereby leaving salts to accumulate in the soils with each irrigation cycle (Munns and Tester, 2008). Halophytic plants are generally not phyto-accumulators of excess salts and do not remove excess salts from irrigation water or saline soils (see Chapter 9).

The development of coastal or wetland golf courses and parklands is a third factor that results in salinity problems from saltwater intrusion in aquifers used for irrigation, dredged soils, acid-sulfate sites, periodic flooding, high tidal influences, and wind-driven persistent salt spray (Carrow and Duncan, 1998; Loch et al., 2006). Resorts and recreational sites are now being developed in arid, semiarid, tropical, and subtropical areas, where potable water is very limited or nonexistent and saline sources are the only irrigation option for grasses and landscape plantings.

The fourth aspect concerning turfgrass salt-impacted sites is increasing environmental concerns over the protection of surface and subsurface waters (such as aquifers) and the sustainable protection of soil quality (Duncan et al., 2000, 2009; FAO, 2009a, 2009b). Secondary salinization of the ecosystem is a constant threat and a whole-system, systematic approach to managing the soil, the water, and the grass or landscape plants must be a primary focus.

Since the ecosystem is a dynamic and constantly changing entity, the introduction of salinity into the system results in constant movement of salts vertically upward (capillary action), downward in the soil profile (infiltration, percolation, and drainage), and horizontally both at the surface and through the subsurface, thereby impacting any plants that are being grown in that ecosystem. Salt migration in the soil is a constant process, depending on climatic changes such as precipitation and evapotranspiration (ET) rates plus gravity. Once salts have accumulated in the soil profile, the subsurface gravity-induced migration of excess salts to low-topography areas is a persistent, recurring challenge to perennial turfgrass species management.

Thus, the “scope” of salinity problems goes well beyond the land area affected by salinity. Rather, it transcends into being “the major management challenge” on turfgrass and landscape sites with the continuous application of saline irrigation water containing moderate to high salinity levels. Management of such areas must be ongoing with flexibility to adjust with the dynamic salinity changes in the ecosystem. These sites normally exhibit reduced plant growth and vigor if salts are allowed to accumulate in the soil; thereby, a high degree of management is required to achieve acceptable plant performance, avoid soil degradation, and prevent salts from affecting surface or subsurface groundwater sources. Maintenance challenges and increasing overall management costs that can escalate on salt-affected sites include labor; amendment selection and costs for soil, plant, and water treatments; infrastructure improvements for drainage; sand capping; irrigation systems distribution uniformity; a high degree of technical salinity management expertise and salt-challenged site assessment capabilities; very dynamic soil fertility and plant nutrition situations; and frequent, proactive monitoring of soil, water, and plant status. When the source of most of the salts is the irrigation water, salinity management becomes a constant ongoing management issue and not a short-term problem that is resolved, after which the manager moves on to other issues (Duncan et al., 2009).

Salinity stresses are complex, and a successful management approach must be science based and holistic: integrating soil chemical, physical, and biological considerations; plant shoot and root requirements and their sustainability; surface and subsurface drainage; irrigation design and scheduling; personnel management; comprehensive and regimented management strategies on a site-specific basis; labor costs with appropriate time allocation; and sustainability of the ecosystem, including soil, plant, water, and wildlife. The central purpose of this book is to address salinity management on turfgrass and landscape sites in all its facets by using a comprehensive, holistic, science-based approach: the *best management practices (BMP) approach to salinity.*

1.4 A SUCCESSFUL SALINITY MANAGEMENT APPROACH

1.4.1 A BMP-Based Environmental Plan

Environmental management challenges are an increasing part of "routine management" on many agriculture and landscape sites. For example, Carrow et al. (2008) noted 17 different environmental issues that golf courses must routinely consider in their management programs (Table 1.3). Each of these issues (e.g., water use efficiency and conservation; pesticide, nutr°ient, and sediment levels related to surface and subsurface water quality; and wildlife habitat management) is complex and requires a successful *environmental management plan*. For a single environmental issue, regardless of its nature, the most successful environmental plan is a *best management practices* (*BMP*) approach (Carrow et al., 2008; Carrow and Duncan, 2008, 2010). Readers are referred to Chapter 19, "Sustainable and Environmental Management Systems," for a more comprehensive treatment of BMPs and other environmental management approaches.

Carrow and Duncan (2008) noted that the BMP approach initially evolved out of the 1977 Clean Water Act for the protection of surface and subsurface groundwater from pesticides, nutrients, and sediments. Each of these environmental issues required a different set of management strategies to deal with the site-specific problem, but the overall approach or philosophy is the same for each—that is, a science-based and practical BMP approach. For the past 30 years, the BMP approach for

TABLE 1.3
Environmental Issues Often Present on a Golf Course with Each Requiring an Environmental Management Plan (Each Issue Can Be Addressed by an Appropriate Best Management Practices Plan)

1. Environmental planning and site design of golf courses, additions, and renovations for environmental sustainability
2. Sustainable maintenance facility design and operation
3. Adapted turfgrass and landscape plant selection—for reduced input of pesticides, nutrients, and water
4. Water use efficiency and conservation
5. Irrigation water quality management for sustainability
6. Pesticides: water quality management
7. Nutrients: water quality management
8. Erosion and sediment control: water quality management
9. Soil quality sustainability
10. Stormwater management
11. Wildlife habitat management
12. Wetland and stream mitigation and management
13. Aquatic biology and management of lakes and ponds
14. Waste management
15. Energy management
16. Clubhouse and building Environmental Management Systems (EMS) concepts
17. Climatic and energy management

Source: Adapted from Carrow, R. N., F. C. Waltz, and K. Fletcher, Environmental stewardship requires a successful plan: Can the turfgrass industry state one? *USGA Green Section Record,* 46 (2), 25–32, 2008.

pesticide, nutrient, and sediment management to protect our surface and subsurface waters has proven that this "environmental management plan" is the gold standard. Just as the BMP approach or philosophy was used for these three diverse environmental issues, it can be successfully applied to all environmental issues, including salinity, because of its basic underlying principles (Carrow and Duncan, 2008). These foundational principles (a) are science based; (b) are holistic or "whole systems" in nature; (c) are environmentally sustainable; (d) involve strategies that are selected and applied on a site-specific basis; (e) incorporate consideration of all dynamic environmental (direct and indirect) impacts; (f) are economically sustainable in that they consider economic effects on the site and on society; (g) have values educated managers who understand sustainable site management concepts; (h) are flexible in that new concepts and technologies can be incorporated as they evolve out of science and practical experience; (i) incorporate ongoing proactive (rather than reactive) monitoring and revisions for the entire ecosystem; and (j) encompass basic turfgrass and landscape management guidelines that can be feasibly implemented.

Key reference materials related to managing salt-affected sites for general agriculture include USSL (1954); Abrol et al. (1988); Rhoades and Loveday (1990); Rengasamy and Olsson (1991); Rhoades et al. (1992); Ayers and Westcot (1994); Jayawardane and Chan (1994); Naidu et al. (1995); Tanji (1996); Hanson, Grattan, and Fulton (1999); Qadir et al. (2000); and Grattan and Oster (2003). Carrow and Duncan (1998, 2010) and Duncan et al. (2009) reported on salinity management for turfgrass sites.

While authors of these references to salinity management on agriculture and turfgrass landscapes present multiple options for salinity management, it is the goal for this book to present a systematic set of all possible salinity management options that, when combined together, result in a *BMP salinity management plan* (Table 1.4). Successful salinity management entails not only controlling surface soil salinity and subsurface accumulation problems but also maintaining the site sustainability of environmental, economic, and turfgrass performance aspects. The remainder of this book considers the many different BMP strategies for the management of salt-affected sites, including initial site assessment to build the knowledge base to make basic informed soil, water, and plant management decisions.

To integrate and assist in the development of the BMP salinity management plan into turfgrass management, a useful approach is to adopt the evolving *precision turfgrass management* (*PTM*) concept, which is based on using advanced site assessment methods to obtain detailed site information to make site-specific management decisions (Krum et al., 2010; Carrow et al., 2009a, 2009b). It is based on a whole-systems science-based approach; intensive spatial mapping of key soil and plant characteristics using mobile sensor platforms; site-specific precision management on inputs; basic management strategies for implementation (salinity is the most complex environmental stress); and the integration of GIS + GPS + new moisture and salinity sensor technology with proactive monitoring. This concept removes a lot of the subjective decisions in management and utilizes science-specific technology to implement maintenance programs with salinity challenges. Applications of PTM are integrated into salinity management in the following chapters:

- Chapter 4, Section 4.1.2, "Soil Sampling," where spatial mapping is used to identify similar areas for routine soil sampling and *soil sampling* for soil laboratory salt analyses.
- Chapter 4, Section 4.3.2, "Approaches to Field Salinity Monitoring," where the PTM concept is targeted to *spatial salinity mapping* of large turfgrass sites using mobile salinity-monitoring devices currently under final testing that were developed specifically for turfgrass situations.
- Chapter 10, Section 10.3.4, "Precision Turfgrass Management (PTM) Water Audit Approach," where PTM is applied to a new whole-site *water audit approach* to determine the irrigation system distribution uniformity of applied water, which has a major effect on the (a) salinity spatial distribution across the landscape and within the soil rootzone, and (b) capability of site-specific salinity leaching.

TABLE 1.4
Summary of BMP Strategies for Salt-Affected Turfgrass Sites for Environmental Protection, Sustainability, and Turfgrass Management

1. **Site Assessment.** To identify factors that will influence salinity management decisions.
    a. Soil Physical Aspects
        - Construction and renovation considerations: impediments to infiltration, percolation, or drainage such as calcic, clay, or rock layers; deep ripping or deep cultivation requirements prior to establishment; future cultivation equipment requirements; surface and subsurface drainage improvements; drainage outlets and salt disposal options; irrigation system requirements; presence of fluctuating or high water tables; sand-capping needs; and pre-plant physical and chemical amendments to improve soil physical condition
        - Identifying all salt additions: irrigation water; water table; capillary rise from salt-rich subsurface horizon; mixing of salt-laden soil during construction or dredging; fertilizers; and drainage onto the site
        - Other: soil texture; clay type; and soil physical analyses of rootzone media, including water-holding capacity
    b. Soil Chemical Aspects
        - Routine soil test information (normal soil fertility test; saturated paste extract salinity test)
        - Additional soil test information: SAR, ESP, ECe, and free calcium carbonate content
    c. Irrigation Water Quality Assessment
        - Complete irrigation water quality analyses
        - Health aspects if needed
        - Multiple irrigation water sources: blending, drainage water reuse, reliability of each source, and stability of each source in terms of constituents over time
2. **Plant Selection.** Salinity tolerance is a primary consideration along with adaptation to climatic, pest, and site use stresses (mowing height, and traffic).
    a. Turfgrass species and cultivars
    b. Landscape plants
    c. Buffer zone plantings
3. **Irrigation System Design.**
    - Uniformity of application
    - Flexibility: for site-specific water applications to minimize drought stress and salinity stresses (i.e., salinity leaching and management)
    - Chemigation and fertigation: flexibility
4. **Irrigation Scheduling and Salt Leaching.** For normal irrigation needs and for efficient salt leaching.
    - Reclamation leaching programs and considerations
    - Maintenance leaching programs and considerations
5. **Identification of Water and Soil Amendment Needs for Site-Specific Problems.**
    - Acidification
    - Gypsum and hydrated lime injection
    - Organic amendments
    - Inorganic amendments
6. **Determination of Proper Amendment Application Protocols for Site-Specific Problems.** This includes equipment needs, rates, timing, and frequency aspects.
7. **Additional Cultural Programs.**
    a. Cultivation needs and equipment. Cultivation programs are very important on many salt-affected sites in order to effectively leach salts and to avoid layers that impede salt movement.
        - Surface cultivation equipment and programs for surface problems
        - Subsurface (deep) cultivation equipment and programs for subsurface problems
    b. Fertilization. Soil fertility and plant nutrition are very dynamic with the use of saline irrigation water due to the combination of constituents added from the water, water treatment materials, and soil amendments, plus leaching programs that differentially leach nutrients and elements. Of particular importance are soil and plant tissue concentrations of K, Ca, Mg, Fe, Mn, S, and Zn; and ratios and balances between and among competing ions.
        - Fertigation flexibility
        - Foliar feeding equipment and programs

TABLE 1.4 (Continued)
Summary of BMP Strategies for Salt-Affected Turfgrass Sites for Environmental Protection, Sustainability, and Turfgrass Management

c. Climatic and traffic stresses. Salinity enhances certain other stresses, such as drought, high and low temperatures, and wear or traffic. Thus, these must be carefully managed.
  - Rounds of golf or foot traffic
  - Cart traffic

d. Cytokinin. Soil salinity suppresses cytokinin synthesis in the roots of plants, and grasses often respond (e.g., by root system redevelopment or hormone stabilization) to the application of this hormone (in seaweed or kelp extract products) on saline-irrigated sites.

e. Pest management.
  - Preventative application program
  - Curative application program

8. Sand Capping, Topdressing, and Soil Modification.
  - Enhancing water infiltration of irrigation water and precipitation

9. Drainage and Wetting Agents.
  - Drainage to intercept leached salts
  - Interception drainage to control surface salt movement
  - Wetting agents for improved unsaturated flow and to alleviate localized dry spots

10. Monitoring.
  a. Turfgrass root and shoot responses
  b. Soil and plant fertility status
  c. Soil salinity: temporal and spatial across landscape and by soil depth
  d. Irrigation water quality over time
  e. Salinity effects on surface and subsurface waters

Source: Adapted from Duncan, R. R., R. N. Carrow, and M. Huck, *Turfgrass and Landscape Irrigation Water Quality: Assessment and Management,* Taylor & Francis, Boca Raton, FL, 2009.

1.4.2 Primary versus Secondary Problems

For any turfgrass field problem, understanding the causes and nature is the starting place for developing a sound management plan; however, identification of the basic problem is not always straightforward. While pest stresses are often relatively easy to identify, many soil physical and chemical problems are not easy to "see." Additionally, what we often view are the secondary effects of a primary soil physical and chemical problem; and this is usually the case for salinity issues. Thus, a brief overview of *primary and secondary problems* is warranted in the context of salinity problems.

Excess salts cause a combination of stresses, namely, (a) four primary salinity problems, and (b) a number of secondary problems that arise out of these primary stresses. A *primary problem* is the basic underlying stress, while *secondary problems* are those that arise out of the primary problem. It is not unusual for a site to have several primary problems present and challenging the ecosystem, and this is the typical situation in salt-affected soils. When primary problems are alleviated, the secondary ones are also alleviated. However, if all the management effort is toward the secondary problem, the underlying cause (primary issue) is never corrected. For example, one of the primary salinity stresses is Na-induced deterioration of soil structure where the soil macropores (pores > 0.075 mm diameter) important for water infiltration and percolation, soil aeration, and plant rooting are greatly reduced. Prevention or alleviation of this salinity stress requires a relatively soluble Ca amendment (usually gypsum) to replace Na from the soil CEC sites, and then leaching to remove the more soluble Na sulfate from the rootzone, as well as practices to minimize Na additions to the site. However, if the Na ions are allowed to dominate, the resulting soil exhibits an array of secondary problems, such as low water infiltration and percolation; poor aeration and anaerobic conditions; limited plant rooting; during rainy periods, soils become waterlogged and saturated; soils are hard when dry; diseases favored by moist, anaerobic surface conditions are favored; and rootborne pathogens increase in population and often will destroy the root system (such as take-all or decline diseases).

When these secondary problems occur, they need to be addressed with appropriate management; but the long-term solution is to deal with the primary problem—that is, excess Na causing loss of soil macropores. Individuals using a turfgrass site often see the secondary problems, but do not realize the underlying primary problem. Thus, an essential characteristic of a good turfgrass manager is to recognize which issues are primary and which are secondary, and then be able to communicate these potential problems to site users or owners. As noted, normally more than one primary salinity problem (as well as other primary problems) are "pancaked" on a site. Each challenge to the ecosystem must be recognized and then an appropriate management plan formulated for each problem. When formulating the BMPs for salt-affected turfgrass sites, our emphasis is on the primary or basic problems in terms of either prevention or alleviation and flexibility in altering management strategies to address the potential salt-related challenges.

1.4.3 PRIMARY SALINITY PROBLEMS

In the context of the previous section on primary versus secondary problems on salt-affected sites, it bears repeating that "salinity" is not a single stress or problem; rather, there are *four major salinity issues*. Each of the primary problems present on a site requires intensive site-specific management attention on an individual basis to each stress. These four "salinity" stresses are:

1. Excessive levels of soluble salts in the soil (Chapter 2)
2. Excessive levels of Na on the soil cation exchange sites and precipitated as Na carbonates (Chapter 3)
3. Ions in the soil or irrigation water that are toxic to roots or shoots as they accumulate, as well as ions that may cause other problems (Chapters 4, 5, and 6)
4. Nutritional levels and imbalances caused by nutrient interactions and other ions in the water or soil (Chapters 4, 5, and 6)

It is the mix and severity of these four salinity issues on a specific site that require a BMP plan to prevent, alleviate, or manage those stresses that are present. At the same time, any secondary problems that arise from these primary salinity stresses must be managed. The focus of proactive soil, water, and tissue testing on salinity sites is primarily toward determining the presence and magnitude of these four stresses before they become limitations to turfgrass or landscape performance or overall ecosystem sustainability. With multiple interactions affecting the ecosystem (namely, the specific turfgrass or landscape plant cultivar, the irrigation water quality, the soil profile, and the climatic changes), sustainability challenges are dynamic and must be continuously addressed.

2 Saline Soils

CONTENTS

2.1 OVERVIEW OF SALINE SOIL PROBLEMS

Soluble salts in saline soils are salt forms with high solubility that exist (a) in the soil solution, especially under irrigated conditions; and/or (b) as precipitated salts under drier soil conditions, where they can easily dissolve as soil moisture increases (Table 2.1). Soluble salts in the soil can induce direct stresses (a) by action of *the total of all soluble salts*, that is, total soluble salts or total salinity, which is the sum of primarily Ca, Mg, Na, K, Cl, SO_4, HCO_3, NO_3, and CO_3; (b) as *individual ions that may accumulate in soil or plant tissues* to the point of becoming toxic to plant roots or shoot tissue (Na, Cl, and B) or cause other problems (SO_4, HCO_3, and CO_3); and (c) as *individual nutrient ion concentrations or imbalances* of ions affecting nutrition, such as Ca, Mg, K, P, N, SO_4, Mn, Mo, Zn, and Na. These three salinity stresses are all related to soluble salts and are normally present at the same time on a site. As total soluble salts accumulate, the potential for individual specific ion toxicities and nutritional imbalances also increases. While these individual salinity stresses often occur together, each problem must be assessed individually by soil, tissue, and water tests and individual management strategies selected as part of an overall best management practice (BMP) plan and precision turfgrass management (PTM) strategy (Carrow et al., 2009a, 2009b). Additionally, *secondary stresses* (such as increased disease pressure when environmental conditions are favorable) may evolve from one or more of the above direct stresses.

Total soluble salt stresses can occur on any soil, but the most rapid occurrence is exhibited by sandy soils due to both lower cation exchange capacity (CEC) and soil moisture retention relative to more fine-textured soils. Consequently, sandy profiles will often salinize faster than fine-textured soil profiles. As a result, fewer salts are needed to sequester on the CEC sites to cause salinity problems, and the inherently lower water-holding capacity of sands can result in higher soil solution concentrations of localized salts. If a sandy soil has higher organic matter content, which provides greater soil water-holding capacity to the profile, this organic amendment can reduce the onset of salinity stress due to increased CEC as well as better water retention compared to the same sand with little organic matter. However, sandy soils are also much better able to leach soluble salts from the rootzone compared to fine-textured soils since sands contain fewer micropores that can retain salts. As microporosity increases, salt retention increases and the effective leaching of accumulated salts is a much slower and a more challenging management process.

Due to high total salt levels, without Na being the dominant accumulated salt, saline soils exhibit similar or even better soil physical properties than the same soil in a nonsaline state. Cation salts aid

TABLE 2.1
Composition and Approximate Solubility[a] of Some Common Soil Salts

Chemical Name	Composition	Solubility (g/liter)[a]	Relative Solubility	Mineral Name
Calcium carbonate	$CaCO_3$	0.006	Insoluble	Calcite, lime
Magnesium carbonate	$MgCO_3$	0.039	Insoluble	Magnesite
Calcium hydroxide	$Ca(OH)_2$	1.73	Slightly soluble	—
Calcium sulfate	$CaSO_4 \cdot 2H_2O$	2.64	Slightly soluble	Gypsum
Sodium bicarbonate	$NaHCO_3$	100	Soluble	Baking soda
Potassium sulfate	K_2SO_4	111	Soluble	—
Sodium sulfate	Na_2SO_4	133	Soluble	—
Langbeinite	$2MgSO_4 \cdot K_2SO_4$	240	Soluble	Sul-Po-Mag
Sodium carbonate	Na_2CO_3	220	Soluble	—
Magnesium sulfate	$MgSO_4$	255	Soluble	—
Sodium chloride	NaCl	357	Soluble	Halite
Potassium chloride	KCl	357	Soluble	Sylvite
Magnesium chloride	$MgCl_2$	546	Soluble	—
Magnesium sulfate hydrate	$MgSO_4 \cdot 7H_2O$	710	Soluble	Epson salts
Calcium chloride	$CaCl_2$	750	Soluble	—

[a] Solubility in the water at 20°C. Solubility in the soil is affected by soil moisture, the presence of other salts, the temperature, and other factors, and may differ from these values.

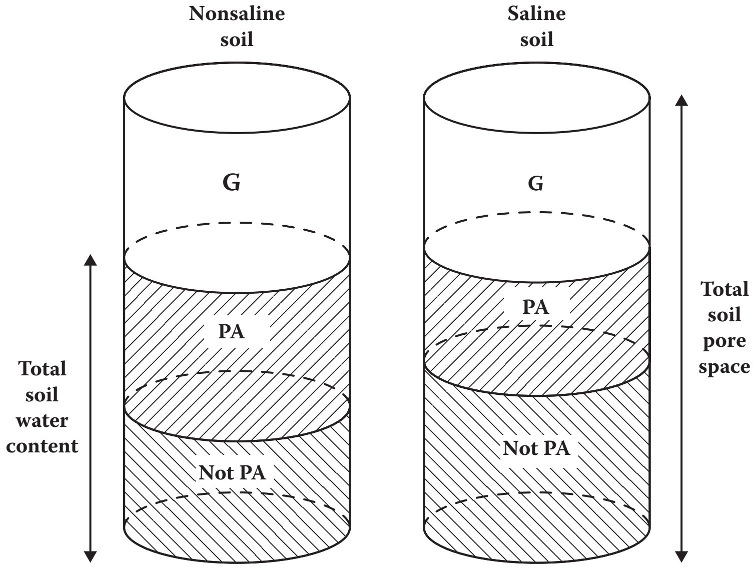
in maintaining soil structure by fostering aggregation and preventing dispersion of clay particles. When saline soils are leached by rain or low-salinity irrigation water, clay dispersion may occur, often causing a collapsing of the soil surface, and may result in sealed layers and reduced permeability to water and air. Soils higher in clay content are the most likely to exhibit this response.

The attention of this chapter on saline soils is to provide an understanding of the (a) direct and indirect stresses arising from total soluble salt ions present in the soil or accumulating from repeated applications of irrigation water or other ion sources (flooding, capillary rise from saline water table, etc.), and (b) visual plant and soil symptoms that may provide insight into the stress-response nature of these field problems. However, soil and water guidelines are not presented in this chapter. Since soil and water quality testing is based on assessing the presence and magnitude of these soluble salt-related problems, including sodic issues discussed in Chapter 3, the soil and water guidelines related to total salinity, specific and problem ions, and nutrient issues are reported in the respective soil-testing (Chapters 4 and 5) and water quality–testing (Chapter 6) chapters. In these chapters, it will be evident that the various soil and water tests are directed toward each of the salinity stresses, and the soil and water report formats often have specific science-based data sections related to these stresses.

2.2 TOTAL SOLUBLE SALTS (TOTAL SALINITY) PROBLEMS

2.2.1 Physiological Drought

When soluble salts accumulate in the turfgrass rootzone, one of the effects is to limit plant-available water (osmotic pressure gradients are often involved) and, thereby, induce water deficits or drought stress on the plant even though the soil profile may be at or near field capacity (Figure 2.1). This is the most prevalent and important of all the salinity stresses in terms of frequency and land area. Increasing total soluble salt concentrations decrease the availability of the soil water for plant uptake; thereby, this salt-induced drought stress is called *physiological drought*.



G = **Gravitational** water that drains after rainfall or irrigation. Soil pores in this range are macropores or aeration pores.

PA = **Plant available moisture** retained in the upper (larger) range of micropores.

Not PA = Soil moisture that is **not plant available** since the water is retained in small micropores and as water films around soil colloids and salt ions. The saline soil contains more salts, which reduces the plant-available water.

FIGURE 2.1 Influence of total soluble salts on plant-available water for turfgrass uptake.

Turfgrass plant response to salt-inducted drought stress can range from rather mild symptoms of some green color loss, blue-green coloration resembling regular drought stress plant symptoms, and initial plant wilting; to increasingly intense plant response symptoms under higher salt levels, such as major green color loss, severe wilting, and actual tissue desiccation of leaves, tillers, and whole plants. Soluble salts (primarily Ca, Mg, Na, K, Cl, SO_4, HCO_3, NO_3, and CO_3) may precipitate into soluble compounds as the soil dries, but these compounds then dissolve again into the soluble ions with rainfall or irrigation water applications. Common water-soluble compounds are sulfated salts such as Na_2SO_4, K_2SO_4, $CaSO_4$, and $MgSO_4$; chloride compounds such as KCl, NaCl, and $CaCl_2$; and carbonate or bicarbonate compounds with high solubility such as Na_2CO_3 and $NaHCO_3$. Insoluble compounds like Ca or Mg carbonates or gypsum do not contribute to soluble salts except as they dissolve over longer time periods.

In terms of soil water availability for plant uptake, both the quantity of soil water and its energy status (activity) are important. Water in the soil is influenced by several forces that determine whether it is retained in the soil, taken up by plants, or moved by capillary action or gravity. For example, *total soil water potential* (ψ_t, the total energy status of the soil water) is a function of the sum of various component potentials acting on the water:

$$\psi_t = \psi_m + \psi_o + \psi_p + \psi_z$$

where ψ_m is the *matrix potential* resulting from (a) *adhesion* of water molecules to solid surfaces in the water films close to the solid surfaces, which are called *water of hydration* and are held so tightly that they are retained in the soil unless heated to about 100°C and are generally unavailable for absorption by plant roots; (b) *cohesion* of water molecules with each other in the outer water films around solid particles, which is available for plant root uptake; (c) *surface tension or* *capillary forces* caused by liquid-gas and liquid-gas-solid interfaces in the irregular-shaped soil pores; and (d) ions on the soil CEC exchange sites that have hydrated water molecules associated with them, which are bound by adhesive and cohesive forces (Figure 2.2). As salt levels increase in a soil, there is more water retained as water of hydration around the salt ions both on the clay colloids as well as on salt ions in the soil solution—this reduces plant-available water, as illustrated in Figure 2.1. The matrix potential is also called the *matrix suction* or *tension*. At saturation, ψ_m is zero, but becomes more negative as the soil dries, resulting in the water becoming increasingly bound and less available for plant uptake or soil movement. The matrix potential is normally the largest component of total potential in partially saturated to unsaturated soils; however, in highly saline soils, the osmotic pressure, discussed below, becomes increasingly important in terms of limiting plant water uptake. The matrix potential can be measured by a tensiometer or in the lab by a pressure plate apparatus.

Osmotic potential (ψ_o), also called *solute potential*, is associated with salts (i.e., solutes) in the soil solution (i.e., water retained in the soil pores, especially the smaller soil micropores of <0.03 mm diameter). Water molecules are attracted to salt ions by adhesive forces in the water films near the salt ion surface and by cohesive forces in the outer water films. As soluble salt concentrations increase in the soil, osmotic potential becomes more negative, thereby reducing the availability of soil moisture for plant uptake. The final result of reduced soil water availability is salt-induced drought stress on the plant even when the soil may appear to be relatively moist or even within hours after the last irrigation cycle. Osmotic pressure is always negative. The relationship between soil osmotic potential and soluble salt concentration in soils is depicted by

$$\psi_o\,(bar) = -0.36 \times ECe\ (dS/m)$$

where *ECe* is the *saturated paste extract* level of soil salinity expressed in units of dS/m (USSL, 1954). In Chapters 4 and 5, the saturated paste extract method of measuring soil salinity is discussed in detail. For soils, the conversion of ECe in dS/m units to *total soluble salts* (*TSS*) is

$$TSS\ (ppm\ or\ mg/l) = 640 \times ECe,\ when\ ECe < 5\ dS/m$$
$$TSS = 750 \times ECe,\ when\ ECe > 5\ dS/m$$

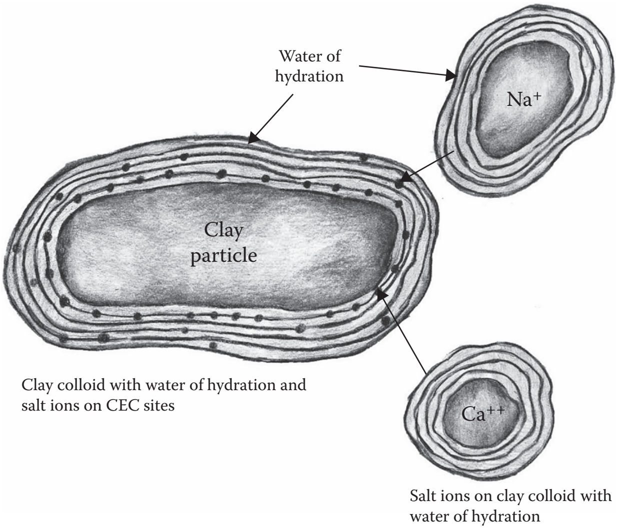


FIGURE 2.2 Clay colloid and salt ions (•) on the clay CEC sites. Water of hydration around clay particles and salt ions (either on CEC sites or in soil solution) is held by adhesion forces (inner water layers nearest the clay or ion surfaces) and cohesion forces (outer layers of water further from the clay or ion surfaces).

In addition to the importance of osmotic potential affecting plant water uptake when soil salts are high, the effects of ψ_o are important in the presence of a selective permeable membrane or a diffusion barrier, which transmits water more readily than salts. Two important diffusion barriers in the soil are (a) the soil–plant root interface, where the root cell membranes are selectively permeable and may selectively take up more water than salts, thus leaving soil salts to accumulate at the soil-root interface or rhizosphere; and (b) the soil water–air interface, where, as water evaporates, the salts are left behind to accumulate at the soil surface.

Pressure potential (ψ_p) is the component of soil-water potential due to hydrostatic pressure exerted by saturating an overlying soil area. When a drainage barrier, such as a soil layer that impedes drainage, allows extra water to be retained in the soil for plant use, the ψ_p is positive below the saturated layer, but is zero at or above the water table. The water table can be a perched water table due to a soil layer, such as in the USGA Green Section construction method for golf greens (USGA, 2010). In an unsaturated soil, $\psi_p = 0$.

Gravitational potential, ψ_z, is due to an elevation difference between two soil points. If the interest is total water potential, ψ_p, at a single point in the turfgrass rootzone, then $\psi_z = 0$, which is the usual situation when concerned with water availability in the rootzone at a particular location. If the concern is about the potential for water to move from a high-topography area of a golf green, for example, to a lower area by gravity (both surface and subsurface movement), then the ψ_z would be considered positive at the low point and the magnitude would be determined by the height difference and a time component (for subsurface migration).

Total soil water potential, ψ_z, is the sum of the above components. It is expressed in various units to describe energy status, but we will use *bar*, where 1 bar = 0.1 MPa = 100 kPa = 100 joules/kg = 100 centibar = 0.987 atm = 1020 cm H_2O. For soils at field capacity or drier, total soil water potential, ψ_z, is considered the sum of the matrix and osmotic potentials:

$$\psi_t = \psi_m + \psi_o$$

At field capacity, $\psi_t = -0.10$ to -0.33 bar (-0.01 to -0.033 MPa) and becomes more negative as the soil dries. At the permanent wilt point, $\psi_t = -15$ bar (-1.5 MPa). Plant-available water is considered between field capacity and the permanent wilt point, but most plant-available water is between $\psi_t = -0.10$ and -4.00 bar.

In nonsaline soils, the matrix potential accounts for the majority of the total soil water potential, while the osmotic potential is low at about $\psi_o = -0.10$ to -0.50 bar. To illustrate the difference between a nonsaline and a saline soil and the effect of ψ_o on ψ_t, first consider a soil with low salinity of ECe = 1.0 dS/m, and at $\psi_m = -1.5$ bar, the total soil water potential would be as follows:

$$\text{Since, } \psi_o\,(\text{bar}) = -0.36 \times \text{ECe (dS/m)} = -0.36 \times (1.0) = -0.36 \text{ bar}$$

$$\psi_t = \psi_m + \psi_o = -1.5 + (-.36) = -1.86 \text{ bar}$$

$$\psi_t \text{ (nonsaline soil)} = -1.86 \text{ bar}$$

Then compare to a saline soil of ECe = 6.00 dS/m and $\psi_m = -1.5$ bar, where

$$\psi_t = \psi_m + \psi_o = -1.5 + (-0.36 \times 6.00) = -1.5 + (-2.16)$$

$$\psi_t \text{ (saline soil)} = -3.16 \text{ bar}$$

These examples illustrate how appreciably soluble salts can greatly reduce total soil water potential and, thereby, the availability of soil water to the plant for uptake. In the above examples, both soils would have the same volumetric soil water content at the matrix potential of $\psi_m = -1.5$ bar, but the availability of this water is substantially less under the saline conditions. Figure 2.1 illustrates the impact in reducing the quantity of water to a plant while the total quantity of water may the same in a nonsaline versus saline soil.

Rengasamy (2010b) found that a soil solution salinity level of 25 dS/m resulted in an osmotic pressure of −9.0 bar, which greatly reduced plant-available water in wheat with 89% to 96% of the field capacity water being unavailable for plant uptake. This was a pot experiment with limited rooting volume, so in field situations where some of the root system may be in less salinized zones the results may be less dramatic. Devitt et al. (1991) noted that in salinized soil, increased irrigation frequency on Bermuda grass with saline irrigation water increased growth. However, on a clay soil, this resulted in less growth because poor soil aeration resulted. This demonstrates the adverse effects of high salinity on water uptake, and corrective measures by maintaining higher soil moisture levels may not work on all soils due to triggering low aeration.

2.2.2 PLANT AND SOIL SYMPTOMS OF TOTAL SOLUBLE SALT STRESS

Soluble salts are very dynamic spatially across the landscape and vertically within the soil profile, while also being temporally dynamic (horizontally both on the soil surface and in the subsurface) in response to irrigation additions, rain, and microclimate variations in evapotranspiration (ET), soil properties, and plant conditions. When coupled with the spatial and temporal nature of normal soil drought stress and the fact that soluble salts cause the same plant responses as actual water deficit or “normal” drought stress, but in a more rapid manner and to a greater magnitude, it is easy to see why this physiological drought stress is considered as the most important of the salinity stresses. Similar to normal drought responses, physiological drought causes a rapid and direct injury to the plant and becomes increasingly visible unless corrected with appropriate management strategies. Reduced availability of soil moisture for plant uptake under high soil salinity exposure causes a number of plant responses that are the same as with normal drought stress, but in a more aggressive pattern because concentrated salts can easily cause varying degrees of tissue desiccation beyond that of salt-induced drought stress alone. This additional plant response is pointed out later in the section on ion toxicities (Section 2.3.1, “Specific Ion Impact [Root Injury and Shoot Accumulation Injury]”).

Important plant responses induced by total salinity that result in *visible plant and landscape symptoms* are:

- Reduced growth rate because cell enlargement requires adequate water volume and osmotic or turgor pressure adjustments.
- Reduced leaf size and leaf area.
- Increased wilting, leaf rolling, and the blue-green coloration evident with drought-stressed grasses.
- Initially, a slight to moderate loss of green color, which may progress into browning or tan color as shoot tissues desiccate.
- Greater potential for desiccation under drought stress since at the same soil volumetric water content, the presence of accumulated salts enhances the degree of the localized water deficit relative to the same soil that is not saline. Tissue desiccation occurs more rapidly under high salinity. The combined discoloration effect of green color loss plus browning or tan discoloration caused by tissue desiccation is often called *leaf firing*.
- If substantial soil drying has occurred to allow salts to concentrate in the soil solution, roots (and especially root hairs) can also be desiccated similar to normal soil drought effects on roots. Roots would appear brown.
- For salt-sensitive plants, sodium levels may be sufficient to cause Na toxicity in the root system, which is exhibited as brown to black, weak, and spindly roots with considerable tissue breakdown.

- Trees and shrubs may show leaf firing and leaf drop, especially in the top branches (a so-called skeleton effect) due to salt accumulation in the leaves.
- The presence of salt-tolerant halophytes in the landscape is another indicator of saline soils. Examples of common halophytes are salt grass (*Distichlis spicata*), cordgrass (*Spatina gracilis*), alkali grass (*Puccinellia nuttalliana*), saltwort (*Salicornia ruba*), marine couch (*Sporobolus virginicus*), kochia (*Kochia scoparia*), or other salt-loving plants (see Chapter 9 for listings of salt-tolerant plants).

In addition to these visible salinity-induced plant shoot and root responses, there are *physiological effects on the plant* that are not visible but are nonetheless important. These physiological effects are similar to normal drought-stressed turf, such as:

- Reduced turgor pressure of shoot cells and cell wall extensibility (pliability or flexibility), where cells become less turgid due to reduced water uptake. Wear injury is greater on plants with reduced turgor pressure. Scalping problems often increase when these symptoms occur on turfgrasses.
- Partial stomatal closure occurs more quickly under saline conditions, which limits CO_2 exchange and transpiration that are important in photosynthesis.
- Photosynthesis may decrease due to reduced leaf area and stomatal closure.
- Transpirational cooling will decline, which is especially important on cool-season grasses in the summer. Plants are generally more sensitive to extreme temperature exposure.
- Reduced cytokinin synthesis in turfgrass roots and subsequent translocation of this hormone to shoots. Cytokinins are involved in many plant processes, including cell division, shoot and root development, chloroplast maturation, cell enlargement, and leaf senescence.
- Respiration increases and the defensive response of the plant is to utilize more stored carbohydrates, which can deplete reserves over time.

Many of these plant responses to high total salinity make the turfgrass more susceptible to other important stresses such as (a) drought stress, (b) indirect and direct high-temperature injury due to reduced water availability for transpirational cooling, (c) wear stress due to reduced turgor pressure and plant vigor for recovery of injured shoot tissues, and (d) predisposition to insect and/or disease attack.

Seedlings or newly established vegetative plant tissues are especially sensitive to these various salt-induced drought stresses due to their roots being confined in the surface zone, where accumulated salts are often concentrated by salt deposition following water loss by ET. Also, the new, juvenile tissues do not have the degree of salt tolerance mechanisms that a more mature plant has. Juvenile tissues are more prone to desiccation stresses. As root volume increases, the plant may be able to obtain water from a less salt-affected soil zone such as deeper in the soil profile and below any salt accumulation zone in the upper soil zones.

The most *visible soil symptom* of high total soluble salts is a white to grayish-white layer on the soil surface. An older term for saline soils was *white alkali* due to the frequent appearance of this white crust of salt arising by soil surface salt deposition as water evaporates or is transpired from the soil surface, leaving behind concentrated total soluble salts. This whitish layer is most apparent on bare soil or on thin turfgrass areas. A soil may have high salinity, but with a good turfgrass stand and canopy density, such as with halophytic (salt-tolerant) grasses, it does not exhibit the surface layer deposition of visible salt accumulation. Obviously, if salts are accumulating at the surface to a point of being visible, even halophytic grasses will exhibit severe salinity stress symptoms, including substantial death of most or all of the turfgrass plants. These saline areas exhibit the same soil structure and permeability properties as a similar nonsaline soil, since Na does not dominate the CEC sites on these saline soils.

Besides the surface crust of salts, saline sites often have subsurface zones of salt accumulation, which may occur from natural origin or be formed at the depth (from downward wetting front migration) of salt leaching by irrigation water or rainfall, especially in arid or semiarid climates. Sometimes these layers or lenses are concentrated enough to be visible in the profile as whitish deposition layers. However, there are other soil types that have white to gray-white layers that are not due to soluble salts, but more often to an insoluble deposition of lime—that is, calcite layers (see Chapter 3, Section 3.4.1). For soil profile layers very high in total soluble salts, it is not desirable for these salt layers to be in contact with the turfgrass root system or to allow salts to rise by capillary action into the root systems and resalinize the rootzone soil. When these total soluble salts move to the turfgrass rootzone or the rootzone is directly in contact with the salt layer, plants exhibit physiological drought symptoms to a pronounced degree and in a rapid manner.

In summary, the soil and plant symptoms caused by high total salt accumulation include the following:

- White or off-white crust on the surface
- Desiccated and dead grass canopy in a random surface zone pattern
- Definite layering in the upper soil profile of cup-cutter plugs
- Wet upper soil profile and somewhat drier soil beneath this salt-accumulated zone
- Rootborne pathogen symptoms on plant roots and at the surface
- Desiccated roots
- Increased incidence of localized dry spots
- Discoloration of the turfgrass or landscape plants
- Decreased wear tolerance in the turfgrass

2.3 ION TOXICITIES AND PROBLEM IONS

2.3.1 Specific Ion Impact (Root Injury and Shoot Accumulation Injury)

As total soil soluble salt level increases, the potential for specific ion toxicity also increases. Soils may contain excessive levels of certain ions that can (a) directly affect root tissues due to multiple soil salt accumulation, and (b) cause injury to plant shoot tissues due to uptake and accumulation in leaves (Duncan et al., 2009). While these ions may be present in the soil at establishment, often the ongoing salt addition source is the irrigation water used on the site. Germinating seeds, young seedlings, and sprigs are especially vulnerable because of their juvenile developing root systems. The ions that most often cause toxicity problems are *Na, Cl, and B*. However, trace elements can also result in toxicity or ion competition (availability for uptake) problems over time in some situations. Guidelines relative to potential for root and shoot injuries from accumulation of these ions are reported in the respective chapters on soil testing (Chapters 4 and 5) and water testing (Chapter 6).

In terms of *foliar uptake*, *accumulation*, and *injury*, any of the total soluble salts in soil solution can be taken up and potentially accumulate in leaf tissues to cause leaf injury. However, as irrigation water salinity increases, two of the most common salt ions likely to be present are Na and Cl. Chloride is a very common anion in irrigation water and can easily be taken up by plants in considerable excess compared to the very small quantities required as an essential micronutrient. As salts accumulate in leaf tips of grasses or outer margins of landscape plants in the topmost actively growing leaves, the salts can (a) cause tissue osmotic stress by reducing water for cell uptake and inducing dehydration of cells, which can eventually lead to tissue desiccation and leaf firing; and (b) also induce direct toxic effects, depending on the salt ion, since some ions can cause disruption of plant metabolic activities as internal concentrations increase.

Turfgrasses are generally less sensitive to Na and Cl uptake into leaves and foliar injury compared to other landscape plants, primarily because routine mowing removes accumulated ions in the shoot tissues. When trees and shrubs accumulate excessive salts, the initial symptom is leaf